INSTITUTION OF CIVIL ENGINEERS

Forensic engineering

a professional approach to investigation

Proceedings of the international conference organized by the Institution of Civil Engineers and held in London, UK, on 28–29 September 1998

Edited by B. S. Neale

Thomas Telford

Conference organized by Thomas Telford Conferences on behalf of the Structural and Building Board of the Institution of Civil Engineers.

Technical Committee:

B.S. Neale, *Health and Safety Executive,* Chairman
G. Butera, *Nabarro Nathanson*
P. Gardner, *Institution of Structural Engineers*
B. Gloyn, *Aon Risk Services Ltd*
B. Madge, *Forensic Engineering Group, University of Cardiff*
J. Maguire, *Lloyds Register*
E. O'Leary, *Veryards Ltd*
M.J. Pepper, *Standing Committee on Structural Safety*

Supported by

Forensic Engineering Group, University of Cardiff
Health and Safety Executive
Institution of Mechanical Engineers
Institution of Structural Engineers
Standing Committee on Structural Safety

Published by Thomas Telford Publishing, Thomas Telford Ltd, 1 Heron Quay, London E14 4JD.
URL: http://www.t-telford.co.uk

First published 1999

Distributors for Thomas Telford books are
USA: ASCE Press, 1801 Alexander Bell Drive, Reston, VA 20191-4400, USA
Japan: Maruzen Co. Ltd, Book Department, 3–10 Nihonbashi 2-chome, Chuo-ku, Tokyo 103
Australia: DA Books and Journals, 648 Whitehorse Road, Mitcham 3132, Victoria

A catalogue record for this book is available from the British Library

Availability: Unrestricted
Content: Collected papers
Status: Refereed
User: Civil and structural engineers

ISBN 978-0-7277-2787-9

Editor's preface

Welcome to this unique book, which draws together thoughts, advice, and opinions from professionals with a wealth of experience in disciplines related to forensic engineering. It is based on the first Institution of Civil Engineers two-day conference held in London, UK in September 1998. These proceedings are an important collection of papers and opinions for those concerned with learning from failures, usually of completed in-service facilities, which are not necessarily catastrophic ones. Value is added by the inclusion of extensive references as well as summaries of the discussions from each session at the conference. The latter enhances its usefulness by allowing the reader to be aware of peer group comments, together with an indication of the authors' responses. Further, this volume will appeal to interests wider than the UK as a number of international contributions are included. Delegates and authors attended from worldwide locations as far apart as South-East Asia, Australasia and the Pacific coast of America.

The purpose of the conference was to present an opportunity to bring together appropriate professionals to discuss topics of mutual interest. Thus the focus of the papers is wide ranging and includes many case histories to illustrate particular points. Papers and contributions are included from professionals such as civil and structural engineers, mechanical engineers and materials specialists, barristers, solicitors, health and safety regulators, and the insurance industry. The approach of loss adjusters was also discussed.

Benefits can be realised by the whole industry, from building and structure owners (by better design, construction and maintenance), through to, where applicable, the investigation of the performance of constructed facilities that, for whatever reason, did not meet the expectation of the clients. Professionals will be able to benefit from the outcomes of the imparted knowledge by better understanding in the spirit of continuing professional development and perhaps, in some cases, in basic learning. Information can also be fed into drafting of codes and standards. Where safety is concerned, the public, including those at work, will benefit.

In a brief overview of the papers, the conference rapporteur considers there are three main categories, and his synopsis is recommended as a concise introduction (see page 164).

A number of people have asked what 'forensic engineering' is – sometimes just to be sure! In the context of this book it is taken to mean 'the investigation of failures – ranging from serviceability to catastrophic – which may lead to legal activity, including both civil and criminal'. The inference is that technical investigation may arguably need to be more rigorous to withstand focused and penetrating scrutiny. This relates to the collection of evidence, the processing of the evidence and the presentation of evidence, including expert opinions – or "a professional approach to investigation".

In the combined discipline of forensic engineering, the communication channels will be to different people – with different understandings and for different purposes. These may include: the public, engineers, materials scientists, lawyers, loss adjusters, insurance professionals, facility owners and facility managers.

The organizing committee was chosen to provide a special multidisciplinary blend, with representation from the Institution of Civil Engineers and most of the organizations below, together with, of course, the legal and insurance industries. We were pleased that formal support was given to the conference by the Institution of Structural Engineers, Standing Committee on Structural Safety (SCOSS), Health and Safety Executive (HSE), Cardiff University Forensic Engineering Group and Institution of Mechanical Engineers.

As part of the international interest in the conference, the World Service of the BBC decided to broadcast a substantial item in its programme *The Works*, which included interviews with four contributors to the conference. Additional media coverage included a lead article in *New Civil Engineer* on the paper bringing attention to the risk of biological attack on concrete.

Links worldwide have been strengthened and the Institution of Civil Engineers looks forward to building on the wishes of delegates that a further conference should be held. Professional colleagues in the American Society of Civil Engineers are also organizing occasional conferences on this topic within the spirit of transatlantic co-operation.

As chairman of the conference organizing committee, I should like to thank all the speakers, chairpersons, delegates, the formal supporters, the Organizing Committee, Thomas Telford Conferences and, in particular, Eamon O'Leary, who volunteered for the arduous task of conference rapporteur and prepared the discussion summaries.

Brian S. Neale
Health and Safety Executive
Chairman of Conference Organizing Committee

Contents

Incident reconstruction

Lessons to be learned

Engineering

W. J. MARSHALL,
William J Marshall & Partners, London, UK.

INTRODUCTION

The three keynote papers which set the scene for this Conference outline the scope and context of engineering in a forensic context and highlight principles which practitioners in this fascinating but extremely demanding field need to recognise. This paper is written from the standpoint of a civil engineer who has witnessed the impact of litigation and forensic inquiry upon our profession and the construction industry generally for more than twenty years. It seeks to introduce the subject and cover as broad a prospectus as possible.

The term "forensic" simply refers to disputed claims which are debated or decided in a public arena: it effectively describes all things pertaining to the administration of justice. Initially, such open hearings were held in the forum - the commercial centre and main market of a city. The close links between public interest, commerce, disputants and the legal profession that were first forged in the marketplace have long been integral parts of our society.

When disputes cannot be decided without an understanding of some specialist activity, tribunals find it necessary to hear the views of appropriately qualified individuals who have studied the relevant areas of contention and formed an opinion for the guidance of the Court. Forensic science is consequently no more than the application of scientific knowledge to matters in dispute, whether in public or private tribunals. Since such differences may arise in any area of professional or commercial activity, the scope of Forensic Engineering can extend to every element of engineering, its practice calls for, at root, no more than sound knowledge of the subject under consideration. The application of that knowledge is, however, conditioned by the particular discipline of the law.

In adversarial systems of justice such as the United Kingdom, each party in a complex dispute will have the technical elements of their case scrutinised and reviewed by separate specialists throughout the action. Such so-called "Expert" witnesses, unlike witness of fact, may express opinions developed from their study of the circumstances of the case in the light of independent investigation and inquiry.

The need for independent analysis and judgement is constantly being stressed. In English jurisdictions, Expert inquiry and evidence must always be given from a wholly independent standpoint and be free from partisan bias. It is therefore a serious error to embark on forensic work solely to support some pre-existing case or to imagine that one is "acting for" the client. In certain other jurisdictions, Experts are expected to strain towards their client's case (the hired-gun approach). To my mind, an Expert is most effective in either jurisdiction giving advice to their client and the Court which they believe, from their knowledge of the case, to

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 1–10

be as penetrating and accurate as possible. Extensive published guidance on this vital part of forensic work, based on a succession of well-known judgements, will be considered in more detail by other speakers.

Disputes in the construction industry often involve large sums of money. The outcome is likely critically to affect the future of many professional and corporate firms as well as individuals. It is the duty of the forensic engineer to probe into problems which have defeated normal commercial negotiation and, where required, form carefully considered views on technical matters which will guide the lawyers' actions throughout the dispute.

Forensic work is unpredictable and extremely demanding on senior time. As with civil engineering, the consequences of misconceptions or oversights can be severe and very public. Sound reputations are hard won and vulnerable. Despite this, association with legal processes yields many valuable insights into our own profession, while the rigour necessary to meet forensic scrutiny can add numerous practical skills to our intellectual armoury.

In essence, the task of the forensic engineer is simply to apply and present a certain standard of technical knowledge within a legal context in the interests of justice. The knowledge required is no more and no less than that called for by the technical issues in that specific case. Additional skills, such as literacy and clear presentation are generally appreciated, but they ultimately should have little effect on the outcome. Perspective, foresight and the proper application of knowledge founded on solid experience will generate the most highly valued advice.

The organisers of this Conference have set the subject nicely into context. In addition to engineers practising across the field, there are contributions from other disciplines with whom the forensic engineer will work: representatives of the insurance industry who are responsible, in one capacity or another, for absorbing and spreading the financial risks implicit in construction generally; a Solicitor who for many years has acted for leading professional and commercial clients and a senior member of the Bar from Chambers specialising in construction law.

GROWTH OF FORENSIC ENGINEERING

The turnover of all facets of the construction industry in the United Kingdom over the years is typically of the order of 7% of the gross national product. Some twelve years ago, at the height of the litigation resulting from the Denning era, I estimated that the cost of all construction disputes which led to civil litigation, including all the costs of the actions, remedial works, and other associated costs, probably totalled not more than one half of one percent of that turnover. I argued that this cost imposed a useful and necessary discipline on practices within the industry which was by no means disproportionate.

In the intervening period, professional and commercial relationships that earlier had been constrained within a few well recognised procurement methods have been radically disturbed in attempts to reallocate responsibilities, duties and risk between financiers, clients, designers, contractors and operators. There has, perhaps unsurprisingly, been an increase in the publicity given in the technical press to failures and other shortcomings in the performance of the industry.

The costs arising from these shortcomings, and in particular that of resolving disputes by litigation, has been much criticised, prompting wide interest in alternative methods of dispute resolution and attempts to streamline legal processes. At the same time Health & Safety legislation has been enhanced, applying further causes of action and the threat of criminal proceedings.

Despite the lack of comprehensive statistics, there is a widely-held perception that disputes in the construction industry have generally increased in scale. Yet I note that over the last fifteen years the number of Official Referees, who hear most large construction cases, has scarcely kept pace with construction activity; professional indemnity and contractors' insurance rates have, despite occasional trembles, seemingly changed little. Where is the extra activity and costs that would result from growth?

Although there may have been marginal changes in the way in which construction disputes are handled, these broad but telling indicators suggest that the relative incidence and cost in real terms of construction claims and litigation is governed more by commercial pressures such as cash flow and the perception of success, rather than any legal structures. It may also be that our perception of growth in forensic engineering is no more than a heightened perception of matters that were earlier less open to public discussion, or perhaps changes in the amount of detail being digested ahead of the hearing.

What is certain is that there have been construction problems which have required informed and disciplined investigation throughout the history of engineering. The capacity for inquiry, the imagination and tenacity needed to trace the causes of unexpected events, should lie within the abilities of every engineer.

Most failures in recent centuries have led to forensic inquiry. For example, any review of papers on early dam and bridge failures, train accidents or boiler explosions will reveal the same pattern and techniques of inquiry and analysis that are used today to trace the source of aircraft accidents, design defects or even complex delay claims. The knowledge gained thereby has frequently advanced the state of the art.

One important reason, to my mind, for any real development and growth in litigation and forensic investigations might be the reluctance within today's managerial systems to accept responsibility for hard commercial decisions. The decisive facts, issues and arguments in major disputes are frequently hidden in masses of peripheral evidence; it takes an exceptionally independent employee to present fully detailed counter-arguments to an aggrieved senior. Plainly, no informed principal embarks on expensive litigation unless they can perceive some prospect of advantage. As a result, many disputes are resolved in the earlier stages of litigation, as the true pattern of events is uncovered through intense investigation and discovery by the forensic teams.

This analysis suggests that forensic engineers are an integral part of the mechanism by which society maintains standards within the construction industry. By proper investigation, explanation and good practice, forensic engineers assist this process, strengthen the industry and bring credit to their profession.

RANGE OF ACTIVITIES

Initiation

Since disputes can be triggered at any stage in the design, construction, operation, decommissioning, or even the ultimate disposal of engineering works, there are few aspects of engineering which might not come under forensic scrutiny.

The engineer must, first and foremost, be competent to inquire into the matters upon which his advice is being sought. A career spent in some extreme specialisation may be ideal in some cases, but a handicap when judgements are to be based on a broader understanding of design or construction procedures. An otherwise thoroughly well-qualified candidate may have unfortunate personal qualities or find it difficult to interpret technical detail for non-technical laymen. The ability to speak and write with authority on complex subjects does not come easily to many engineers, but it is a singularly helpful talent, provided it is combined with the capacity to organise and analyse detail and sound engineering judgement.

All engineers are required to have a measure of training in law and the administration of contracts. As their career develops, they gain further practical and theoretical knowledge of their profession and match their skills with those of fellow engineers. With increasing experience comes a broader understanding of engineering principles and the standards that other engineers bring to their work. It is *that* knowledge which the law needs to tap, whether it is in deciding state of the art questions (such as arise in professional negligence cases) or in interpreting contractual terms in the light of common usage.

All that I have said so far has indicated that forensic work calls for no knowledge of engineering beyond that which is expected of the practitioners in the field in question. However, there are without question certain qualities and techniques which, as an engineer, I have come to appreciate as being valuable attributes in forensic work. It is these attributes which are to be highlighted by the various speakers at this conference.

This action is restricted to outlining my perception of the work that an engineer will be called upon to perform in the course of a formal hearing of fair size in the English High Court. I leave other speakers to expound on the role of the other participants and the qualities lawyers (whether Solicitors, Barristers or Judges) seek in their engineer witnesses. The basic pattern of events are likely to be less detailed but broadly similar in principle in smaller cases or before different tribunals.

Many engineers first come into contact with forensic work when they become embroiled in a dispute. It is also not uncommon for an engineer, first called in to rectify a problem, then to devise remedial works and later be drawn into subsequent litigation as an Expert, rather than a witness of fact. Many engineers are introduced to forensic work by this route. Although the independence of evidence given by such engineers is frequently questioned, the Law sets no different standard: engineers are expected to act equally responsibly when fulfilling their professional duties. Every participant in a case, whether commercial or professional, witness of fact or Expert, has a duty to eliminate extraneous matters from the dispute, and, in common with other witnesses, swear an oath to tell the whole truth. As, in effect, independent technical advisers to the Court, Expert witnesses can be held publically to account if these obligations are breached.

All disputes arise from circumstances which give rise to a claim from one party for compensation from other parties. The claim is likely to be initiated and first defended by the individuals most closely involved in those circumstances. Battle lines may have been drawn between personalities long before the start of litigation

There are, as everyone attending this conference will know, innumerable causes of construction disputes. Mechanisms exist either within the contract or by constructive negotiation which in practice resolve all but remarkably few disputes before they boil over into the hands of insurers and lawyers. For example, a survey of Official Referees Court cases some years ago revealed that of all claims notifications made to insurers by Defendant professionals, some 40% were withdrawn and a further 40% settled even before a writ was issued (that is, the start of public litigation): only 20%, or one in five notifications, reached the very first stage of litigation. Some 4% of the original disputes were then dismissed or withdrawn and another 14% settled in advance of an award. Only 2% of the disputes initially notified (that is, one in ten of the one in five cases which reached court) were the subject of an award. I am aware of no similar statistics for other tribunals, but experience in my practice is consistent with less than 10% of the forensic matters on which we are instructed leading to an attendance at Court.

The cost and distractions created by litigation are widely recognised. Few disputants embark on such a bruising course without the belief that their arguments can be sustained. Many outside observers believe that bringing in lawyers exacerbates and sustains a dispute: be that as it may, the fact remains that the processes in advance of the full hearing lead in the more complex disputes to eighteen out of every twenty disputes pleaded by writ being resolved by negotiation rather than by an award. Since the parties must be assumed always to have been well informed about the details of the dispute, the vital role in resolving the competing arguments must be the well-honed procedures initiated and monitored by the Judge and legal teams prior to trial.

It is in this context that the forensic engineer can make a contribution which is at least as important as giving evidence during trial. Other engineers speaking at this conference will be describing their techniques of inquiry: this paper describes the circumstances in which those inquiries will be generated and the results compared very critically with those of your peers advising other parties.

The service of a writ initiates the pleadings stage of litigation, during which the points in issue are exposed, examined, digested and as far as possible eliminated. At the end of that stage, which in a small building case might take a few months as opposed to one or two years for heavier cases, the real differences in the dispute should, whether in the allegations or in the evidence, have been refined into a form which can be considered during the hearing.

Appointment

On being approached for forensic advice, engineers must first check that they are not compromised by a lack of knowledge, a conflict of interest, or previous commitments. Programmes for litigation tend to be elastic, which can cause severe strain at the cutting edge against fixed deadlines. It is prudent to seek preliminary details of the case, define the issues in dispute and the points on which advice is to be given. At this stage there is an additional risk of conflicts of interest. If the case concerns members of your own or associated professions, you are required as a matter of professional courtesy to contact that person and check formally that they have no objection to your inquiring into their work. The industry is sufficiently small for names to reappear and sufficiently mature for some distant overlap of interests to be tolerated. "Chinese walls" must be strictly maintained in these circumstances.

All being well, terms of engagement should be settled by an exchange of correspondence. Instructing Solicitors are, unless agreed otherwise, responsible for paying the fees of Expert witnesses. All litigation is contentious and every additional cost is unwelcome even to the most successful party: it is therefore prudent to monitor costs against budgets with care and ensure that everyone with financial obligations is aware of and accepts the rate of expenditure (a precaution which is of particular relevance in the more intense periods of a difficult case). The consequences of putting the interests of the case before financial considerations are not necessarily rewarding.

Pleadings and analysis

Soon after appointment, the engineer receives details of the dispute as it then stands with instructions as to the matters on which engineering advice and opinion is required. The way in which this material is presented varies markedly between firms of solicitors and with their progress into the case. Some will prepare comprehensive indexed briefs such as are given to Counsel and await your opinion; others will expect you to be an active member of their team from the beginning. There are no fixed guidelines. Common sense will indicate how to locate sufficient information for the purpose of understanding the case, making appropriate inquiries and developing and presenting advice.

Advising a potential Plaintiff places heavy responsibilities on the engineer, whose advice will underpin and set in motion a lengthy and expensive process. The Statement of Claim, setting out the allegations, must include Particulars of the technical case and will define the whole pattern of the dispute. The Defendant will quickly identify weaknesses in the facts or argument; they will respond with a Defence and Request for Further and Better Particulars which seek to expose those weaknesses. These legal exchanges will be recycled with amendments and serve to define the case with ever more precision. Claims which are constantly forced to shift ground betray insufficient preparation and what I call a "short" approach to case management. In one classic "long" claim for a very mature client, the Statement of Claim included two thick volumes of technical reports and opinion (prepared in the preceding year) which proved sufficient without the least amendment to carry the case through almost to trial two years later.

The engineer has therefore to anticipate potential developments and avoid rash statements. Where there is uncertainty, the range of risk posed by various outcomes must be explained.

Every engineer will recognise this advisory role as being no different from everyday practice. What makes forensic inquiries especially interesting is that no two cases are alike, that the personalities, situations and difficulties vary widely and that, unlike some classes of design, there are no received solutions.

As the preparation for trial continues under the direction of the Solicitor and Junior Counsel, there will be a search for relevant documents involving all parties by a process known as Discovery. A major project generates enormous quantities of paper and in some disputes key documents may be found widely distributed and in unexpected places. In negligence or delay and disruption claims, it is often necessary to reconstruct the chronology of events in great detail. While recent developments in document retrieval can speed some parts of this process, they can also create yet further masses of information, all of which has to be digested into manageable order.

To my mind, the difficulty of tracing the key events and their effects lie at the root of many unnecessarily prolonged and misdirected disputes. Once the scope of the dispute has been established, the first priority of any investigation must therefore be to establish the facts, analyse their significance and prepare a chronology of key events. Studying this chronology will reveal critical sections and any gaps in the pattern of events. It will act as a valuable aide memoire to all concerned with the dispute, being updated with new material as that becomes available.

As events fall into place, the engineer will start bringing the matters in dispute into focus. At this point, a Defendant's Expert will be developing views on the claim and expressing those views in Advice Notes, in Conference or perhaps in Affidavits. Defences and Requests for Further and Better Particulars will be drafted, discussed and settled. Further parties may be drawn into the proceedings and the scope of the pleadings will multiply.

The party being advised by the engineer is likely to have strong views on the case; within that organisation will lie (if it can be located) much knowledge about the matters in dispute. Some specialist sub-contractors will have unique insights into their product. The legal team relies on the engineer to extract this information and monitor the development of the technical argument critically and closely: far better that weaknesses are exposed in good time. Facts often cut both ways: events which in one light appear to be adverse can, once recognised prove surprisingly valuable in the legal context. If only for this reason, seemingly discreditable evidence must be prised opened to scrutiny.

Analysis of the evidence may disclose uncertainties that can only be resolved by further investigation, such as soils investigations, load testing or more refined structural analysis. Sometimes this work will bring the engineer to the limits of current knowledge and there may be the opportunity to extend those limits. It may be necessary to seek guidance from a specialist in some field outside one's own experience, employ a specialist testing laboratory, or initiate research. All activities should aim to clarify issues in the case and, of course, be instituted with the full knowledge and approval of the legal team.

The time which is necessary to expend on discovery, the preparation of chronologies and on further investigation can be grievously high. They are critical, but tedious and largely mechanical tasks. Insufficiently alert juniors might miss vital evidence, but senior staff might overload the budget. The engineer is likely to be involved in this search for documents and indeed, in some very technical cases, may do much of it alone. A surprisingly effective and sociable solution is "round-table" Discovery, whereby the Solicitor's team, including Experts, the Insured and occasionally Insurers, distribute disclosed material between themselves in one room to label and, if appropriate, comment on items and events as they come to light.

Experts' meetings

Should the dispute not be settled beforehand, timetables set for the preparation of the case will in due course call for the Experts of like disciplines to meet, probably "to agree facts and narrow issues". At this stage in the proceedings, the pleadings should be well developed; major changes are unlikely but if introduced certain to create dissatisfaction either amongst the parties to the action or on the Bench. The issues that remain in dispute should be now well defined. It is the task of the Experts to narrow these issues as far as possible through direct Without Prejudice discussion.

The Judge will often order the meetings of Experts to begin some time before reports are due to be exchanged, on the basis that it is easier for Experts to shift ground if they have not previously nailed their colours to the mast. This is generally a sound arrangement, although there may be difficulty in understanding the reasoning behind a contrary opinion if the originator is not prepared to expose his own methods to scrutiny.

The conduct of Experts' meetings and the protocols that govern them are well documented and are beyond the scope of this paper. Serious problems can arise if the conventions of these meetings are ignored. When a wide measure of agreement is reached, negotiations between principals are facilitated and settlement will usually follow. It is therefore in the nature of litigation that only those matters about which Experts still disagree reach the hearing. Jaundiced comments about Experts being eternally at odds are rarely justified, either by the statistics quoted earlier, or by my personal experience.

Experts' meetings present the best possible opportunity for responsible engineers truly to understand the source of their differences. Some of these might lie in their knowledge of the facts of the case, a situation which can quickly be corrected. Their interpretation of those events might not be the same due to differences in their training or experience: both approaches would then be legitimate, be accepted as such by the other Experts and properly be included in any agreement on their Opinions for the use of the Court. Since Experts receive information by different routes, their perception of events will have a different perspective. All these differences should be explored and resolved by point by point discussion.

No minutes are taken at Experts' meetings, but one member (usually the Plaintiff's Expert) will keep a record of the areas of agreement and - equally important - disagreement. An Expert who rejects some point may yet find it hard to go on record as believing the opposite: such situations can flush out the real sticking points and lead to much clarification. Reflecting on the way in which the point will be met in the witness box can concentrate a wavering mind.

There will remain the risk, common to all negotiations, that premature disclosure of agreements through the medium of Experts' meetings will serve to sharpen the arguments of the other parties. So it might, but it is not the role of Experts/Forensic engineers to negotiate or be partisan; it is to present an independent opinion to the Court. This opinion will be tested by hostile cross-examination in the witness box.

Experts' meetings will normally continue while they make progress. Not unusually, they resume after the exchange of Expert reports and may continue during the trial itself.

Reports and opinions

It goes without saying that the engineer should have the ability to express his findings in clear, concise reports in which each element has its place. Technical detail must be explained in terms accessible to the layman and not allowed to obscure the line of argument. Further explanation and detail can be put into Appendices.

It is not the engineers' role to advise on liability: that role lies with the lawyers. Engineers will address issues of causation, namely, the relation between cause and effect. In an accident investigation, as with a delay claim, there is some known effect which causes damage. The engineer must examine the evidence to work back to its cause. The cause of events may be complex and obscure and it is by the exercise of insight and imagination during the investigation stages that the true mettle of the engineer is revealed.

The Hearing

The period leading up to the hearing will, even in the best regulated case, make heavy demands on the engineer. At some point Leading Counsel may be briefed and bring changes in approach; with greater concentration on detail, fresh issues will emerge and require examination. The activities of the other parties, who will also be busy, will generate further exchanges calling for review by the engineer. All their activities will be co-ordinated by the instructing Solicitor in accordance with the needs of Counsel.

It is at this point that the merits of a thoroughly prepared case brings dividends. If timetables have not been met, the necessary work will be compressed into an ever narrowing period and there will be problems. These will be made worse by any major shifts in the case introduced by other parties, who have little interest in assisting your progress. Duties will pile onto every member of the legal team as Witness statements are finalised, supplementary reports exchanged and Counsel's queries met in a succession of further briefings and conferences. Counsel earn their living by their intellectual gifts: once seized of a point they are off like greyhounds. Woe betide the engineer who loses sight of that particular rabbit!

The engineer will probably be required to attend Court at least while matters within the engineer's purlieu are being heard. It is unwise for Expert witnesses to be absent when evidence of fact is given, as important new evidence may emerge from unexpected places.

Normal good manners and alert observation are sufficient to sustain a witness who is in command of his subject through giving evidence. Practice in the Civil Courts such as the Official Referees Courts is in the hands of skilled professionals, who have no need of the overt histrionics of fiction. Witnesses are treated fairly and with precision. It is inconsiderate and counter-productive to give slipshod replies, answer a different question or be other than one's natural self. Gratuitous comments cloud the argument and are best avoided.

Finally, it is well to remember that the privilege of giving Expert evidence is contingent with that evidence being of genuine personal opinion, independently arrived at for the benefit of justice. The construction Bar is not especially large and unreliable or misdirected witnesses are remembered.

CONCLUSIONS

The title of this paper, quite deliberately, is "Engineering" rather than "Forensic Engineering". While there may be certain scope for forensic specialists in the field of accident investigation, civil (as opposed to criminal) cases generally involve considerations of industry practice which calls for solid experience and precludes narrow specialisations.

Many things can be learnt from forensic work, but the process of disseminating that knowledge, save in high profile cases, tends to be indirect and slow. A surprising number of cases involve unwitting departures from well-established practice. Others relate to untoward events that, until recently, would have been viewed as part of the risks associated with major construction. If , with hindsight, such events could have been avoided by one or other of the participants, it is now too often found that they, being insured, have attracted liability.

Much can be learnt from the great “state of the art” failures, which rarely lack for publicity. Problems which cast a shadow over major commercial interests come into a different category: proceedings other than in Court are confidential and permission to publish may be withheld. Lessons from such events tend to emerge from academic sources or the professional literature over a period.

More menacing are the problems which creep up on the industry through a combination of small changes in materials, design methods or service conditions. Many of these problems are first identified accurately by forensic investigation following some lack of performance ascribed first to other reasons.

By means such as have been described, forensic engineering will continue in the future to play an essential part within the regulatory mechanisms of the engineering industries. It is my hope that this conference will draw engineers’ attention to forensic procedures and point to standards of excellence and distinction which the law is right to expect from the engineering professions.

The Unrecognised Importance of Insurance

BILL GLOYN,
Chairman, Commercial Property Division, Aon Risk Services

The title of this paper was not chosen lightly. More than 30 years experience in the insurance industry, linked with the commercial property and construction sectors, have certainly demonstrated repeatedly to me that the priority which is given to insurance is very low. This is perhaps not surprising as very often those involved in these sectors are practising optimists. Otherwise they would perhaps find some other career. There is certainly a general unwillingness to face up to issues concerning risk, especially when it involves paying part of profit away in the shape of an insurance premium!

Insurance does however have a very important role to play in business life in general. If matters go smoothly it is rarely apparent. Unfortunately things do go wrong and that is when it is needed. The cover provides the financial resources required for legal obligations to be met, damaged property to be replaced and a business to be maintained.

In common with most things however insurance repays careful preparation. Unfortunately this does not always happen and the inevitable shortcomings are detected once a claim arises. Extreme diligence and caution therefore needs to be exercised, both professionally and personally, in the handling of insurance affairs. There is a need as never before for specialist and expert advice - insurance today is not for amateurs. It demands careful consideration by the client, consultants and contractors to ensure that each one is adequately protected against their own risk exposures.

The aim of this paper is to dispel some of the uncertainty which exists regarding the subject. In particular I will look at some of the basic principles of insurance, very often ones which create the complications. I will also outline the various types of insurance which could be involved in an incident which would require forensic engineering. Finally I will give my own thoughts on the issue of claims management. I do this from the viewpoint of the client; you will have the benefit of a far more technical outlook in the paper being presented by a loss adjuster tomorrow.

RISK MANAGEMENT

Insurance is the traditional way of transferring risk. As such it forms only a part of the risk management process. This consists of a three part process:

- Risk analysis and quantification
- Elimination or reduction in risk
- Transfer or retention strategies

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 11–18

The time available today is too short to go into a detailed examination of the whole risk management process. It can be dealt with very simply but effectively by experienced practitioners. On the other hand far too much time can be spent over minute analysis which can often lead to overlooking major risks, not least of all because "analysis paralysis" often sets in before the exercise is complete.

The minimisation and reduction process should be an ongoing one. Insurers can quite rightly, and legally, expect that an insured will be taking all reasonable steps to avoid a claim. Insurance is there to protect against the unexpected and fortuitous. It is for that reason that the market in general is imposing wide ranging exclusions in respect of the Millennium Bug. Not only is this problem so internationally widespread as to be a potential source of insolvency for the world insurance market but more importantly it is a matter substantially in the hands of those at risk. Insurance should never be considered as a licence for poor performance although occasionally it is regarded as such. A valid method of risk reduction is by careful contract drafting. Insurers are doing just that by contractually excluding Millennium problems from their contracts - otherwise known as insurance policies.

Many organisations, after adequate thought, are well able to absorb a certain amount of risk. This is often more cost effective than insurance which theoretically involves profit for a number of other parties. For many larger organisations this absorption is achieved by means of their own captive insurance company. For others the answer may lie in a mutual insurer as many firms of major architects discovered when they set up the WREN to insure their professional indemnity risks. Yet another option is merely to expose the profit and loss account. It is, however, when a particular risk exposure threatens the stability of the balance sheet that some other form of risk transfer may be considered. Insurance may of course be imposed contractually; leases, funding agreements and building contracts are typical examples. Another possibility is the statutory imposition of an insurance requirement, as found under the Road Traffic Act or Employers Liability Insurance regulations.

Whether imposed or chosen, the insurance route is well trodden. We are fortunate in having London as the world centre of the insurance market, not least of all for the benefit that brings to the UK economy. We also have one of the most mature markets in the world with a level of expertise which is unparalleled anywhere else. It is worth noting, however, that this international position is far from safe. Not least of all the insurance companies, the traditional risk carriers, are threatened by other newcomers to the scene in the form of banks and capital markets. On a personal level we have seen this with the rapid development of the direct insurers for personal lines business. Many major commercial insurance contracts, especially those for international organisations, have substantial elements of risk transfer into the capital markets via a wide range of sophisticated financial instruments.

It is not my intention to dwell on these but rather to focus on the complex web of interlocking insurance policies with which we will all be more familiar. In a rapidly changing world it is however important to be aware of what might be just around the corner. To use a favourite risk management comment - it is better to avoid a claim than to have an efficiently administered one. Ask anyone who has suffered a motor accident recently!

INSURANCE - CHAIN MAIL OR STRING VEST?

In the main the insurance policies which are likely to be concerned in a forensic engineering exercise come under four headings.

- Property Damage
- Consequential Loss
- Legal Liabilities
- Personal Protection

The first of many likely complications comes from the fact that not all of them will be arranged by the party which suffers the immediate loss. It is indeed possible that none will be so arranged. As a result there is unlikely to be a commonality of interest between the insurers, the insured and the claimants. This is bad news for those who suffer the loss, and aggravation or worse for most of those involved. It is however extremely heart warming for the litigation industry. Taking one particular type of insurance as a example, the DTI report on professional liability suggested that upwards of 80% of claims payments under PI policies were needed to fuel the litigation process. This leaves only 20% to satisfy the claims of those who suffered the loss. Although I have no way of knowing what the total PI claims outlay is for the UK or internationally it is not a small sum. 80% of it is not small either!

Before examining some of the policies in a little more detail it is worth considering some of the legal principles which help to frustrate the claims process and help to underpin the concept that insurance is not a subject for conversation at polite social gatherings.

SOME OF THE LEGAL PRINCIPLES EXAMINED

With so much money going into the litigation process it is hardly surprising that it is legal issues which come to the forefront rather than practical ones which seek to address the problem. There are some interesting nuances which serve to assist this process very effectively. I shall focus on just a few.

Insurers Profit & Loss Account - The overriding responsibility to deliver corporate results is perhaps the underlying cause which drives all others forward. Over the past 15 years or so there has been an enormous surge in market capacity throughout the world. Very often this has been accompanied by a reduction in premium rates. Rarely has it been accompanied by a reduction in claims frequency and cost. The result was a number of years of severe underwriting losses which had to be seriously addressed. Insurers fought to reduce their expenses by cutting staff and reducing their branch operations. In the end however the largest single outlay for an insurer is claims payments. In addition in attempting to control the costs of the claims they will pay, there has been a perceptible move to question the validity of any substantial claim, often using some of the techniques outlined below.

Insurers Security - As a result of the difficult trading period a number of substantial insurers have disappeared into insolvency. Some of the best known were the Municipal Mutual, although they were partially rescued by the Zurich, and the Builders Accident. Throughout the international scene there have been many others, both direct insurers and reinsurers. Their failure has put even more strain on the stressed market. A number of policies continue to give protection for a considerable time after the period of cover has elapsed. Amongst these, and pertinent to the topic of this conference, would be public and products liability insurance, the latter giving protection in respect of injury or death and damage to third party property caused by the supply of a defective product. This cover would be called upon in the event of a component failure which in turn led to substantial property damage and subsequent injury. The possibly unrecognised failure of an insurer could jeopardise the protection available to interested parties.

Utmost good faith - It is a basic principle that insurance is a contract of good faith. This requirement at least applies to the insured who has many duties but particularly that of disclosing all material facts. Unfortunately there is no clear way of identifying what these might be, at least not until the claim arises. The duty upon the insured is to disclose to the insurer all facts that would affect a prudent underwriters assessment of the risk. Failure to do this, or to misrepresent facts, generally gives the insurer the right to avoid the policy. It does not matter that the claim is not connected with the fact; for instance, incorrect information about the previous history of flood damage can give rise to the insurers right to avoid a fire claim. There have been a number of high profile court cases on this subject over the past few years but these have done nothing to relieve the insured of a total obligation. It is important to note that the failure of a material damage claim can also lead to the avoidance of a consequential loss claim. It is a fundamental proviso that a successful claim for the former must precede the other.

Inter-relationship of insured parties - There is continued confusion over the rights of a party whose interest is noted on a policy. It is still a frequent requirement but in reality means little or nothing. The only real protection that can be obtained is to be a joint insured under a policy. Also required is an express provision of severability to avoid the contract-breaking actions of other parties, including joint insured, prejudicing any interest in the contract. The joint insured party is entitled to a share in the control of the claims procedure and subsequent proceeds together with rights of notification of the cancellation of the policy. It should be noted, however, that without express provision there is no right to be notified of the non-renewal of an expired policy. It may not come as a surprise to learn that claims involving a number of joint insured may themselves be difficult to negotiate. Insurers have no duty to act as arbitrators between disputing insured. They are likely to seek to satisfy policy liability by issuing a cheque in joint names leaving it to the parties concerned to fight it out amongst themselves.

Subrogation rights - After playing all the other cards, if an insurer is forced into the position of having to pay out will the matter stop there? It most certainly will not! Indeed here is perhaps the nub of why insurance is so important but often unrecognised. Under a contract of indemnity, and following payment of a claim to the insured, the insurers have the right to be placed in the position of the insured in pursuing rights and remedies against third parties. There are no subrogation rights against joint insured, another good reason to seek this status. Insurers may agree to waive their rights against specified parties, often on payment of an additional premium. This is however not the case in a landlord/tenant relationship where case law has established that the tenant who pays the premium, by way of rent, may not be subrogated against.

These are however exceptions rather than the rule. Material damage and liability insurers will seek to find another party to at least partially repay their loss. The only way they can do this is using the threat of litigation, a threat which often extends to the courtroom door and beyond. It tends not to be an area in which gentle persuasion is terribly effective.

WHAT INSURANCES MIGHT BE INVOLVED?

As previously stated there are four major classes of insurance which might be encountered in a serious incident which affects a building. This could be a building under construction or completed and occupied. It could also be some other form of structure, such as bridge, chemical plant or even a ship. All are likely to be insured in a similar way although marine and aviation insurance do have their peculiarities which are outside the scope of this paper.

Property Damage

During construction there will be a **contractors all risks** policy effected in accordance with the contractual requirements of either a recognised standard form or some manuscript derivation prepared by the clients professional advisers. Following completion of the contract cover will be transferred to either a **commercial all risks** policy a **fire and specified perils** cover. There may also be an **engineering breakdown** insurance which is often coupled with a **statutory inspection** contract.

Within the building are likely to be contents. If the property of the building owner they may be covered under the same all risks policy as the buildings but a separate contract may exist. A tenant will obviously have a separate **contents** insurance, possibly on an all risks basis and possibly with **theft** insurance included or as a separate policy.

A particular form of insurance becoming more common in this country provides cover for the building owner in respect of **latent or inherent defects.** Failures in design, workmanship or materials are specifically excluded from almost every other type of insurance. A combination of the prudence of the building owner and the lack of confidence of tenants and funders has created a surge in interest in this cover for commercial properties. The **NHBC Scheme** has obviously been in existence for many years in respect of residential property. **Decennial** insurance in France and other Napoleonic countries is a statutory requirement designed to give direct protection to those who suffer damage who might otherwise only have legal and contractual remedies to rely upon. As the damage may only become apparent some years after practical completion, and after changes in ownership, those remedies can be diluted by time or dissolve completely following insolvency.

Consequential Loss

This cover comes in many guises. In essence it is designed to protect against the financial consequences of insured damage to property. As previously stated the cover must follow the same basic provisions as the material damage insurance and may provide for **loss of rent**, or for the tenants or occupiers **loss of profits**. It may be on a wider **business interruption** basis providing an amalgam of various protections including **increased costs of working**. The cover may be on an anticipated basis, for buildings under construction; it can reflect turnover at historic levels or perceived expenses. Whatever the basis it will be for a set period, often quite short for profits, perhaps twelve or twenty-four months, but much longer for rents where periods of 5 or 7 years are not uncommon. Consequential loss claims are always likely to turn into a negotiation which ends in a compromise. The settlement of a fixed contractual amount, such as loss of rent, is relatively easy but the crystal ball gazing needed to estimate future profitability of the disrupted production of a factory is much more complicated. This only adds to the subsequent difficulties when attempting to exercise subrogation rights; the basis of settlement agreed by insured and insurer may not be acceptable to the professional indemnity insurers of a negligent professional.

Legal Liabilities

We all have a tendency to look for blame in others if something goes wrong. As a result there are a selection of liability insurances designed to give protection, both in respect of costs and damages awarded by the court following the establishment of a legal liability and also the costs involved in attempting to avoid that uncomfortable situation. **Public Liability** insurance gives protection in respect of injury or death to third parties and damage to third party property arising out of the business of the insured. A variation on this is **Property Owners** liability cover which obviously limits the activity to ownership of property although management and other peripheral issues may also be covered. As previously indicated **Products Liability** insurance is protection for the supplier of a defective product although this does not include any responsibility for the replacement or repair of the product itself, merely the consequences. A rare example of a statutorially imposed insurance requirement is that for **Employers Liability** insurance. This provides protection for the employer in respect of legal liability arising to an employee following injury, disease or death. Unlike **Workmen's Compensation,** as found in some other countries, it does not pay an immediate benefit to the employee but merely provides the financial wherewithal to allow the employer to do so if found legally liable.

From the same stable but rather different is **Professional Indemnity** insurance. This is designed to protect the professional in the event that their activities create a liability arising from error, omission or neglect in the provision of professional services. Unlike the other liability policies examined, PI cover is on a claims made basis - the policy in force when the claim is made is the one that responds rather than the one that was in force when the incident occurred. It therefore has to be kept in force for as long as a potential liability exists. The terms and conditions of the cover can also change at any renewal. This may turn out to be an unpleasant surprise if care is not taken to monitor the cover. Although provision for monitoring is usually included in professional appointments and warranties in practice it is rarely undertaken.

All liability policies have an important factor in common. They are designed to protect the insured against whom some legal liability is being alleged. They do not provide direct protection to the party who has suffered the loss.

Personal Protection

Many private individuals and employees will be covered by **Life Assurance**. There may also be **Personal Accident & Sickness** cover often coupled with **Private Medical Expenses** insurance. Although individuals may take out these covers they are at least as likely to be provided as part of an overall employee benefit package. Within such cover there may be protection for the employer to mitigate the costs of absence from work, either temporary or permanent, of **Key Staff**.

On scanning through the above list it is easy to see how many separate contracts arranged by a wide variety of parties could be involved in even a relatively small incident. Serious damage to a multi-occupied property involving death or injury to third parties as well as the employees of the responsible party with subsequent interruption to business will involve literally dozens of separate contracts of insurance. The basic provisions of them all will have to be satisfied before each claimant feels that they have obtained a satisfactory settlement. The fact that this does not always happen is very often the responsibility of the claimants themselves.

CLAIMS MANAGEMENT

Major incidents, it is true, do not happen that frequently. As a result they often find the various insured concerned very ill prepared.

Often the insured will have arranged cover with the assistance of a broker. Immediate advice and support should therefore be at hand, provided by an experienced claims team for whom such an incident is not a one-off experience. Some insureds, admittedly, find comfort in dealing direct with their insurers. It is sometimes in the event of a major incident that their confidence is undermined - remember the profit and loss account. No matter what the circumstances it is important to give immediate notice to the insurers of any circumstances which are likely to give rise to a claim. The mechanics of doing this are generally clearly set out in the policy document and form part of the conditions of the contract. Failure to comply with them will offer yet another potential route to the insurers for avoiding a claim.

It is quite likely that the insurers will appoint their own professional advisers. Amongst these will be a loss adjuster in respect of material damage and consequential loss claims and a claims investigator, often in-house, for liability matters. The latter are also likely to see lawyers appointed as will a damage claim if the circumstances begin to give any cause for hope that a plea for avoidance may be justified. Any of these parties may well call in an expert to conduct forensic investigation but you will hear more of the circumstances in which that might be needed in tomorrow's more detailed paper.

It is worth noting that the insurers will not call in a loss assessor. That will be the prerogative of the insured who will have to meet the resultant fees. It is not likely that the services of a loss assessor will be required where the broker is performing a proper function and other professional consultants are engaged as appropriate. There may be a role for the assessor in dealing with a complicated stock damage loss when the client does not have sufficient resources to prepare a statement of claim. A competent broker should however always be in a position to negotiate at least as good a settlement with the insurers once the actual claim is prepared. The broker should also see the remainder of the claim, for damage, consequential losses or liabilities, through to a successful conclusion.

Recalling the basic requirements for the acquisition of subrogation rights it is only when claims have been paid that the insurers have a right to seek recovery from third parties. In practice, however, this process is likely to start at an earlier stage, especially if the sums are big enough.

AN EPILOGUE

With the potential complexity of interconnecting insurance policies involved in a major incident it will not come as a surprise that the subsequent recovery actions and litigation become one big carousel. The blame cannot be laid at the door of the lawyers - the insurance industry has basically bought it upon itself. The concept of doing away with subrogation rights and letting the claims rest where they are originally made has been examined on numerous occasions. Seemingly blind to the costs of pursuing all the inter-related actions, insurers appear to be unwilling to give up those rights, even though they publicly state that they rarely exercise them. It is however insurers who pay the vast majority of legal costs and indeed meet a substantial percentage of court awards in one way or another.

Is it time that, as part of this Lord Chancellors attempts at wide ranging legal reform, a regime of no fault liability was carefully examined at senior government level? Or might it be that there are too many vested interests in preserving the current system.

One thing is certain - there should be no reduction in work for forensic engineers. Incidents will still occur and will need to be investigated. Without the fear of recriminations and litigation it is more likely that the results of the investigation will become public knowledge. The lessons learned can therefore be put to good effect with a subsequent reduction in the corporate disasters and personal tragedies that so often ensue. Who knows - in time some may even be avoided altogether.

What are lawyers looking for?

JOHN WARD
Partner in Beale and Company, London, UK

INTRODUCTION

1. I am taking "forensic engineering" to be engineering which is in some way connected with or used in courts of law, a relatively simple definition, but one which I hope will suffice for today's conference.

   Engineers have to face the fact that proceedings in courts of law are controlled by lawyers, including judges, and that therefore engineers who wish to practice "forensic engineering" will have no choice but to deal with lawyers on a daily basis.

   In the UK, we have an adversarial system of civil justice, not an inquisitorial system. Lawyers owe a duty to the court in the conduct of litigation, particularly a duty not to mislead the court in any way, but, subject to that duty to the court, lawyers' duties are owed to their clients. Engineers called to give expert evidence in court are in a more difficult position, because they have to give evidence. Lawyers do not give evidence. The expert is being paid by the client, but is expected to be independent when giving evidence to the court. It is this apparent conflict which lies at the root of most of the issues which arise in relation to forensic engineering.

2. It is an unfortunate but undeniable fact that many parties to litigation, particularly commercial litigation, do not see it as a search for objective truth; they see it as a contest which they wish to win, and winning may include settling on the best terms available. Engineers instructed as expert witnesses need to be aware of the pressures which they are likely to face as a consequence of the adversarial system. Engineers should be under no illusion about this: judges rely on and need good expert evidence, but if judges take the view that many experts are now no more than additional advocates for their client's case, then those experts will carry less weight, and the need for, or value of, such expert evidence may be called into question.

3. In fact, in my view, experts fulfil a vital function in the whole dispute resolution process, not just litigation.

   Firstly, they may be involved very early, perhaps when a client knows a problem exists but does not know the cause of the problem and may not even have considered the question of whether or not a legal dispute may arise. At this stage, the engineer's work is investigation and advice. If no dispute is contemplated at this time, the

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 19–26

client's instructions to the expert and the expert's advice may well not be privileged in any future legal proceedings.

Then, when (if) a dispute occurs and cannot quickly be settled, the expert will be needed to investigate the technicalities, including the history of the matter, advise the client about the technical aspects of the case and also perhaps advise the client about the standard or performance of those concerned with the project. Advice may well also be needed concerning the correct level of remedial works and the losses which are likely to have been suffered by the client as a consequence of the problem. The advice is likely to encompass work on assisting lawyers to plead the client's case in the dispute, the preparation of expert's report, attendance at experts' meetings, and, in a small minority of cases, giving expert evidence in court.

The expert's role is a very demanding one.

4. It is worthwhile setting out the duties and responsibilities of expert witnesses in civil cases, as identified by Cresswell J in "The Ikarian Reefer":-

(i) expert evidence presented to the court should be, and should be seen to be, the independent product of the expert uninfluenced as to form or content by the exigencies of litigation;

(ii) an expert witness should provide independent assistance to the court by way of objective unbiased opinion in relation to matters within his expertise. An expert witness in court should never assume the role of an advocate;

(iii) an expert witness should state the facts or assumptions upon which his opinion is based. He should not omit to consider material facts which could detract from his concluded opinion;

(iv) an expert witness should make it clear when a particular question or issue falls outside his expertise;

(v) if an expert's opinion is not properly researched because he considers insufficient data is available, then this must be stated with an indication that the opinion is no more than a provisional one. In cases where an expert witness, who has prepared a report, could not assert that the report contained the truth, the whole truth and nothing but the truth without some qualification, then that qualification should be stated in the report;

(vi) if, after exchange of reports, an expert witness changes his views on a material matter having read the other side's expert evidence or for any other reason, such change of view should be communicated (through legal representatives) to the other side without delay and when appropriate to the court;

(vii) where expert evidence refers to photographs, plans, calculations, analyses, measurements, survey reports or other similar documents, these must be provided to the opposite party at the same time as the exchange of reports.

No doubt a great deal will be said about these duties and responsibilities over the two days of this conference.

5. Every expert should expect to be cross-examined about the principles set out above. The expert may not be told directly the purpose of that cross-examination. Its purpose will be to see whether or not the evidence is admissible as expert evidence, and so every expert should be aware of those principles when appearing as an expert in a civil case.

6. The need to call expert evidence is not confined to civil litigation. Experts may be called in criminal cases, in public enquiries, planning appeals and even Parliamentary hearings. It is important for the expert to establish the requirements of the particular role in each case.

7. Although it is principally the lawyer's responsibility, it is important to see that the right kind of expert is being called for the case. For example, in a recent case concerning an alleged negligent survey of a building by a building surveyor, one of the parties sought to call a structural engineer to give expert evidence about the performance of the surveyor. The allegations against the surveyor were of the usual negligence type, i.e. that he had failed to exercise the standard of skill and care to be expected of a reasonably competent surveyor. The court ruled that a structural engineer cannot give expert evidence about the standard of care required of a building surveyor and refused to allow the structural engineer's evidence to be given. As set out above, there is a duty on experts to declare that any particular issue is not within their expertise and competence. Any expert who tries to give evidence outside his or her competence may well end up footing the bill. Experts should therefore be careful to check that they are able to give the kind of expert evidence required, and you should refuse to give expert evidence in matters outside that competence.

8. The adjudication provisions of the Housing Grants etc Act 1996 came into force on 1st May 1998. The extent to which the construction industry uses the right to adjudicate remains to be seen. Also, it will be interesting to see the types of disputes which are referred to adjudication. It is likely that experts will play an important role in at least some adjudications. Any dispute about the standard of performance of contractors or professional people is likely to involve experts assisting the parties and, of course, the adjudicator is entitled to engage technical experts if necessary.

   The time limits for adjudication are very short. Experts are going to need to be geared up to act very quickly to respond to their clients' needs. Adjudications are not in any sense judicial proceedings, and it is very unlikely that adjudicators will call for experts reports to be served. However, there is nothing to prevent any party from putting in an expert's report as part of the information supplied to the adjudicator, nor to prevent an expert appearing as part of the client's team at an adjudication. Adjudication may therefore present opportunities for experts.

9. Experts need to be wary about referring to privileged documents in their reports because it is likely that the other party will call for a copy of such a document, particularly if it can be shown that the expert is basing at least part of the report on that document or information contained in that document.

I will mention some of the things I am looking for in an expert, some of the things which I believe judges are looking for, and then I will mention some of the reforms which Lord Woolf is proposing in relation to expert's evidence.

LAWYERS REQUIREMENTS

I stress that these are some of the things which I look for in an expert, and they are my personal views. They do not necessarily reflect the views of other lawyers.

10. (i) Honesty.

Experts need to be honest with their clients, the lawyers, the courts, and themselves. If there is bad news to be given, I need it straight from the expert, and so does my client. Given an early and honest appraisal of the client's position, it is often possible to take steps to bring about an early settlement, or to decide that a case is not worth pursuing. It is in the client's interests to be given bad news earlier rather than later.

(ii) Clarity of Thought.

Experts need to think logically and clearly about the issues in a case. This is not always as easy as it sounds. Issues and facts are often in a disorganised and confused state when a client first comes to the lawyer, and if the expert is brought into the case, the expert needs to be wary of adding to that confusion, and of getting caught up in it. The lawyer should sort out the factual and legal issues, so as to identify the client's real problem, and possible solutions to it. The expert's role will be to sort out the technical issues, again to assist the client to come to conclusions about the correct approach to the technical issues in a case.

(iii) Clarity of Expression.

This usually follows on from clarity of thought. Experts often have to explain, both orally and in writing, complex issues and ideas. They need to be able to express themselves clearly and accurately, in language which is non-technical but not patronising. Experts should not underestimate the importance of this. It is not always easy for judges to decide between competing views of different experts, and the clarity in which an expert's opinion is expressed may well be a factor which weighs on a judge's mind in such difficult cases.

It is often said that experts should not be advocates for their client's case. This is undoubtedly true. However, once an expert has carried out the requisite investigations, and reached an independent view of the issues in the case, the expert is entitled to advocate his or her own opinion. This can be a subtle distinction, but it is an important one.

(iv) Thoroughness and Open Mindedness.

They go together. Experts need to approach each new case with an open mind. Experts should resist the temptation to "pigeon hole" problems on the basis that they have seen other similar problems, probably in the recent past.

It is very difficult for an expert to change radically an opinion which he has already given, unless new evidence comes to light which affects that opinion. Whilst an expert may believe, on an initial impression, that a new problem is very similar to one seen in the recent past, and therefore to have the same cause, that temptation should be resisted, and each new problem should be looked at afresh.

Equally, experts need to be thorough in their investigation, because overlooking as important detail can be fatal to their client's case, and to their credibility. There may be budgetary constraints on the amount of time and effort which an expert can devote to a case, and if that is so, and if those budgetary constraints are affecting the expert's work, then the expert needs not only to warn the client of the likely effect of those constraints, but also to consider whether he or she can continue to act where insufficient resources are being devoted to the investigation.

(v) Tough Mindedness.

Because litigation is an adversarial process, and because experts take part in it, they need to be aware of what might occur. As anyone who has been involved with litigation will know, it is a challenging and demanding process. Lawyers, and their clients, will make demands on the expert's time and intellect. They may also make demands on the expert's integrity. Experts need to be mentally tough to deal with these demands.

Expert's meetings are potentially full of pitfalls, and experts need to be aware of some of the traps which might be set for them. For instance, there are sometimes attempts to agree "facts" at expert's meetings which are not provable, and certainly which are not within the province of expert evidence;. Occasionally, an expert might wish to direct attention away from the pleaded case, and to discuss the case which that expert believes ought to have been pleaded. The conduct of expert's meetings requires the expert to be tough minded, if not streetwise, to avoid both the expert and the expert's client getting into difficulties.

Appearing as a witness in a court case is a gruelling process, and cross-examination, even of experts, can sometimes be brutal. Experts must have the mental stamina and mental agility to cope with it.

11. Some experts proclaim that lawyers should have no input at all into expert's reports. This view is misconceived. It is a lawyer's duty to check:-

(i) that the expert's report deals with the issues as they are pleaded in the case. An expert's report which fails to deal with all the issues or which attempts also to deal with other issues, will not assist the client;

(ii) that the report is clearly expressed in language which the court will understand, including such things as simplified drawings and sketches;

(iii) that the report deals adequately with the other side's pleaded case;

(iv) that the expert's report will not fall foul of any other requirements laid down in the various cases concerning expert evidence, particularly the Ikarian Reefer;

(v) that the expert's report does not refer to privileged documents.

12. The expert's role is a demanding one; it can also be an intellectually stimulating and enjoyable one, particularly for those engineers who relish a challenge, and who do not object to their views being challenged by others. It is time consuming – lawyers and courts are not flexible concerning certain time limits, particularly those concerned with trials. Also, some law firms, my own included, are wary of instructing so called "professional experts", preferring to instruct people who are practising in their fields. It can be difficult to accommodate the time needed to carry out work as an expert with the day to day demands of practice. Despite the challenges, acting as an expert can be a rewarding and stimulating experience, so I'm told!

LORD WOOLF'S PROPOSALS

13. Lord Woolf has published far-reaching proposals to reform the way in which civil litigation is conducted in England and Wales. Those proposals are wide ranging, and include proposals to change radically the way expert evidence is prepared and given in civil cases.

To put his proposals into context, it is worth quoting from Lord Woolf's final report:

> *"It was a basic contention of my interim report that two of the major generators of unnecessary cost in civil litigation were uncontrolled discovery and expert evidence. No-one has seriously challenged that contention."*

It is fair to say that Lord Woolf is particularly concerned about the impact of expert evidence on smaller civil claims, and part of his proposals include new rules to limit expert evidence in such cases. If the rules are made in the way proposed by Lord Woolf, many smaller cases will not have any expert evidence given in court at all, but any expert evidence will be confined to written reports before the case. In his interim report, Lord Woolf had proposed that instead of each party appointing its own expert, the court should appoint a single expert to act on the court's behalf, particularly in smaller cases. This met with great opposition, particularly from those lawyers who usually act for Plaintiffs in small personal injury cases, and in his final report, he diluted some of his proposals concerning expert evidence.

Nevertheless, if his proposals are enacted, there will be very great changes to the way in which expert evidence is given in civil litigation. Lord Woolf published some draft new rules of court, to govern the procedures by which civil litigation should be conducted, and one of those new rules deals with the question of expert evidence. In summary, Lord Woolf's proposals concerning expert evidence are:-

(i) it will be expressly stated that the expert's duty is to help the court impartially, and this duty will override any obligation owed to the expert's client;

(ii) the court may direct that expert evidence is to be given by a single expert, jointly appointed by the parties, or appointed by the court. Such an expert may be appointed instead of the parties appointing their own experts, or to replace experts already instructed by the parties, or in addition to experts instructed by the parties. The experts may also be appointed by the court to assist the court in assessing the evidence to be given by the parties' experts. In fact, a similar power exists already in the rules of court, but it is very rarely used. It relies on one of the parties making an application to the court. The court does not, at present, have power of its own volition to appoint its own expert. It will be interesting to see the extent to which the courts are prepared to force the parties to accept the appointment of a court appointed expert, the terms on which such expert will be appointed, the information which the parties are ordered to disclose to that expert, and the way in which such an expert will conduct an investigation;

(iii) a party instructing an expert must give every other party notice of the name and address of that expert, and the scope of the instructions to be given to the expert. Such a notice must be given in enough time, and with enough information, to enable the other party to consider the same expert, or to instruct another expert to carry out an examination with the expert named in the notice, or to instruct another expert to prepare a joint report. Again, it will be interesting to see the ways in which these rules are developed by the courts;

(iv) the expert's report must be addressed to the court, and not to the expert's client or instructing solicitor;

(v) the rules contain some detail about what the expert's report should contain, much of which should already be contained in an expert's report complying with the current rules. However, in addition, an expert's report under Lord Woolf's proposals would also have to state that the expert understood his duty to the court, has complied with that duty, that the report includes all matters relevant to the issues on which the expert evidence is given, and that details have been given in the report of any matters which might affect the validity of the report;

(vi) lastly, and most contentiously, the expert's report has to have attached to it a copy of all written instructions given to the expert, any supplemental written instructions given to the expert since the original instructions, and a note of any oral instructions given to the expert. There is still a resistance to these proposals, because they would abolish privilege in relation to communications between the expert, the expert's client and the lawyer concerned, a revolutionary step. It remains to be seen whether these proposals will survive the rule making process.

If Lord Woolf's proposals are enacted, there will inevitably be a period during which the extent and the effect of the new rules are tested. There will also be a learning process both for lawyers and experts about how best to adapt to the new rule.

SUMMARY

The role of the expert in litigation is a demanding one, requiring the expert to be honest, thorough, open-minded, good at communication, clear thinking, and with the ability to withstand the pressures of litigation. Nevertheless, it can be a rewarding role.

Lord Woolf's proposals, if they are enacted, will change dramatically the way in which expert evidence is prepared and given in court, and should help experts resist some of the pressures which may be exerted on them. Those proposals will make it very clear that the expert's duty, in giving evidence, is to the court.

Lessons from the Collapse of the Ramsgate Walkway

J. C. CHAPMAN, BSc, PhD, FEng, FCGI, FICE, FIStructE, FRINA
Chapman Associates, Visiting Professor, Imperial College

INTRODUCTION

Port Ramsgate Ltd is a medium size roll-on roll-off ferry port. In common with other ferry ports it is subject to changes in ship design and to competition from other ports. The life of a ship to shore structure is uncertain, but is typically about 20 years. Yet the service conditions are onerous and the design is complex. The structures move to accommodate tidal movement, ship impact, and wave action, and are therefore subject to machinery regulations as well as to construction regulations.

The seaward end of a ship-to-shore structure is lifted either by mechanical means, or by a pontoon. Berth 3 had operated for several years with a single deck linkspan (vehicle bridge), supported at the seaward end by a pontoon. The pontoon had been designed to support an upper linkspan, should that be required in future. In due course the requirement for an upper linkspan eventuated, and at the same time it was decided to build a covered passenger walkway, to segregate vehicles and passengers (**Figure 1**). The walkway was a truss structure consisting of square hollow sections (**Figure 2**), clad in 6mm steel plate (**Figure 3**), so the structure was torsionally, as well as flexurally, very stiff. It provided an apparently secure environment for passengers boarding the ferries.

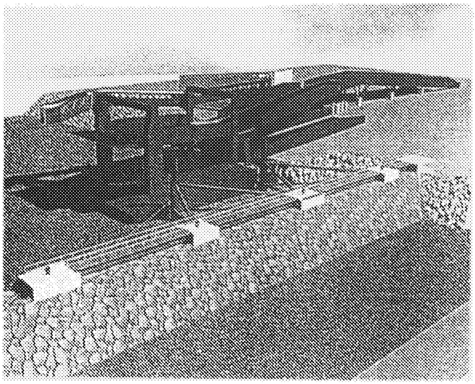


Fig 1. View of Berth 3

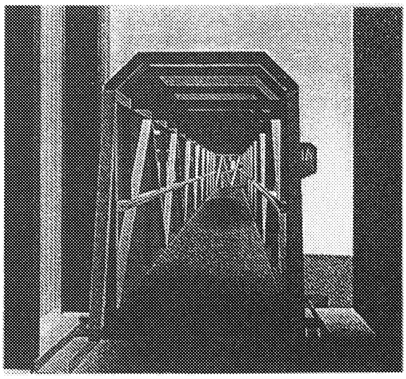


Fig 2. The walkway seen from the passenger building

After four months in service, at 00.45 a.m., the seaward end of the shore span of the walkway fell without warning about 10 metres to the deck of the pontoon (**Figure 4**). The violent deceleration caused the death of six passengers and seriously injured seven others.

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 27–38

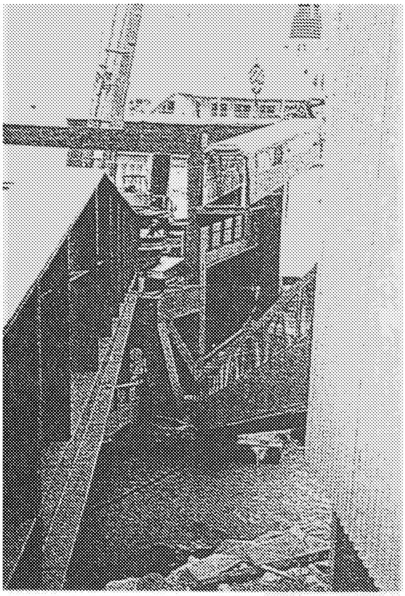


Fig 3. The collapsed walkway

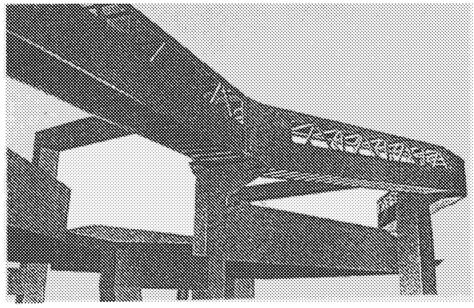


Fig 4. The walkway

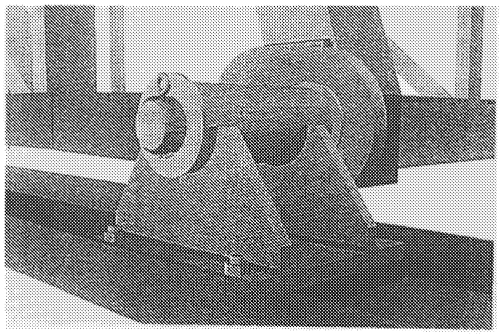


Fig 5. Sliding bearing, shore end

The designers, constructors, checkers and the owners, Port Ramsgate, were charged with offences under The Health and Safety at Work Act. Port Ramsgate was also charged under the Docks Regulations. A more detailed account of the procurement, design, construction, collapse, and trial is given in [1].

The collapse was caused by bad engineering, and there are lessons to be learned.

PROCUREMENT

The existing pontoon and linkspan were designed by FKAB, a Swedish firm of naval architects and consulting engineers, which is a subsidiary of Mattson, an engineering group. They were manufactured and installed by FEAB, a shipbuilding and fabrication company, which is also a subsidiary of the Mattson group. The contract was for design-and-build and was placed with FEAB. FKAB/FEAB had also designed and built other linkspans at Ramsgate, at other ports in the UK, and in northern Europe. As naval architects, consulting engineers, shipbuilders and fabricators, they were well qualified to design and construct the ship to shore connection. The project manager for the construction had recently returned from the Falklands, where he had been engaged on a project for the British Government.

FKAB's association with Berth 3 began in 1983, when they commissioned the Technical Research Centre of Finland and the Swedish Maritime Research Institute to report on wave conditions, pontoon motions, pontoon stability, and mooring forces, on the basis of which FKAB had designed the pontoon and lower linkspan. It was therefore natural and prudent to engage FKAB/FEAB for the upper linkspan and walkway.

In February 1992 FEAB gave an indicative price and an outline arrangement for the pontoon modifications and for the linkspan, and in March 1992 FKAB gave a price for design. In April 1992, Ramsgate asked FKAB to proceed with design of the linkspan, with the condition that work could be stopped if Ramsgate's negotiations with a ferry company (RMT, the Belgian national shipping company) did not proceed satisfactorily. In May 1992 there was correspondence regarding a walkway, and FKAB said they would make a proposal. In August 1993, FEAB provided a bar chart for the construction of the upper linkspan, leading to commissioning in January 1994. Also prices were given for the construction of the linkspan and the walkway. A price was also given for design, making reference to work done in 1992.

Agreement between Ramsgate and RMT was signed on 21 September 1993. RMT required that Berth 3 should be at least partly operational by 1 January 1994 (in the event, the lower linkspan was available in mid-January). On 23 September 1993, Ramsgate authorised FEAB to order materials, and the order for the upper linkspan was placed on 29 September 1993. An offer for the design and construction of the walkway was received on 15 November 1993, with delivery on 4 February 1994. The offer was accepted on 18 November 1993, and Ramsgate asked FEAB to expedite. However, there was no penalty for late delivery, and in the event the walkway entered service on 12 May 1994.

The passenger building was procured under a separate design and build contract from Kayover, a local fabricator, who had already carried out a variety of tasks for Ramsgate over several years. Kayover and FEAB were asked to liaise on matters affecting the interface between walkway and building.

It was a condition of the contract that the design, fabrication, and construction would be checked by Lloyds Register, who had certified the existing pontoon and linkspan, and had performed regular surveys since commissioning.

The contract was entered in a spirit of co-operation and trust based on past association, a propitious circumstance for a successful enterprise.

DESIGN

The walkway enabled passengers to walk from the passenger building, at about 10m above ground, to an upper deck of the ship. The walkway consisted of three spans. The shore span extended 33m from the passenger building to a bracket on the outside of the first portal frame which was supported on the pontoon (**Figure 4**). The pontoon span extended from the first bracket to a bracket on the second portal frame. The ship span extended from the second bracket to the ship, and the ship end was raised and lowered by hydraulic jacks on to the ship's deck. Weather protection at the span junctions was provided by flexible bellows.

The tidal range at Ramsgate is about 4.5m. The moored pontoon moves approximately vertically with the tide, and is also subject to wind, waves, vehicle forces, and ship impact. For the linkspans, steel on steel sliding bearings were provided at the shore end. Lubrication was applied by Greasomatics (actuated by chemically induced pressure), and manually. The vertically hinged bearings were placed under the main girders. In the walkway, the sliding bearings hinged about externally projecting stub axles which were welded within a hole in a disc, which was site welded to the walkway structure. The shore bearings could slide in channels (**Figure 5**). A pad of low friction material was attached to the under-side of the bearing, and was believed by FKAB/FEAB to require no lubrication. The right hand (seen from the shore) seaward bearing was retained in position by a pintle passing through the plating of the bracket (**Figure 6**). The left hand seaward bearing had no pintle. It can be seen that of the six degrees of freedom of the pontoon, surge, sway, heave, pitch, and yaw were accommodated, but roll was not.

A 6mm tapping was provided on the underside of each sleeve (**Figure 7**), to receive the supply tube from a Greasomatic, which had not been fitted.

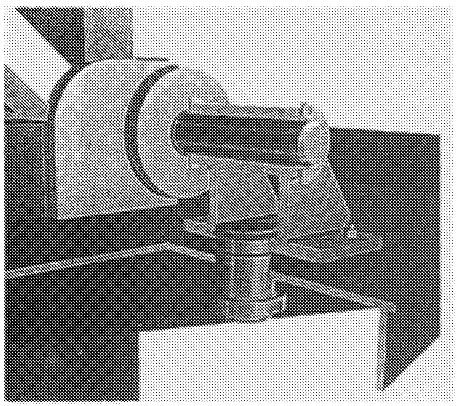


Fig 6. Right-hand seaward bearing with pintle

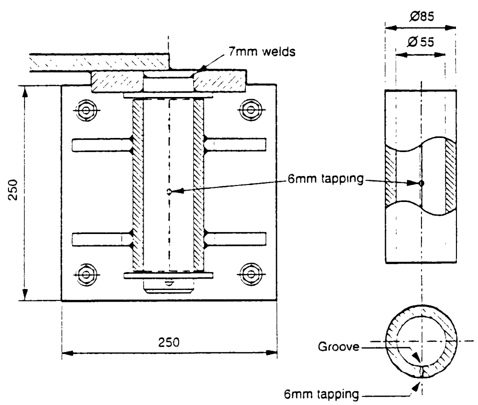


Fig 7. Bearing details, with hole for Greasomatics

CONSTRUCTION

The bearings had been assembled at works, with the axles fixed within the bore of the discs by two circumferential welds (**Figure 7**). The disc was site welded to the D plates around half the circumference and on the vertical diameter (**Figure 6**).

The walkway, which weighed about 21T, was lifted into position by crane. It was then apparent that the slideways were in the wrong position, because Kayover had assumed that the bearings would be under the trusses of the walkway. It was also apparent that the walkway was too short, and might drop off the edge overnight on the falling tide. Two projecting railway sleepers were therefore lashed to the building and greased, the walkway being supported on its bottom end frame. During the night an appendage fouled and damaged the edge girder of the building, so imposing an abnormal force on the pintle and deforming the hole in the plate of the supporting platform. Also the retaining bolt which passed diametrally through the pintle was bent; although the bolt had been fitted, there was insufficient clearance to fit the nut. Therefore FEAB removed the bolt and welded a retaining collar. Thereafter it was only possible to remove the bearing from the platform by grinding away the weld. After several days a triangular extension 700mm long (**Figure 2**) was supplied and fitted, and the slideways were aligned with the bearings.

It should be noted that until the remedial work had been completed, the shore end of the walkway was supported on the end frame, and the bearings were freely suspended, but the seaward bearings were subject to horizontal forces caused by friction at the shore end, and vertical forces caused by rolling of the pontoon.

When the construction was complete, Lloyds Register conducted a load test on the walkway, as part of the installation certification. The only unexpected result was that the measured deflection was 2mm (span/16850), which was recorded without comment.

OPERATION

When the slideways had been relocated, and the shore bearings were supporting the walkway, but the building was incomplete, the building was observed to vibrate. This was caused by juddering of the bearings on the slideways, which in accordance with FEAB's belief that lubrication was not required, had not been greased. Ramsgate, with FEAB's agreement, then greased the slideways, and the juddering ceased. The walkway then entered service. The only remarkable behaviour was that a bearing was observed to lift. This was at first attributed by FEAB to incorrect ballasting of the pontoon, but lifting was inevitable, as a result of the inadequate articulation.

COLLAPSE

The collapse occurred as passengers were boarding a ferry at 00.45 a.m. on 14 September 1994. Rescue operations were very difficult and there was much suffering. The seaward end of the walkway had penetrated the pontoon deck. The shore end of the walkway rested on the edge of the passenger building, and the bottom chord was bent where it had impacted the edge girder of the building, presumably as a result of the rotation caused by the impact at the seaward end. There was no other damage to the structure and the windows were not broken. The right hand seaward bearing remained on the platform, to which it was attached by the pintle; the welds attaching the axle to the disc had failed. The left hand seaward bearing was missing, but it was recovered by divers from the dock, whence it had been propelled by the impact. The shore bearings were still attached.

INVESTIGATION

The right hand seaward bearing was removed by cutting out a section of the supporting platform. The shore bearings were removed by cutting out a section of the structure. Structural and metallurgical investigations were carried out at the HSE laboratories in Sheffield. Their investigations were careful and their report was thorough and objective.

The dominant cause of the collapse quickly emerged from the design calculations supplied to HSE by FKAB. Nominally the resultant reactions to the vertical and horizontal forces applied to the bearing were at the centre of the bearing pads. Prudently it would have been assumed that the reactions were at the outer edges of the pads, and the bending moment on the axle at its connection to the disc, and the axle and weld stresses, would have been calculated accordingly. The section modulus of the axle was calculated, but it was evidently then decided that the axle bending moment was zero. This was frankly confirmed in response to HSE's questions after the accident; the response included the assumed bending moment diagram. It was decided that the axle and welded connection need only be designed against shear. The axle and connection were therefore grossly overstressed according to any reasonable assumption regarding the position of the resultant reaction. The pintle was in fact predominantly in shear, and it is strange that no one thought it anomalous that the axle section area was only 47% of the pintle area.

Bending was not absent from their consideration. Because the axle was contained by a sleeve, which was stiffer and stronger than the axle, they checked the sleeve alone for bending. The moment was taken as the force applied at the disc multiplied by the distance from the disc to the first vertical support plate (**Figure 8**). It appears that the designers visualised that the forces were applied without moment at the disc and that the moment was resisted by the bearing, which was prevented from rotating, whereas the reverse was true. A smaller, but still major, error was to assume that all reactions were equal. The explanation given to HSE was that they had thought that the torsional stiffness of the structure would be small enough to justify that assumption. Also the design concept was inappropriate.

The checkers made similar mistakes, but the forces were assumed to act on the axle with a very small lever arm (less than half the axle diameter), perhaps recognising that the axle would not be fully supported by the sleeve in the immediate vicinity of the connection.

The metallurgical examinations established that all axles had extensive fatigue cracking. The cracking had completely severed the right hand seaward connection (**Figure 9**). This bearing could only tilt to the extent permitted by the pintle retaining ring, and it seems possible that the end of the axle remained within the disc for a short period before being dislodged. The left hand seaward axle was largely cracked, but final failure occurred when the bearing struck the pontoon deck. Both shore bearings had advanced fatigue cracking. There were a number of weld defects, some of which reached the surface of the weld.

Because Greasomatics had not been fitted (though Ramsgate had supplied FEAB with Greasomatics to fit where required) none of the axles had been lubricated since installation. The right hand seaward axle and both shore axles had retained the original lubrication, and the shore axles could rotate freely within the sleeves. The right hand seaward axle could only be turned by applying a torque which would not have caused a significant increase in weld stress. The left hand seaward axle, which had impacted the pontoon and had been immersed, could not be turned. It was removed by slitting the tube, and when examined it had no grease.

Having regard to the fact that the shore bearings had not experienced the exceptional loading which occurred during construction, and were less exposed to the weather, the behaviour of the four axles was remarkably similar. This suggests that neither welding defects nor lack of lubrication had a significant effect on collapse, but they might have caused the collapse to occur a little sooner than it would have occurred if the welds had been perfect and if lubrication had been applied. All the experts agreed that the design errors made collapse inevitable. The cause of the collapse was design error; the mode of failure was fatigue.

In view of the gross design errors it is perhaps surprising that the walkway survived for four months. The reason is illustrated in **Figure 10**. The axles bent sufficiently to transfer the resultant reaction close to the disc. In this respect the load test could have been beneficial, because it caused the transfer to take place before most of the cyclic loading occurred (before any cyclic loading of the shore axles). On the other hand it might have enlarged initial weld defects, but the consistent behaviour of the four axles suggests that that was unlikely.

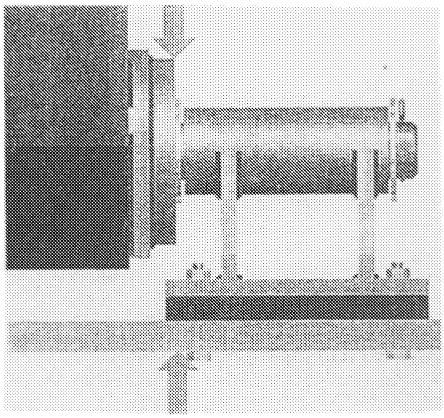
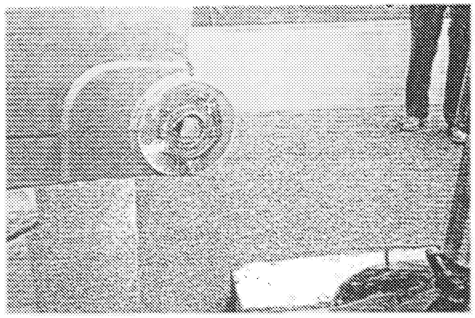


Fig 8. Designer's assumption for position of bearing reaction (the bolts are fictitious)



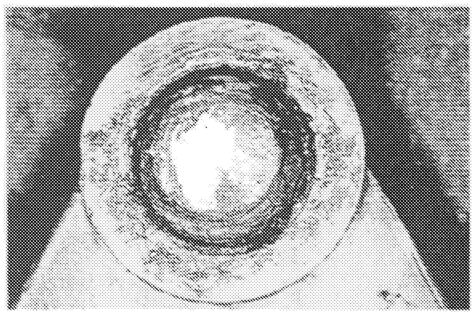


Fig 9. Fracture surface of right-hand seaward axl

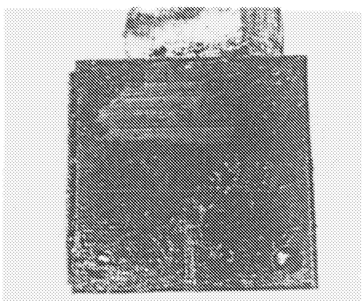


Fig 10. Sliding marks

A freight clerk crossed the walkway 35 minutes before the collapse. After the accident, he recalled seeing a rusty strip about 10mm wide between the edge of the flap bridging the gap between the shore span and the pontoon span, and the non slip surface of the walkway. This indicated that the walkway had moved shorewards about 25mm relative to the supporting platform. Surviving passengers recalled seeing more pronounced abnormalities. The walkway was inspected by the insurer's inspector, who was certificated to inspect ship-to-shore structures, one month before the collapse; he found nothing amiss, and of course there was nothing, apart from fatigue cracks which could only be detected by dismantling the bearings.

THE TRIAL

The trial took place at the Central Criminal Court, before Mr Justice Clarke. The first six days were occupied by legal argument, and the selection of a jury. During this period Lloyds Register pleaded guilty to a lesser charge whereby they admitted error but Lloyds Rules were not impugned. FKAB and FEAB did not plead, and did not attend, so a formal plea of not guilty was entered on their behalf. Thus only Ramsgate remained in contention.

The main issue before the Court was whether under the Health & Safety Act the owner was responsible for errors made by his professional advisers, in this case the designers. The onus was on Ramsgate to show that they had taken all "reasonably practicable" steps to ensure safety. However the prosecution had to prove that design was part of Ramsgate's "undertaking". The prosecution contrived to argue that Ramsgate had been involved in design, because the walkway had been "tailor made" and not selected from a catalogue, so had brought design within their undertaking, and also to argue that Ramsgate had not been sufficiently involved and therefore had not taken all "reasonably practicable" steps. Both arguments were of course rubutted by the defence.

Docks Regulation 7(1) states that safe means of access "shall be provided" - that is, it imposes an absolute obligation on the owner, regardless of fault. Although this appears to be over-ridden by Regulation 4, which states that an employer's duty "shall extend only to matters within his control", it seems that in an earlier case which went to appeal, the court ruled that 7(1) prevails. As both charges related to the same alleged offence, Ramsgate were obliged to plead not guilty to both charges, but at the conclusion of his closing speech counsel for the defence invited the jury to convict under 7(1) of the Docks Regulations.

The judge informed the jury that it was his job to define the law, and theirs to determine facts. Yet the jury were required to decide:

(a) Whether Ramsgate's undertaking included design and construction.

(b) The intended meaning of "reasonably practicable". Did the jury think it meant "not wholly practicable", "practicable without undue difficulty" or "reasonable and practicable"? It would be practicable to commission five or ten independent checks, but it would not be reasonable. Clarity and reason would be satisfied if the requirement were defined as "reasonable and practicable".

(c) It was reasonable and practicable for Ramsgate to have used a standard form of contract and to have specified proper quality assurance procedures. That would have been prudent, especially for commercial reasons. But it is extremely unlikely that that would have averted the tragedy, so the jury had to decide the extent to which non-causative acts or omissions should affect their verdict.

(d) In their answers to the judge's questions the jury made it clear that they thought Ramsgate should have seen the need to fit safety chains. Perhaps this followed from their decision that design and construction were part of Ramsgate's undertaking.

(e) Whether the offence lies in the existence of danger and not on the consequences, as has been authoritatively stated, and whether the timing of the accident was relevant to the offence. Despite submissions from the defence, the judge had refused to define risk. In the sentencing proceedings the judge said he could not accept that the offence could be detached from the consequences, in which case the extent of the offence would be a matter of chance.

Thus the jury were required to decide matters of law and opinion, as well as fact.

The jury found all the defendants to be guilty as charged.

The judge gave the background to his decisions on sentencing. He accepted that Ramsgate's culpability was significantly different from that of the other defendants, but Ramsgate had not pleaded guilty, so was not entitled to credit on that account. Is it fair that a defendant should be penalised for defending himself? Ramsgate's case was hardly frivolous - the judge took seven hours to sum up, and the jury took eight hours to reach a verdict.

The judge also said "By its verdict the jury had found, in my view correctly - that an owner and operator of a port cannot simply sit back and do nothing and rely on others, however expert". They had hardly "done nothing" - they had appointed checkers of world renown, which they were not obliged to do, who had performed independent calculations. He did not explain what other steps might have prevented the accident.

SAFETY IN PORTS. CIRIA GUIDE ON PROCUREMENT, OPERATION AND MAINTENANCE

The project was initiated in June 1996. The scope is limited to linkspans and walkways. Design was not included because a BSI drafting committee already existed. The project was supported by the Port Safety Organisation, individual ports, Lloyds Register, insurers, HSE and DETR. Tenders were invited from consulting practices with relevant experience, and Posford Duvivier were selected from several strong contenders. Work began in December 1997, and publication is expected at the end of 1998. The cost is a small fraction of the cost of the trial. The project is guided by a steering group whose members are drawn mainly from the funders.

A detailed questionnaire invited information from ports on number and type of structure, procurement methods, operational performance, incidents and their consequences, maintenance, training and qualifications. An analysis of the results of the survey will be included in the report.

Dock structures are now subject to an array of regulations, in particular Docks Regulations, Management of Health & Safety at Work Regulations, Supply of Machinery (Safety) Regulations, Provision & Use of Work Equipment Regulations (PUWER), Construction (Design and Management) Regulations (CDM), Lifting Operations and Lifting Equipment Regulations (LOLER), EU Amending Directive to the Work Equipment Directive (AUWED). The research contractor thought it prudent to retain the services of a consultancy (LACS) which provides advice on the scope and application of regulations. The machinery regulations and directives provide for a series of supporting standards; it is expected that about 600 will be required.

The Guide will assist owners in specifying and procuring structures and mechanical/ electrical systems which are designed to be safe, reliable, and efficient in operation and maintenance, and in ensuring that best practices in operation, maintenance, recording, and reporting are adopted. Advice will also be given on procedures which must be adopted in order to conform with the regulations.

LESSONS AND COMMENTS

(1) Investigators have the benefit of hindsight, and there is a tendency to think that a mistake should have been obvious to the designer. If two experienced organisations make the same mistake, then we should ask whether a chance in a million occurred, perhaps requiring no further action, or whether action should be taken to prevent a recurrence. In the writer's opinion the action of the bearings as designed, although "obvious" was less obvious for example than the need to design system-built multi-storey flats against gas explosions, or the need to design bearings for bridges in an earthquake zone so that the bridge cannot be dislodged from the abutments. Yet those oversights occurred in full view of the structural engineering profession, and the design of the unsatisfactory connection of the system built flats, when presented in a published paper, excited no comment. It seems safer to assume that as a mistake was made, it cannot have been obvious to the designer, and that positive steps such as the following should be taken to prevent a recurrence.

(2) A risk analysis should examine all possible modes of failure, under factored and extreme loads. This requires the designer and checker to consider for each component under what extreme loading or circumstance the component or structure would fail or collapse, as distinct from checking that specified design loads can be supported. Whether that process would have revealed the wrong visualisation of the action of forces can only be conjected. The analysis should also extend to operational reliability, and to construction.

(3) Bearings or auxiliary attachments should prevent a bridge from being dislodged from the abutments under all possible loadings.

(4) Bearing design should facilitate maintenance, but deficient maintenance should not lead to collapse.

(5) Where four-point supports are provided for ship to shore structures, the bridge and its supports should be designed on the assumption that only two supports are effective.

(6) Performance feedback to codes, to guidance, and to education, should be encouraged and facilitated.

(7) Engineering courses should include an obligatory module devoted specifically to safety in design, construction and operation, illustrated by actual failures. Students should experience the engineer's most difficult art - to visualise what is not yet apparent.

(8) Engineering courses should inculcate a physical grasp of structural behaviour. Computerised analysis makes this more necessary and computer graphics make it more possible.

(9) Structures should be designed to facilitate maintenance. Ship to shore structures should also be designed for safe and efficient operation.

(10) Ship to shore structures are potentially exposed to extreme loading during ship arrival and departure. However, persons can be excluded from the hazardous areas during these operations.

(11) Training and qualification of operating personnel should be encouraged, in addition to equipment - specific training. This should lead to more thoughtful and responsible operation, the ability to cope with unforeseen events, improved career prospects, and greater job satisfaction.

(12) The first priority following an accident should be prevention. The Ramsgate trial prompts a number of questions:

(13) Is criminal law the appropriate instrument to punish genuine mistakes?

(14) Is trial by jury appropriate in cases where lawyers and judges have difficulty in grasping the issues? Lawyers have the benefit of specialist advice; juries do not.

(15) Should non-causative actions or inactions be taken into account in assessing guilt?

(16) What is the meaning of "reasonably practicable"? A key decision taken by the jury was that it was reasonably practicable for Ramsgate to have fitted safety chains. They were probably encouraged in reaching this opinion by the judge's instruction "the question is not what is reasonable but what is reasonably practicable". It was certainly practicable to have fitted chains, but was it reasonable to expect Ramsgate to foresee the need when the designers, checkers, and the insurance inspector had not done so?

(17) Is design part of a port's undertaking regardless of whether they themselves do the design or whether they commission independent designers?

(18) It has been stated authoritatively that the offence lies in the existence of danger, not in the consequences, but the judge failed to define risk or to instruct the jury on the matter, and subsequently stated that he did not accept the proposition. This enabled the prosecution to argue that if the accident had occurred at any other time the particular passengers would not have been victims and hence the question of lubrication was vital. What is the legal position? Does the judge's opinion prevail?

(19) Each regulation is drafted with good intent, but is the totality reaching the point of diminishing return? Perhaps good practice guides for specific tasks, with relevant distillation from the generalities, will reduce the burden.

"FORENSIC ENGINEERING"

"Forensic" means "pertaining to, connected with, or used in courts of law; suitable or analogous to pleadings in court". Most engineering investigations of failures or collapses do not lead to a court of law. Pleadings in court are biased towards or against the accused. Engineering investigations must be objective. The design of processes or devices for the detection or prevention of crime, or the apprehension of criminals, may appropriately be called forensic science or forensic engineering. The sub-title to this conference conveys what is intended. Why introduce a term which appears to undermine the essential quality of professional engineering investigation?

Reference

1. Chapman J C. Collapse of the Ramsgate Walkway. The Structural Engineer, 1998. Volume 76, No. 1. 7 January 1998.

Ramsgate walkway collapse: legal ramifications

JOHN BARBER
Consulting Engineer & Lecturer in Construction Law, King's College London, UK.

AIMS OF PAPER

It is a sad truth of engineering that we can learn more from failure than from success. The occurrence of failure reveals the dangers to be avoided or overcome. Learning from failure is the foundation of progress. We should therefore sift carefully through the wreckage to extract maximum understanding. The wreckage is not merely the heap of tangled steelwork, it is also the damaged finances and reputations of people and organisations involved, and their shattered or dented self-confidence that they knew what they should be doing and how to do it.

On 14 September 1994, a high level passenger walkway spanning between the terminal building and a portal frame mounted on a floating pontoon at the Ro-ro terminal, Berth 3, Port Ramsgate, collapsed. Six people died and seven were seriously injured. Several organisations involved were prosecuted and a lengthy criminal trial took place at the Central Criminal Court, London, in early 1997. One result of the court case is that much valuable information has come into the public domain, enabling detailed study.

The Standing Committee on Structural Safety (SCOSS) was provided by the Health and Safety Executive (HSE) with a copy of key sections of the 3165-page trial transcript (namely the judge's summing up and remarks on sentencing, together with the closing addresses of counsel for the Crown and Port Ramsgate) for perusal to glean any points having wider significance for structural safety. The technical issues have been described by others. This paper considers the legal and organisational ramifications, particularly regarding

- the application of health and safety legislation to latent defects in structures, and
- the duties of clients procuring works by design and construct contracts.

The first part of this paper is an analysis of the judge's words. As the transcript of the summing up is very long and not readily available, passages have been quoted verbatim, with page numbers in the transcript noted for reference. The remainder of the paper looks beyond the transcript to consider related legal developments, some practical topics which featured in the case and, finally, the contribution of this case and the related legal developments to structural safety and the implications for procurement and working practices.

I am grateful to HSE and to my fellow members and the secretariat of SCOSS for their help and comments, but the views expressed in this paper are mine, and do not necessarily represent the views of SCOSS.

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 39–60

THE FACTS

The walkway at Berth 3, Port Ramsgate, had been constructed, together with a more substantial linkspan for vehicles, under a design and build arrangement as part of a scheme for double level loading of Ro-ro vessels. The scheme had been developed, designed, constructed and installed between 1 May 1992 and 12 May 1994. Documents indicate that the main decision to proceed was made in September 1993 and the design of the walkway elements was carried out in or about December 1993. The walkway had been completed and brought into service four months before the failure occurred.

A detailed investigation of the collapse was carried out by HSE. This revealed a catalogue of errors, mostly in the design. The primary technical errors, according to evidence at the trial, were a failure to take account of the pontoon's freedom to roll when designing the walkway support, and an incorrect assumption as to the effective lever arm when calculating bending stresses in the stub axles. Both are essentially errors of visualisation of the structural or mechanical concepts and of the behaviour of the walkway and pontoon in use.

In the light of its findings HSE instigated a prosecution, in the name of the Crown, against four defendants:

- the Swedish design and build contractor, Fartygsentreprenader AB, known as FEAB
- the Swedish design sub-contractor, Fartygskonstrucktioner AB, known as FKAB
- Lloyd's Register of Shipping, who had been responsible for certifying the walkway, and
- the port owners and operators, Port Ramsgate.

All four defendants were charged with breach of the duty under Section 3(1) of the Health and Safety at Work etc. Act 1974. (The Act is referred to as either 'HSWA' or 'the 1974 Act'.) Port Ramsgate were also charged with breach of the duty under Regulation 7 of the Dock Regulations 1988.

The case was tried over 25 days during January/February 1997 at the Central Criminal Court, which is a Crown Court, before a High Court judge, Mr Justice Clarke, with a jury. The two Swedish defendants did not appear and were not represented at the trial, although they had earlier co-operated with the HSE investigation. A plea of 'not guilty' was entered on their behalf. Lloyd's Register pleaded guilty. Port Ramsgate pleaded not guilty to both charges. The Swedish defendants and Port Ramsgate were found guilty on all charges and fines were imposed on all four defendants, together with orders to pay the costs of the prosecution, as follows:

FEAB fined £750,000 }
FKAB fined £250,000 } with costs of £251,500
Lloyd's Register fined £500,000 with costs of £252,500
Port Ramsgate fined £200,000 with costs of £219,500.

The figures of costs do not include the defendants' own legal costs, nor the costs of the court itself. Issues of civil liability towards those killed and injured, and their families, have been settled separately by insurers. Insurers cannot cover criminal penalties.

There have been no appeals against conviction or sentence. At the time of writing, it is understood that the two Swedish defendants have not paid any of the fines or costs.

CRIMINAL LIABILITY FOR LATENT DEFECTS

There are two aspects of this case which effectively change the law as it had been understood. First, the convictions represent the imposition of criminal liability under HSWA for latent defects. Such an application of HSWA was previously unknown or, at least, very uncommon. There was no question of construction work being in progress, nor of the people injured being employees or people at work. The fatalities were the result of latent defects in the works, and the convictions related to the creation of the latent defects. The only special requirement was that the defects should have been such as to pose a risk to the health and safety of the public. Second, the range of persons held criminally liable was much wider than might have been expected. The four parties convicted were the contractor, the designer, the certification body and the client.

The alleged breach of the Dock Regulations was not a significant issue at the trial and is not considered here. The main offences all related to HSWA Section 3(1), which states:

> *"It shall be the duty of every employer to conduct his undertaking in such a way as to ensure, so far as is reasonably practicable, that persons not in his employment who may be affected thereby are not thereby exposed to risks to their health or safety."*

Breach of the duty under Section 3(1) is made an offence by Section 33 (as amended), which also lays down the penalties. The relevant words state:

> *"(1) It is an offence for a person*
> *(a) to fail to discharge a duty to which he is subject by virtue of sections 2 to 7;...*
> *(1A)...a person guilty of an offence under subsection (1)(a) above...shall be liable –*
> *(a) on summary conviction, to a fine not exceeding £20,000;*
> *(b) on conviction on indictment, to a fine."*

"*On summary conviction*" means that the case is heard in the Magistrates' court; "*on indictment*" means that the case is heard in the Crown Court. The HSE decides whether it wishes to press for trial on indictment, but the decision is subject to the discretion of the magistrates. "*To a fine*" means that the fine is unlimited, in the discretion of the judge.

The use of HSWA (as distinct from, say, a charge of criminal negligence or corporate manslaughter) to impose criminal liability is particularly significant, because HSWA reverses the normal burden of proof, at least in regard to the issue of compliance/non-compliance with the statutory duty. This comes from HSWA Section 40, which states:

> *"In any proceedings for an offence under any of the relevant statutory provisions... consisting of a failure to comply with a duty ...to do something...so far as is reasonably practicable...* ***it shall be for the accused to prove...that it was not...reasonably practicable to do more than was in fact done to satisfy the duty****..."*

This may be regarded as beneficial, in that a person accused cannot escape liability merely by staying silent. On the other hand, it is very difficult for a defendant to know what he is expected to prove, since HSE does not have to particularise in the charge what the duty entails. This tends to conflict with a basic tenet of criminal law, that conduct constituting a criminal offence should, if possible, be clearly defined in advance. As will be seen, if the accused pleads 'not guilty' to the charge, it then becomes necessary for HSE to assert at the trial, by means of expert evidence, what a person in the position of the accused should have done. The duty is thus effectively defined retrospectively.

BASIS OF THE CONVICTIONS AND SENTENCES

In a trial by jury, issues are to be decided by the judge or jury according to whether they are classified as 'questions of fact' or 'questions of law'. The rule is that decisions on questions of law are to be made by the judge alone, while decisions on questions of fact are to be made by the jury. The jury reaches a verdict after being instructed by the judge on the law and as to the questions of fact which they are to address. If convicted, a defendant is entitled to submit a plea in mitigation before sentence is passed. The judge alone then passes sentence.

Value as precedent

The decisions of the judge on questions of law and his identification of the questions of fact appear in his summing up. It is rare for a judge's summing up in a criminal trial to be published in full - usually criminal cases are only reported if taken to appeal, when particular aspects of the summing up may be considered in detail. A judge's summing up to a jury tends to omit the reasoning for the conclusions of law that would appear in a judgment in a civil matter. However, as a matter of principle, decisions or comments of a High Court judge on questions of law have value as legal precedents, with binding or persuasive force for future cases as statements of the law or interpretation of a statute.

I would emphasise that the basis on which Port Ramsgate was eventually convicted may not be the same as the basis on which HSE originally took the decision to prosecute. This is not unusual: facts emerge during a trial, and arguments refine or even transform the issues. The HSE's reasons for bringing the prosecution are superseded by the judge's summing up and they cease to have any significance, save perhaps insofar as the HSE policy on bringing prosecutions is a relevant matter.

In this case, the only witnesses of fact were those put in by HSE. However, both HSE and Port Ramsgate presented expert witnesses: Professor Chapman and George Steele, Chief Engineer at the Port of Felixstowe, for Ramsgate; Mr Dawson and Sir Bernard Crossland for HSE. It is an interesting point whether decisions on standards of conduct based on the expert evidence amount to decisions on questions of law or questions of fact. Probably, the more generalised principles may be classified as questions of law. For example, whether the duty under Section 3(1) includes a requirement on a client to have an adequate system of risk assessment or quality assurance is probably a question of law, but what is an adequate system of risk assessment or quality assurance is a question of fact to be decided in each case.

Four elements for existence of duty

In his summing up the judge first explained the respective roles of judge, jury and expert witnesses, and stated the statutory provisions and burdens of proof, as set out above. He then listed the four elements which had first to be proved by the Crown, to establish the existence of the duty under Section 3, before the reverse burden of proof comes into play. He stated at p2712:

> *"Under Section 3, the Crown must make you sure of the following facts. One: that the defendant was an employer... Secondly, that the defendant was conducting an undertaking... Thirdly, that the defendant was doing so in such a way as to expose persons not employed by it who might be affected by the conduct of its undertaking to risk to their health and safety. Fourthly that the offence occurred in Great Britain."*

As regards the first element, the test for a defendant to be an 'employer' is rather simple, merely that it employs a number of people. (It may be noted that HSWA Section 3(2) imposes a similar duty on the self-employed.) The judge stated at p2713/4:

"The first matter [that the prosecution has to prove] is the requirement that the defendant must be an employer. In this case, although like all questions of fact, it is a matter for you to decide, you may think that there can really be no doubt that FEAB, FKAB and Port Ramsgate were all employers...because each of those companies employed a number of people."

The question in regard to the second element was framed as whether each defendant was conducting its respective undertaking and what was that undertaking. The judge outlined the allegations as to the nature of their undertakings at pp2716,18:

"The Crown say...that FEAB's undertaking was the design, construction and installation of the walkway...that FKAB's undertaking was the design of the walkway...that Port Ramsgate's undertaking was the provision and operation of the walkway."

Elsewhere in the transcript, it appears that Lloyd's Register's undertaking was alleged to be the "checking of the safety in accordance with the rules of design, construction and installation".

Where offence occurred

So far as the two Swedish defendants were concerned, the only real issue was whether the relevant section of HSWA affected them. This turned on whether the alleged offence was committed within Great Britain. Some, at least, of the design and fabrication of the walkway was probably carried out in Sweden, and the management was probably based there. Unfortunately, as neither defendant was legally represented, the judge had to reach a conclusion on the law without the benefit of argument. In doing so he merged his third and fourth elements, concluding at p2714:

"On the question where the offence was committed...the duty of an employer is to conduct his undertaking...to ensure that members of the public are not exposed to risk to their safety. The purpose of the statute is to protect the public from risk, thus, if an employer fails in that duty and exposes members of the public, in England, to risk the offence is committed here. It is for you to consider whether... members of the public were exposed to risk in England, although there can surely be no doubt about that, can there be, since the walkway collapsed at Ramsgate with the consequence that six people were killed and seven people injured, some very seriously."

While the lack of competence shown by the Swedes may encourage a desire that they should not escape conviction on a legal technicality, this portion of the judgment demands further scrutiny. If it is correct it suggests that HSWA could be used, for example, to prosecute a manufacturer in China who produced defective toys that caused the death of children in the UK. The point has further significance when it comes to sentencing, since it places the emphasis on the consequences of the breach of duty, rather than the degree of carelessness in the breach itself.

Scope of client's undertaking

As regards Port Ramsgate, the key issue related to the second element. It was, however, more on the basis of what was the nature and scope of their undertaking, in the circumstances where they had employed a contractor on a design and build basis, and had appointed a certification body. Ramsgate relied on the evidence of their experts to support the contention that their duty as client was actually to do nothing, because to do otherwise would be an inappropriate interference with a design and build contractor.

At p2651, counsel for Ramsgate expressed the argument as follows:

> *"Professor Chapman and George Steele ... both said to you effectively this: That under a design and build contract, in theory at least, the lines of responsibility are totally clear. Everybody involved in it understands who is undertaking to do what, and that the one thing you do not do if you are an employer and you have a design and construct contract is to start interfering with the way in which your contractor does his job, because there are huge disadvantages to it."*

It appears that Port Ramsgate's inaction was not absolute. Comments by counsel indicate that they had employed an engineer up till the end of August 1993. During the period from August to December 1993, they made no engineering input. From some time in January 1994 they employed, on a part-time basis, a consultant whose main experience was in coastal defence work. Counsel for Ramsgate highlighted the dilemma for a client choosing a design and build procurement route: in the absence of any authoritative guidance as to what is required or appropriate for him to do, the client can always be criticised that he did not get it right. Counsel, significantly, did not suggest that Ramsgate had sought to address the dilemma, but he argued that it appeared that they were effectively damned if they did get involved and damned if they didn't. He said, at p2654:

> *"There is, in fact, a great irony here, which in its own way is very revealing. For the purposes of trying to bring design, fabrication and installation under the umbrella of Ramsgate's undertaking, the Crown has suggested to you that Ramsgate was effectively getting involved in interfering in those three processes [design, construction and installation], and then, the moment they suggest that they had established that, they say directly the opposite, that all the things, as it were, that can be said against Ramsgate are: that they did not do anything, they did not interfere enough, they did not get involved."*

He continued, at p2657, that there was no suggestion of reliance by the designers or contractors, no *"suggestion that Ramsgate should play any part whatever in the entire process, other than tell them what in broad terms they want, where it should be, what it should look like and so on."* He argued, at pp2659,60, that the evidence of George Steele was to the effect that, *"The responsibility on the design and build contractor is such that Ramsgate, in his view, were not obliged to have checks."*

At p2661, counsel for Ramsgate was emphatic that non-interference was a deliberate strategy, *"They never sought to exercise any form of control over design, or indeed over anything, the whole way up to delivery, not in design, not in manufacture, and not in its installation."* Similarly, as regards Ramsgate's relationship with Lloyd's Register, he stated at p2671, *"Everybody understands that people have individual responsibilities and they do not interfere with everybody else's exercise of those individual responsibilities."* He concluded at p2687, *"We are suggesting that there was nothing that Ramsgate could have done that was reasonably practicable to prevent it happening altogether."*

In his summing up on this aspect, the judge stated, at pp2749,50, Ramsgate's contention that the position was *"akin to the purchase of a fleet of cars"* and that, *"Unless Port Ramsgate, in fact, interfered in some way with the design, installation and construction of the walkway, the design, construction and installation would not be part of their undertaking, but only part of FEAB's undertaking."*

The analogy with purchase of a fleet of cars invites the conclusion that, in some situations, particularly the purchase of mass-produced manufactured goods, the client or purchaser is not expected to become involved in the design or production. On pp2750,51, the judge set out the counter argument, that procurement of the linkspan and walkway was a different situation:

> *"The Crown say...that the design and installation and construction were part of the undertaking of Port Ramsgate ...because Port Ramsgate did not simply buy a complete upper linkspan and walkway, they decided to arrange for the design, construction and installation of the walkway by entering into a design and build contract with FEAB. The Crown say that a person who enters into such a contract has, ordinarily, as a matter of practice, certain responsibilities."*

He prefaced his resumé of the evidence of the expert witnesses on the point with a comment, at p2756 (emphasis added):

> *"You may think that there is a stark difference between the evidence of the [two sets of experts]. [The experts for Port Ramsgate] said it was perfectly satisfactory to leave all questions of safety of the design and construction of the walkway to the experts, namely FEAB and FKAB, especially since they were to be checked by Lloyd's Register. [The expert for the Crown] said, having regard to the provisions of the 1974 Act,* ***it was incumbent upon an operator like Port Ramsgate to have proper management systems in place to ensure that they had some control over the process of design and construction."***

At p2798, the judge identified four particular areas which had emerged as key issues:

> *"First of all, what might be loosely called Port Ramsgate's control of the contract, quality assurance and all that sort of thing. Secondly, hurry, in so far as that is different. Thirdly: a fail safe system such as chains. Fourthly, consideration of the Lloyd's Register certificates"*

At p2799, he summarised Port Ramsgate's argument that their acts and omissions were immaterial to the occurrence of the accident: *"Port Ramsgate say that even if they had done whatever had been suggested was reasonably practicable, the accident would still have happened."*

Control of contract

In considering what is probably the most important issue, namely the client's role in control of a design and construct contract, the judge quoted at length from the evidence of the Crown's expert, Mr Dawson. At p2826, he quoted Mr Dawson saying he would not expect Port Ramsgate to employ an independent consulting engineer to carry out detailed design checks:

> *"'I would not expect a client to employ a design and build contractor or require a classification society to survey the design and construction, and then also employ an independent consulting engineer to carry out detailed checks of the design and construction as well. This would make the classification society's role redundant'...His view was that that is all right, provided that the contract requires the contractor to have proper quality assurance systems."*

The proposition that a client in this situation should establish a contract with adequate provisions for quality assurance emerges with approval from the trial, but, as discussed further below, there are mixed messages as to what was envisaged as 'quality assurance'.

At p2827, the judge quoted Mr Dawson saying, *"Even though the client chose to appoint a design and build contractor, the client necessarily retains overall responsibility for the project and its safety"*.

Hurry

Excessive haste or hurry was floated during the trial as a possible contributory cause of the failure but, by the end, the allegation had virtually been dropped by the prosecution. Thus at p2841, the judge says of Mr Dawson that he was asked about the allegation of hurry and his evidence was that he was not complaining about hurry as such. He directed the jury, at p2862, *"You should not regard the hurry point as a separate and distinct allegation."* He also noted, at p2863, the view of Professor Chapman, that he *"did not accept that there was any relevant haste or hurry. He pointed to the fact that work had been done in advance, and referred to the fact that the contract did not contain a penalty clause."*

On the other hand, it appears, at p2550, that contract formalities were waived by Ramsgate in view of time constraints. At p2552, the Crown tried to turn hurry into a non-issue, stating *"the Crown do not criticise speed in itself, but what they say is that if you are going to go fast, you have got to be sure to have proper control"*, but prosecuting counsel also quotes Sir Bernard Crossland, at p2559, as saying that *"the only explanation [for the multiplicity of errors by the designers] that makes any sense is that they were under pressure, they were being hurried."*

Experience elsewhere suggests, firstly, that inadequate contract preparation and errors of visualisation are both often associated with haste; secondly, that commercial or personal pressures can be at least as significant as penalty clauses in inducing haste. It should not be assumed because the point was conceded by some of the experts at this trial, that hurry will be a non-issue in all cases.

Fail safe systems and risk assessment

An appropriate reaction of a diligent client to the risk of a high level walkway falling off its supports was said to be the provision of safety chains, as was provided for a walkway at another port after the Ramsgate failure. The possible application of secondary protection measures is a valuable lesson from this failure, but the fact that it was later done elsewhere surely has little evidential value except as to its feasibility. However, the point does introduce the idea that a client should carry out a risk assessment of a proposed scheme and take appropriate steps to deal with identified risks to health and safety. This idea seemed to find favour at the trial, although it was not fully explored.

At p2835, the judge quoted Mr Dawson on the topic:

> *"The client is required to make an assessment of risks – that follows directly from the Health and Safety at Work Act – and is required to identify the risks and make sure that those risks are properly managed... All those things should have been confirmed and recorded... FKAB should have done all the right things. It was the duty of Port Ramsgate to ensure that they did..."*

At p2840, he quoted Mr Dawson again on priorities and policies:

> *"Well, it is said the clients tend to set the tone for a project, set the priorities and the policies. I mean on this project the priorities had to be safety, and cost, and time and function. The only two that were set down were cost and time. They were set down very clearly, but there was no reference to any objectives in the document."*

Sentence

After the jury had delivered its guilty verdicts, the judge explained the basis of the penalties which he imposed. At p3132, he stated, *"FKAB and FEAB were responsible for what were gross errors in the design. In short, they were guilty of gross negligence."* As regards Lloyd's Register he concluded, at p3139 that *"In my judgment, the facts in the instant case demonstrate gross negligence on the part of Lloyd's Register or, more accurately, its employees."*

At p3148, the judge came to Port Ramsgate. He stated that he accepted that Port Ramsgate should be judged against the background that it had employed contractors of the highest reputation and (apparent) competence, and that they had required that safety of the linkspan and walkway be checked by Lloyd's Register with its international reputation for safety which was second to none. He proceeded to consider, at p3150, the basis on which the jury had reached its verdict. He stated:

> *"There remains the question whether the jury convicted Port Ramsgate on the basis that Port Ramsgate failed to ensure that appropriate quality assurance provisions were included in the contract, or on the basis that Port Ramsgate failed to take steps to fit a fail-safe system such as the chains in order to ensure that the walkway did not collapse, or on some other basis. It is true that it is not possible to tell from the verdict precisely on what basis Port Ramsgate was convicted in this regard...it seems likely to me that failure to fit chains is not the only basis upon which it was convicted, but that it was also convicted on the basis that it should have ensured proper quality assurance provisions were included in the contract with FEAB in order to satisfy itself so far as possible that FEAB and its sub-contractor had proper checking systems in place."*

He summarised the impact of the jury's verdict at p3153, stating:

> ***"By its verdict, the jury has found, in my judgment, correctly, that an owner and operator of a port cannot simply sit back and do nothing and rely on others however expert.*** *If thought had been given to its responsibilities, especially having regard to the provisions of the 1974 Act, Port Ramsgate would have appreciated that there were potential risks, albeit perhaps very small risks having regard to the expertise of those involved. Further, once it was appreciated that there were potential risks, it would have appreciated that such risks should have been guarded against because of the catastrophic consequences if anything went wrong."*

At p3156, delivering sentence, the judge justified the level of fines, stating:

> *"One of the purposes of the Health and Safety at Work Act 1974 is to ensure that the public is safe, that it is protected from...all risk of this kind. It is unacceptable that ordinary members of the public going on board a ferry in the course of their ordinary lives should be exposed to the risk of death or serious injury. The purpose of these fines is, in part, to bring it home to the boardrooms and to the controlling minds of other entities who may be employers that the safety of the public is paramount."*

RELATED DEVELOPMENTS IN THE LAW

In order to appreciate the ramifications of this case, it is helpful to be aware of some related legal developments. The chronology is of particular interest in relation both to this case and, more generally, to the evolution of the state's involvement in health and safety matters.

Departmental policy

One intriguing question thrown up by the Ramsgate trial is why, if the 1974 Act imposes criminal liability for latent defects in new construction work, it has taken more than 20 years for such an application of the Act to emerge. The answer appears to lie in Departmental policy, based on a ministerial direction issued at the time the Act first came into being. It is understood that the relevant Ministers were concerned at the potentially open-ended application of Section 3 and, seeking to contain it, wrote to HSC to advise that there were *"two matters closely related to your responsibilities but which are not within your remit, firstly consumer safety, and second the structural safety of buildings"*. The letter went on to say, *"The structural safety of buildings and building regulation matters generally remain the responsibility of the Departments concerned with building controls."*

The result is that Section 3 has not been used as a vehicle for promoting or ensuring the long-term structural safety of buildings or other construction works. It is unclear whether the HSE decision to prosecute the parties in this case on the basis of Section 3 represented a deliberate change of policy. It is hoped that HSE will clarify its future intentions in this respect, but it is doubtful what reliance can be placed on any statement of intention - the original policy appears to have been promulgated after the Act passed through Parliament and therefore has no significance for the courts interpreting the statutory provisions.

Increase in fines and costs

The object of the criminal law is to motivate desirable conduct and discourage undesirable conduct. It does this by setting rules backed by sanctions. The sanctions available under HSWA in relation to corporate bodies (apart from the special powers of HSE to serve Improvement and Prohibition Notices), mainly consist of fines. The level of fines has been dramatically increased in recent years. Under the original Act, the maximum fine permitted on summary conviction was only £400. By 1991, this had been increased, roughly in line with inflation, to £2,000 in respect of breaches of sections 2-6, but the Offshore Safety Act 1992 then increased the maximum fine on summary conviction to £20,000. The wording has not changed in regard to the power on conviction on indictment to "impose a fine" (which is unlimited), but it may be inferred that the level of fines on indictment should normally be related to the ceiling on fines on summary conviction.

As regards costs, the orders against the four defendants in the Ramsgate case to pay a total of £723,500 prosecution costs was based on a recent change in practice. The point was noted by the judge, at p3158, in delivering sentence that:

> *"The Court of Appeal has recently considered the approach to costs in this class of case in **R v Associated Octel Company Ltd**, in which judgment was delivered on 29th October 1996. It was then recognised that it would ordinarily be appropriate to order defendants who were convicted or pleaded guilty in this class of case to pay costs of the HSE."*

Independent contractor

If Port Ramsgate considered at the relevant time (i.e. 1992/93) what were their duties under HSWA Section 3, they might have noted a statement in the authoritative textbook on health and safety legislation, Redgrave, Fife & Machin at p384, that *"An employer is not criminally liable under s2 for the acts of an independent contractor"*. Port Ramsgate's defence was effectively based on the Swedish contractor and designer and Lloyd's Register all being independent contractors. HSWA Section 2 is similar to Section 3, but the judicial interpretation of Section 3 actually changed between the time when the Ramsgate scheme was being implemented and the time when the case came to trial.

In January 1994, a case on the interpretation of HSWA Section 3 came before the Divisional Court, on appeal from a Magistrates' court. The case, reported as *RMC Roadstone Products Ltd v Jester* [1994] 4 All ER 1037, concerned a company which had engaged an independent contractor to do some work including the removal of some asbestos-cement sheets from the roof of a disused factory for reuse. The system of work adopted by the independent contractor was unsafe. One of their men fell through the roofing sheets and was killed. The defendant company was prosecuted for breach of the duty under HSWA Section 3. The decision of the court, delivered by Smith J, dealt with two issues. The first was whether the activity of the independent contractor was part of the company's undertaking. He stated at pp1044,45,46,47:

> *"The question which falls to be determined is whether by acting through contractors, instead of using their own employees, the appellant can still be said to have been conducting its own undertaking...It appears that the magistrates accepted the proposition that only the activities over which the employer had complete control would fall within the ambit of the conduct of his undertaking. Mr Hoskins [for HSE] invites us to infer that as there is no mention of control in s3, the concept of control is an irrelevant consideration.. He contends that any activity which is for the benefit of the defendant must be regarded as part of the conduct of his undertaking...I find myself unable to accept that 'conduct of an undertaking' should be so widely construed. Nor am I able to accept that control is irrelevant to the conduct of an undertaking. In the alternative...Mr Hoskins submitted that complete control is not necessary, only partial control...He says that where a principal instructs an independent contractor to do something required for the purpose of his undertaking, both the principal and the contractor may have some control over the activities, and each may be said to be conducting his undertaking...I find myself attracted to Mr Hoskins' alternative submission and, with great hesitation, I have come to the conclusion that it is well founded...**I am unable to accept that the mere capacity or opportunity to exercise control is enough to bring the activity within the ambit of the employer's conduct of his undertaking** Before he can say that an activity is within his conduct of his undertaking, the employer must, in my judgment, either exercise some actual control over it or be under a duty to do so."*

The second issue was whether the duty under the criminal law was intended to be the same as the duty imposed by the civil law of negligence. Smith J stated at p1048:

> *"Mr Richardson submitted that if the appellant were to be held to be under a duty under the 1974 Act to devise a safe system of work for those independent contractors, it would extend its duty under the criminal law far beyond the limits of his duty under the civil law. Mr Hoskins submitted that as this is a penal statute, whose objects include the promotion of the health, safety and welfare of people at work, there is no reason why, as a matter of policy, the duties imposed should not extend beyond the bounds of the duty at common law. However, Mr Hoskins' submission does not accord with the proposition accepted by the Court of Appeal in **R v Swan Hunter** [1982] 1 All ER 264 that the duties under the Act were not intended to extend beyond the defendant's duties at common law."*

In June and July 1994, the Court of Criminal Appeal heard another appeal involving interpretation of HSWA Section 3, reported as *R v Associated Octel* [1994] 4 All ER 1051. The defendants in this case had employed an independent contractor to carry out maintenance and repair work, including grinding and cleaning an area with acetone inside a tank. The independent contractor's workman used an electric light which broke. The acetone vapour ignited and the workman was badly burned by the explosion.

The argument was raised by counsel for the defendant (as noted by Stuart-Smith LJ at p1056) that *"the duty imposed by the section is coterminous with the duty imposed by the law of tort in respect of the activity of a person to those who are not in his employment and that this does not, save in exceptional cases, involve liability for the acts of independent contractors."* Counsel for the Crown responded that the words 'conduct of his undertaking' are not confined to criminalising breaches of the common law duty in tort, but are wide enough to embrace the activities of independent contractors carrying out works which are necessary for the conduct of the employer's business or enterprise.

The Court of Appeal, in a unanimous judgment delivered by Stuart-Smith LJ, accepted that the words of Section 2 simply echo the common law obligation of an employer to his workman, but held, at p1059, that *"Section 3(1) is quite different and introduces the concept of 'conducting his undertaking' which is not an expression used in the law of tort to define the scope of liability"*.

Stuart-Smith LJ continued, at pp1062,63:

> *"In our judgment Mr Carlisle is right. The word 'undertaking' means 'enterprise' or 'business'. The cleaning, repair and maintenance of plant, machinery and buildings necessary for carrying on business is part of the conduct of the undertaking, whether it is done by the employer's own employees or by independent contractors. If there is a risk of injury to the health and safety of the persons not employed by the employer, whether to the contractor's men or members of the public and, a fortiori, if there is actually injury as a result of the conduct of that operation there is prima facie liability, subject to the defence of reasonable practicability."*

The Court considered that the question of control went to the issue of what was reasonably practicable, which was a matter of fact and degree in each case

Leave to appeal to the House of Lords was refused in the *RMC* case, but was granted in the *Associated Octel* case. The decision of the House of Lords was delivered in November 1996, shortly before the Ramsgate trial, and is reported as *R v Associated Octel* [1996] 4 All ER 846. The House of Lords, in a unanimous judgment delivered by Lord Hoffmann, upheld the Court of Appeal decision and criticised the Divisional Court's decision in *RMC*. A key passage from Lord Hoffmann's speech was quoted by the judge at the Ramsgate trial in his summing up, at p2649:

> ***"If an employer engages an independent contractor to do work which forms part of the conduct of the employer's undertaking, he must stipulate for whatever conditions are needed, to avoid those risks and are reasonably practicable. He cannot, having omitted to do so, say that he was not in a position to exercise any control."***

According to the commentator in the 1996 All England Reports Annual Review, the point at issue is *"whether the liability of employers under the HSWA should follow common law principles or should be interpreted independently (and thereby more expansively)."* He states his view that *"Strongly following the Court of Appeal's line, the House of Lords held that s3 is not to be interpreted by reference to the common law, but is to be construed as it stands."*

Speaking as an engineer, I hope that that view is incorrect. It can only lead to confusion and uncertainty, if the duties of care imposed by the criminal law and the civil law are to follow unrelated paths. As it is written, if the trumpets sound with an uncertain voice, who shall follow? The promotion of health and safety of the public is more likely to be promoted by the law if there is a consistent and coherent approach to the duties expected of clients and other employers. I am pleased to say that, on my reading of Lord Hoffmann's speech, I do not see any sign of support for the Court of Appeal's semantic approach to interpreting Section 3. On the contrary, it seems to me that the true basis of the House of Lords' decision is to be found in the very practical statement by Lord Hoffmann on p850:

> *"[The argument by the employer] is based on what seems to me a confusion between two quite different concepts: an employer's vicarious liability for the tortious act of another and a duty imposed upon the employer himself. Vicarious liability depends (with some exceptions) on the nature of the contractual relationship between the employer and the tortfeasor. There is liability if the tortfeasor was acting within the scope of his duties under a contract of employment. Otherwise, generally speaking, the employer is not vicariously liable.* ***But s3 is not concerned with vicarious liability. It imposes a duty upon the employer himself.*** *That duty is defined by reference to a certain kind of activity, namely, the conduct of his undertaking. It is indifferent to the nature of the contractual relationships by which the employer chooses to conduct it.*
>
> *I would not accept the extreme position of Mr Carlisle QC for the Crown, who submitted that works of cleaning, repair and maintenance which are necessary for the conduct of the employer's business attract the duty under s3(1)."*

The House of Lords' approach recognises a distinction between the imposition of liability and the existence of a duty. The imposition of liability may differ between criminal and civil law, but that does not entail the duty differing. The point is that even if an employer entrusts work to an independent contractor, the employer nevertheless retains some residual duties. The employer has a duty to exercise appropriate control and must stipulate the right to exercise such control. It may even be correct still to say that "an employer is not criminally liable for the acts of an independent contractor", but the employer may be separately liable for failure to exercise appropriate control over the acts of the independent contractor. That leaves open the question – what is 'appropriate control'?

Common law duty in tort

When the HSWA was proposed it was intended that the general duties would reflect the common law obligations of the parties. The difference was that under the HSWA regime the obligations could be enforced directly by inspectors, not just after an accident but in anticipation of a danger that might arise from work being carried out. Common law duties of care in tort are, of course, only actionable after the occurrence of injury or damage.

It is submitted that the conclusions of the judge on the duties of a client in the Ramsgate case do not involve any conflict with that original philosophy, having regard to the current state of the common law. Examination of cases and statutes on civil liability may actually help to clarify the nature of the duty, although one may have to conclude that the law is evolving and cannot yet be regarded as settled.

The common law duty of care in the Ramsgate situation is that of an owner or occupier of premises towards visitors. This is conveniently set down in the Occupiers' Liability Act 1957, which codified the common law. Section 2(4)(b) of the Act includes an exception in respect of the work of independent contractors:

> *"Where damage is caused to a visitor by a danger due to the faulty execution of any work of construction, maintenance or repair by an independent contractor employed by the occupier, the occupier is not to be treated without more as answerable for the danger if in all the circumstances he had acted reasonably in entrusting the work to an independent contractor and had taken such steps (if any) as he reasonably ought in order to satisfy himself that the contractor was competent and that the work had been properly done."*

On a literal interpretation, one might argue that 'had been properly done' implies only inspection on completion, but judicial interpretation has stretched the owner's duty to include the exercise of control during execution of the work. In *AMF International Ltd v Magnet Bowling Ltd* [1968] 1 WLR 1028, a claim had been brought under Section 1(3) of the Occupiers Liability Act 1957 in respect of damage to some property. The defendant sought to rely on the independent contractor defence in Section 2(4) (b), but Mocatta J stated, at p1044, that 'necessary steps' included ensuring that a contract was in place to allow the owner to exercise adequate control. He stated:

> *"In the case of the construction of a substantial building or of a ship...I should have thought that the building owner, if he is to escape subsequent tortious liability for faulty construction, should not only take care to contract with a competent contractor or shipbuilder, but also to cause that work to be properly supervised by a properly qualified professional man such as an architect or surveyor, or a naval architect or Lloyd's surveyor."*

As regards liability for latent defects which pose a risk to health and safety of owners and tenants, the Defective Premises Act 1972, particularly Section 1(4), places an inescapable duty on developers of dwellings to take care to ensure that the dwellings will be fit for habitation when completed. However, the Act only applies to dwellings; the doctrine of caveat emptor still enables developers to escape liability in regard to commercial property.

In *D&F Estates v Church Commissioners* [1989] AC 177, the House of Lords had to deal with a latent defects claim against a main contractor arising out of faulty workmanship by its plastering subcontractor. The claim was brought on the basis of negligence. The contractual route was not available due to expiry of the limitation period and the effects of the doctrine of privity. The claim was rejected unanimously by the House of Lords in two reasoned speeches, by Lord Bridge and Lord Oliver.

Dealing with the independent contractor issue, Lord Bridge stated at p208:

> *"It is trite law that the employer of an independent contractor is, in general, not liable for the negligence or other torts committed by the contractor in the course of the execution of the work. To this general rule there are certain well-established exceptions or apparent exceptions...* ***But it has rightly been said that 'the so-called exceptions are not true exceptions (at least so far as the theoretical nature of the employer's liability is concerned) for they are dependent upon a finding that the employer is himself in breach of some duty which he personally owes to the plaintiff****... '"*

That is the same point as made by Lord Hoffmann in *R v Octel*. However, on the facts in *D&F Estates*, the House of Lords was unwilling to infer a general tortious duty on the main contractor to supervise their sub-contractors to ensure that the subcontracted work was not negligently performed so as to cause defects. The effect of such a widely framed duty would have been effectively to impose vicarious liability. Lord Oliver did allow, obiter, that there might be some duty to supervise imposed by the common law in regard to matters which threatened the health and safety of the occupants.

Eckersley v Binnie [1988] 18 Con LR 1 is a very strong case on a client's civil liability for risks to health and safety arising out of a construction project. A number of visitors to a water pumping station were killed or seriously injured by an explosion of methane gas. The gas had accumulated in a related tunnel, which was vented into the pumping station. The victims or their families sued the consulting engineer, the contractor and the water authority client in tort. The judge at first instance found all three defendants liable and he allocated blame and liability between the three defendants 55%: 15%: 30% respectively.

The three defendants all appealed to the Court of Appeal, which held that only the consulting engineer was liable. The contractor's duty to test for methane was only relevant to safety during construction. As regards the water authority, Russell LJ, with whom Fox LJ agreed, stated at p76:

> *"In my judgment it is facile to observe that the third defendants did nothing to prevent the disaster...The fact of the matter is that... the third defendants had no reason to suspect that the first defendants had failed to fulfil their obligation to supervise the construction of the work."*

Bingham LJ agreed that the water authority was not liable, basing his conclusion on the protection of Section 2(4) of the Occupiers' Liability Act 1957. He held that the protection was effective *"unless the danger ought reasonably to have been foreseen by an ordinarily competent water authority in the position of the third defendants during the period of operation"*.

It thus appears that the law of tort has recognised the existence of an independent duty on clients to control their independent contractors and to stipulate the right of control, but the duty is not to be framed so as effectively to create vicarious liability. The duty may be more onerous where there is a risk to health and safety. Reliance on appointed professionals to exercise the control is acceptable, so long as there is no reason why, on an objective test, the client should have been alerted to the danger.

MHSW and CDM Regulations

In the criminal law, there have been significant changes in the duties imposed on employers generally (in the HSWA sense) and clients in particular, relative to health and safety in construction works as a result of two sets of Regulations. The first in time is the Management of Health and Safety at Work (MHSW) Regulations 1992, which came into force on 1 January 1993; the second is the Construction (Design and Management) Regulations 1994, which came into force on 31 March 1995. These are both 'health and safety regulations' made under Section 15 of HSWA, and attract criminal penalties under Section 33. Civil liability for breach of both sets of the Regulations is explicitly excluded, except for two specific duties under the CDM Regulations.

The MHSW Regulations introduced a duty on employers generally to make risk assessments. Regulation 3(1) provides, so far as it affects risks to the public:

> *"Every employer shall make a suitable and sufficient assessment of...the risks to the health and safety of persons not in his employment arising out of or in connection with the conduct by him of his undertaking, for the purpose of identifying the measures he needs to take to comply with the requirements and prohibitions imposed upon him by or under the relevant statutory provisions."*

The CDM Regulations impose several duties on clients:

- to appoint a planning supervisor and a principal contractor;
- to be satisfied that the principal contractor and any designers and contractors which the client appoints have competence and will allocate adequate resources to perform their respective functions;
- not to allow construction to start until the construction phase safety plan has been prepared;
- to provide certain information to the planning supervisor;
- to ensure that the health and safety file is available for inspection.

Amongst the duties of the planning supervisor is a duty to ensure that risks to health and safety are assessed and taken into account by designers as considerations in their designs. This applies to risks to "*the health and safety of any person at work carrying out construction work or cleaning work in or on the structure at any time, or of any person who may be affected by the work of such person at work*". Guidance is included in the Regulations on the approach to responding to identified risks.

The role of the planning supervisor has not, to date, been commonly interpreted as concerned with risks to occupiers or the public after completion due to latent defects. However, when one appreciates that the walkway at Ramsgate could have collapsed and killed people during the construction phase due to the same defects, the division is revealed as artificial and unhelpful. The role of the planning supervisor could and, arguably, should be extended, by either interpretation or amendment, to embrace risks to the health and safety of occupiers and the public due to design failures and latent defects. This would provide an appropriate way to deal with the responsibilities of a client adopting design and construct as a procurement method.

Manslaughter

As mentioned earlier, in reaching his conclusion that the offences under HSWA Section 3 could have been committed by the Swedish defendants within Great Britain, the judge in the Ramsgate trial held that HSWA was directly concerned with preventing death or injury, so that the offence is committed at the place where people are put at risk to their health and safety. The contrary view is that HSWA is concerned with promoting good management practices as a means to safeguarding health and safety, and that the offence is complete when and where the bad management practices take place. It is respectfully submitted that if the true nature of the offence is causing death by carelessness, then the appropriate charge should be corporate manslaughter.

To appreciate why the prosecution in the Ramsgate case would have been brought under HSWA, one needs to be aware of an earlier prosecution arising out of the sinking of the Herald of Free Enterprise. In that case, the company operating the ferry was prosecuted for manslaughter, but the trial was terminated by the judge due to a legal problem.

As the law stood, it was necessary to identify the individuals in the company who were responsible for safety in order to hold the company responsible. Turner J directed the jury that there was no evidence upon which they could properly convict the company of manslaughter. This was *"despite the findings of a judicial inquiry, in the Sheen Report, that all concerned in management must be regarded as sharing responsibility for the failure of management and that from top to bottom the body corporate was infected with the disease of sloppiness."*

To overcome the difficulties in that case, the Law Commission has since published a report *Legislating the Criminal Code: Involuntary Manslaughter*, Law Com No 237, recommending a new offence of corporate manslaughter, broadly corresponding to the individual offence of causing death by gross carelessness. It would be committed only where the defendant's conduct falls far below what could reasonably be expected. The Law Commission recommends that the offence under HSWA should be available as an alternative verdict. The recommendation is framed as follows:

> *"For the purposes of the corporate offence, a death should be regarded as having been caused by the conduct of a corporation if it is caused by a failure, in the way in which the corporation's activities are managed or organised, to ensure the health and safety of persons employed or affected by those activities."*

In delivering sentence at the Ramsgate trial, the judge stated that three of the defendants had been found guilty of gross carelessness. He did not suggest that this was the position with Port Ramsgate. The identification of two clear levels of culpability is considered desirable.

It is submitted that the Law Commission proposals are strongly to be welcomed and should be implemented as soon as parliamentary time permits. In the case of latent defects, however, it may be necessary to clarify whether the legislation will be retrospective, since failure due to latent defects may take place some years after the act of carelessness.

RISK ASSESSMENT, QUALITY ASSURANCE AND STANDARDS

It is tolerably clear that the law has moved to a position where a client has a personal duty to exercise appropriate control over its independent contractors and to stipulate powers to exercise such control. It is less clear what is 'appropriate control', particularly where a design and construct procurement method is adopted. It appears from the Ramsgate trial that there was no authoritative guidance available on the point at the relevant time, either from HSE or any other major body. This created difficulty for the client in its defence. It also meant that the experts at the trial had to deal with issues of what actions the client could and should have taken, and whether such actions would have made a difference to the outcome. It appears from the judge's summing up that the evidence suggested that appropriate control could have been in three areas: risk assessment, quality assurance and stipulating adherence to specific Standards.

Counsel, judge and jury seem to have satisfied themselves that they understood what was entailed, but the summing up actually reveals a degree of confusion. Also, there appears to have been limited attention to chronology and the effect of international contracting; the salient events occurred in 1992/93 and not all the parties were UK-based.

In commenting on this aspect, I make some reference to CIRIA Report SP 84 entitled *Quality Assurance in Construction – Contractual Aspects*, published in 1992, for which I was the research contractor and author.

Peer review

Before commenting on the judge's digest of the experts' evidence, I would state my own opinion that there are two effective means to prevent failure due to errors in visualisation, such as occurred at Ramsgate. The first is independent peer review of the design, the second is review of the works during construction. Simple checking of the existence or accuracy of calculations is of no benefit.

CIRIA Report SP 84 included, at p138, some helpful quoted comments on peer review:

- *Peer review is needed to point out errors in visualisation.*
- *It is remarkable how keen people are in criticising the work of others. We have found the reviews do pick up problems. The review asks real questions about the philosophy of the design. There are difficulties, however, in finding time on rush jobs.*
- *Peer reviews only have credibility if the peers have relevant experience.*

It will have come as a shock to many people to discover that the checks carried out by Lloyd's Register were not in the nature of peer reviews

Risk assessment

The expert evidence suggested that a risk assessment should have been carried out by the client at Ramsgate, possibly leading to a decision to provide secondary protection in the form of safety chains. Presumably the risk assessment might also have led to a decision to exercise a higher degree of control of the design/build contract or to require an independent review of the design, having regard to the special risks inherent in the movement of floating structures and the prototypical nature of the design.

It is doubted that HSWA directly required a risk assessment. Such a requirement was introduced by the MHSW Regulations 1992 with effect from 1 January 1993. Leaving aside the question of the dates, Section 3 of the Regulations, quoted above requires a degree of interpretation to apply to a client procuring new construction works in the way contended. Indeed, when one looks at the further statutory requirement for risk assessment introduced by the CDM Regulations, which is to be undertaken by the designers and planning supervisor for new construction works, there is scope for overlap and, possibly, conflict.

It is submitted that there should be an integrated approach to risk assessment for new construction projects as regards matters affecting health and safety. The statutory role of the planning supervisor should be extended to include responsibility for co-ordination of all such risk assessment during the pre-construction phase. Unlike the MHSW Regulations, the CDM Regulations actually provide guidance on what is required as a response to identified risks. This guidance may also be appropriate, with a little adjustment, to the risks of latent defects. Powers to exercise 'appropriate control' could also be provided through amendment to the CDM Regulations.

Quality Assurance

The judge's summing up conveys a general conclusion that Port Ramsgate should have done something about quality assurance and that they should have done this through stipulation in a contract, but specific comments raise three different approaches without noticing that they are different. Was the conclusion that:

- the client itself should have had a quality system?
- the client should have stipulated in a contract with the contractor and designer that they would operate quality systems complying with ISO 9000 series?
- the client should have stipulated in a contract with the contractor and designer direct powers of control?

The judge quoted a comment in his summing up, at p2756, that it was "*incumbent upon an operator like Port Ramsgate to have proper management systems to ensure that they had control over the process of design and construction*". It is, however, a root problem that the ISO 9000 series has its origins in manufacturing and is directed towards the 'purchasing a fleet of cars' situation. It is part of the ISO 9000 philosophy that the ultimate purchaser's only quality function is to spell out its requirements. As was pointed out in CIRIA Report SP 84, there is no model specification in the ISO 9000 series for a quality management system for procurement.

The second approach, that the client should have stipulated for the designer and contractor to operate their own quality management systems, appears particularly in the evidence of Mr Dawson, summarised at p2837 and of Sir Bernard Crossland, summarised at p2843. This has some merit, particularly since ISO 9001 Clause 4.4 allows for peer review. There is a certain inconsistency within the judgment, however, as regards belief in the effectiveness of quality management systems in preventing design errors. The judge, at p2847, quotes the example of Lloyd's Register having quality assurance in abundance without effect: *"They were very strong on procedures. They had an enormous safety manual but it didn't prevent those mistakes being made."*

As regards contractual stipulation of quality management systems, CIRIA Report SP 84 noted in 1992 that there was a popular view that adoption and application of quality management systems by contractors and designers in construction was better obtained through the tender prequalification process, rather than by contractual stipulation. There were also difficulties noted in regard to requiring overseas contractors to have quality management systems. Although ISO 9000 is an international standard, it is derived from a British Standard and its use was and is more widespread in the UK than elsewhere. Other countries have different approaches, for example peer review in the United States, appointment of a prufingenieur in Germany, using an independent checker for decennial insurance in France. Even in the UK, the implementation of quality management systems has not been made an express statutory requirement for contractors or designers in construction.

In any event, to stipulate that a designer and contractor will operate quality management systems complying with ISO 9001 only involves a couple of lines in the contract, with words to the effect that "The contractor shall operate a certificated quality management system". Surely the mere failure to include such words cannot be a satisfactory basis for conviction of a client; nor doing so constitute satisfactory discharge of the client's duty.

The third approach is that quality assurance entails some direct reservation of powers and action by the client. This was described by George Steele, who was actually giving evidence for the defence. He is quoted at p2853 as saying that *"he would have used an ICE design and build contract."* The ICE Design and Construct Conditions were first published in 1992. Prior to that there had been no appropriate ICE Conditions, largely because there was no consensus as to the proper role of the Employer and the Employer's Representative in such an arrangement. Some clients had adapted the standard ICE Conditions, but the result was usually inappropriate. The ICE Design and Construct Conditions advanced matters, as they provided a defined role and powers for an Employer's Representative. Clause 8(3) allows for stipulation of quality management systems, but it is optional. Clause 8(4) provides that where Regulations require that a separate check on the design shall be carried out, the Contractor shall arrange and pay for such a check. Clause 6(2) requires the Contractor to submit designs and drawings to the Employer's Representative for consent.

Perhaps such a comprehensive arrangement is really what Mr Dawson had in mind when he said, in what the judge quoted, at p2842, as the 'backbone of the Crown's case on this aspect':

> *"Well if you are talking about a management system and control you are necessarily talking in fairly general terms. I think it would have [made a difference], the measures I am talking about, I think would have been likely to have ensured that FKAB had done the design and in a properly controlled way... Without doing any detailed checks at all you could see that the proper attention had not been given to the design..."*

Standards

The Judge's summing up included several references to BS 5400 and suggestions that the client should have stipulated adherence to it. BS 5400 is, however, a Standard for bridges with fixed supports. The Standard may well include elements which could be applied to a walkway supported on a floating pontoon, but this would need to be done with caution. Some recommendations are probably based on assumptions about the support system.

There does not appear to have been any mention of it at the trial, but there was in force a British Standard which purported to deal specifically with pedestrian accessways to floating pontoons, namely BS6349 *Code of Practice for Maritime Structures* Part 6 (1989) *Design of inshore moorings and floating structures.* This Part includes an ample description of the six degrees of freedom of a floating pontoon, but when it comes to dealing with the interaction between access walkway and pontoon, the Standard is sadly deficient. The relevant passage states:

> *"Examples of the use of floating pontoons include...Ro-Ro berths...Where possible, independent vehicle and pedestrian access should be provided. The accessways should, where possible, be independent of the restraining system for the structure, and be connected to the structure so as to avoid undue stresses from motions of the structure... Walkways to floating structures should allow for vertical as well as horizontal motions."*

CONTRIBUTION TO STRUCTURAL SAFETY

One can go back several thousand years, to the Code of Hammurabi, to observe efforts by the law to prevent latent defects which threaten health and safety. Then the penalty was slaying of the builder or, in some cases, his child. It is still tempting today for legislators to assume that there is a simple answer, for example, that bigger fines mean safer structures. Needless to say, most cures have side-effects, which may sometimes be worse than the cure.

A good example can be observed in the law on civil liability for latent defects. In 1972, the Court of Appeal decided that local authorities could be held liable in negligence for latent defects in new buildings, arising out of the powers to approve plans and inspect buildings during construction conferred on local authorities by the Public Health Act 1936. The initial effect of imposing liability was beneficial in that the quality of local authority building control was dramatically improved. The House of Lords enthusiastically endorsed the ruling in 1977. It soon came to be realised, however, that there were bad effects. Due to the doctrine of joint and several liability, local authorities assumed the role of unpaid insurers, with total liability for the faults of builders and architects who ceased trading or had no money. Defending the cases was an enormous drain on resources. Eventually, in 1990, the House of Lords overturned its previous decision.

As a one-off, the Ramsgate prosecution has done an enormous amount of good, particularly in drawing attention to the duties of clients and making clients realise that they cannot abdicate responsibility for matters affecting health and safety. The level of the fines and the length of the trial have concentrated minds. The case is a powerful means of both clarifying the law and disseminating the message.

The defendant client may, however, feel somewhat aggrieved at having funded this public education and legal development process, particularly since the trial has also revealed serious gaps in guidance and Standards. It should not be overlooked that the case has only provided so much insight because Port Ramsgate defended it. This not only brought us the debate between the experts, and the judge's analysis, but it also allowed the material into the public domain and stopped the dead hand of legal confidentiality, which is frequently an obstacle to learning from failures.

The large fines imposed actually promote the likelihood of defendants pleading not guilty and going to trial, but several other points in this case discourage it:

- first, the order that the party who defended the case pay the prosecution costs of the trial;
- second, the application of the rule that a defendant who chooses to defend a case is penalised more than one who pleads guilty;
- third, the emphasis on the outcome of the offence rather than the degree of negligence;
- fourth, the practice of leaving the particulars of alleged good practice to emerge through expert evidence at the trial.

As it is, we have not had the benefit of the appeal process, which might have helped further. I would also submit that it is important that employers should believe that it is worthwhile mounting a defence following an accident, if they are in a position to give evidence that they operated reasonable working practices. The motivation to operate such practices is lost if conviction follows automatically from the occurrence of an accident. For both reasons, I suggest that, at least in marginal cases, the defendant who pleads not guilty should not be subject to prosecution costs of the trial, nor lose the mitigation obtained by pleading guilty.

The case also raises the question, whether trial by jury is an appropriate means of dealing with such offences. The involvement of the jury probably led to much of the cost and the length of the trial. It is doubtful whether the jury understood fully the technical evidence. On the other hand, the need to reduce complex matters to terms which a jury can understand can sometimes be beneficial, and if the judge's summary of the jury's verdict is correct, it demonstrates that a very robust and common sense approach can emerge.

The money and resources involved in the prosecution is a major concern. Would a proliferation of such prosecutions be a good use of resources to promote health and safety? Above all, one is prompted to ask how a government finds it so easy to apply hundreds of thousands of pounds to a criminal prosecution to protect health and safety, but finds it so difficult to provide tens of thousands of pounds to fund better Standards for the same purpose.

The Ramsgate case has itself contributed to the establishment of new and helpful legal principles, but it has also revealed the need for further work or action to:

- Provide authoritative guidance on the role of a client who adopts a design and build procurement approach, having regard to the complexity and novelty of the specific project;
- Establish statutory powers for appropriate control of design and build contractors and, in particular, to specify in Regulations when independent design checks are required;
- Review HSWA and the Regulations made under it to ensure that the requirements are both clear and practicable;
- Reconsider both the use of jury trials and the rules and principles governing fines and costs in HSWA prosecutions;
- Review procedures for ensuring that published Standards do not contain serious inadequacies;
- Override legal confidentiality to release information relevant to the future protection of health and safety;
- Implement the Law Commission recommendations on corporate manslaughter.

My own proposal, particularly to overcome the dilemma facing clients adopting design and build procurement of construction works, is that the role of the planning supervisor should be extended to embrace design matters affecting risks to the health and safety of occupants and the public after completion.

Investigation of non-catastrophic failures

Dr P. Lindsell and Dr S. H. Buchner
Peter Lindsell & Associates, Southampton, UK

INTRODUCTION

Many material failures occur in practice without resulting in partial or total collapse of a structure. For example, the presence of large surface cracks in a concrete section is normally an indication of localized overstress in the concrete material, but the inherent strength of the section may be unaffected. The physical nature of the composite action between the internal reinforcement or prestressing steel can be a contributory factor to the resilience of a section. However, the methods of erection, timing of construction events, degrees of redundancy, articulation and external restraints can create important secondary effects, which may initiate or prevent the failure of a structure. Over a long period of time, the combination of constituent materials, hidden defects and environmental conditions may eventually lead to a structure becoming unserviceable or an unacceptable risk of a sudden failure mechanism.

The primary aim of this paper is to illustrate the principal causes of a number of non-catastrophic failures. Several case histories have been selected to demonstrate the importance of designing for durability and a degree of redundancy in any structural system. The potential risk of a sudden collapse is assessed, together with the measures required to achieve an acceptable factor of safety.

SEVERE CRACKING IN A RIGID FRAME STRUCTURE

An in situ reinforced concrete (r.c.) frame was designed in the form of a six-legged table structure to support a section of a heavy industrial plant. The manufacturing process required a circular hole through the centre of an r.c. slab, which acts compositely with substantial r.c. beams. The beams are integral with six r.c. columns, forming a rigid frame structure.

The primary vertical loading on the concrete structure occurs during operation of the plant, as large quantities of raw material are passed through a furnace. However, under normal working conditions, the concrete slab around the perimeter of the furnace can reach temperatures of 200°C, while the supporting beams may be at 40 - 60°C under steady state conditions. The concrete slab is also subject to significant dynamic loads created by hydraulic rams which control the operation of the furnace.

Initial cracking in the slab, beams and supporting columns occurred within 12 months of operation. Routine maintenance operations required shut down of the furnace on an annual basis and this allowed the concrete structure to cool down to ambient conditions during mid-winter. Consequently, a large temperature reversal occurred at the same time as a significant weight of raw material was removed from the furnace. Over a period of 15 years, a series of major stress reversals in the structure produced an accumulated non-linear response, causing severe cracks to develop in all sections. Areas of the r.c. slab formed a pattern of yield lines, with localised

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 61–68

spalling of the surfaces on the compression faces. A typical pattern of cracks at one corner of the structure is illustrated in Figure 1.

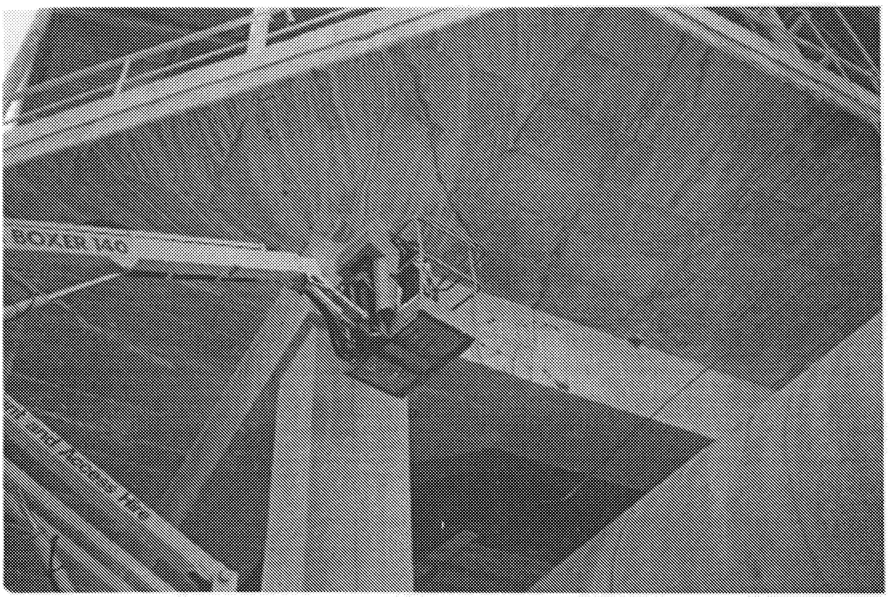


Figure 1. Cracking to soffit of main beams and slab.

A review of the design loading and reinforcement details indicated that the original design appeared to make no specific provision for thermal gradients and associated movements in the concrete structure. A detailed analysis of the loading regime demonstrated that the main source of distress in the structure arose from excessive compressive stresses immediately around the perimeter of the furnace. A balancing system of tensile forces was required to maintain internal equilibrium and this system of forces was primarily responsible for the initial cracking around the supporting beams and outer sections of the slab. Subsequent stress reversals merely served to aggravate the distress as localised yielding and debonding of the steel occurred at critical sections. The risk of concrete fragments falling onto personnel was high and a strategy for strengthening the structure was required as a matter of urgency.

Initially, a scheme was considered for stabilising the structure by introducing a pattern of external prestress to prevent collapse of the main beams. Prior to any remedial works, a pattern of strain gauges and temperature probes were introduced to monitor the behaviour of the structure over a shut-down period. The information gained from this investigation indicated that a safer, more cost-effective approach was to provide a series of steel props from the existing columns in order to support the main beams and the yielding sections of concrete slab. The strain gauge monitoring system was left in place so that the plant operators had the facility to detect sudden deterioration of critical concrete elements in the future.

FLEXURAL SHEAR FAILURES IN POST-TENSIONED CONCRETE BEAMS

A special inspection of a post-tensioned concrete viaduct was undertaken following the discovery of widespread flexural/shear cracking in the main longitudinal I-section beams. The most significant areas of cracking were found in the midspan region, between the central pair of transverse diaphragms. A major crack adjacent to a diaphragm is illustrated in Figure 2. A review of the original design calculations, drawings and construction records highlighted a series of important factors which could have contributed to a significant loss of pre-compression in the bottom flanges. The design was based upon the first UK Code of Practice for prestressed concrete, CP115[1], which has now been superseded by BS 5400[2].

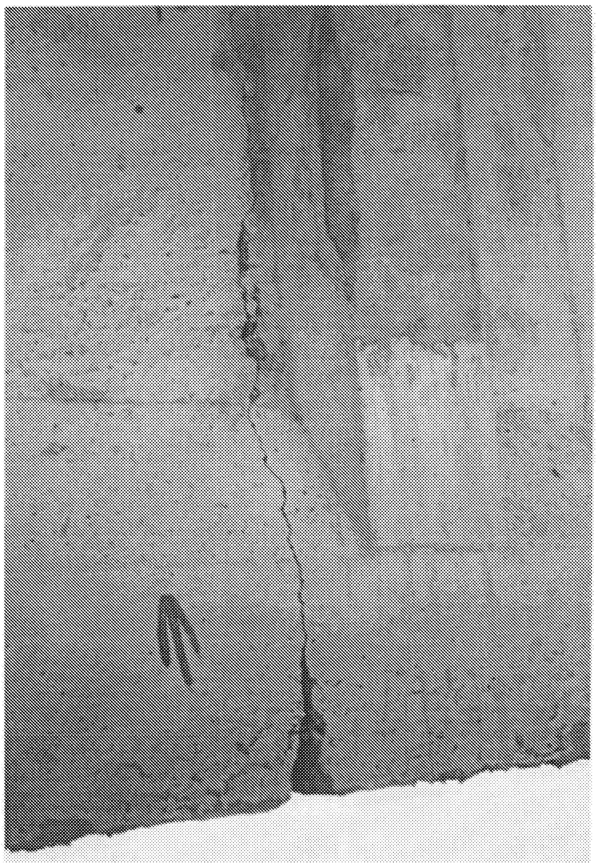


Figure 2. Flexural shear crack in bottom flange and web.

An internal examination of the prestressing system in the main beams confirmed that the tendon ducts where predominantly ungrouted. Fortunately, there was little evidence of surface corrosion of the prestressing tendons, in spite of the water leakage into a number of ducts. However, the risk of a sudden collapse of an individual beam or a complete span was considered to be unacceptably high, due to the severity of the flexural shear cracking and the potential sudden failure of the unbonded prestressing tendons.

In order to quantify the full range of stress conditions in the main beams, a series of in situ concrete stress measurements and a live load test were conducted on both a fully cracked span and an uncracked span. The evidence gathered from these tests demonstrated the vital contribution played by the asphalt surfacing and edge details on top of the deck. The overall effect was to raise the neutral axis of the edge beam by a significant amount, allowing severe live loading of the deck to initiate cracking in the bottom flanges. Once these cracks had developed, the neutral axis continued to rise into the top flange of the I-section beams. An asphaltic concrete wearing course was laid directly onto the top flanges of the beams. Hence, the deck surfacing and edge parapet details were subjected to very significant levels of compression in order to maintain equilibrium under dead and live load conditions.

The loss of prestress, combined with the loss of structural stiffness and unbonded tendons, allowed the main beams to sag downwards under dead load conditions. Furthermore, the dynamic response to passing traffic was greatly increased, as the reduction in flexural rigidity occurred across the middle third of the beams. These conditions required immediate precautions and a weight restriction, coupled with one-way working, was introduced to minimise the live load effects. The strategic importance of the route did not allow total closure of the structure.

Consideration was given to a variety of strengthening techniques to maintain the viaduct in service. Partial replacement of the worst affected beams appeared to be a feasible option, in spite of the difficulties involved in maintaining traffic. Overall, the most appropriate remedial scheme to the majority of spans was based upon the application of additional external prestressing to restore the compression in the bottom flanges of the I-section beams.

CORROSION OF EXTERNAL PRESTRESSING

When the post-tensioning cables supporting the unusual roof structure, shown in Figure 3, were found to be corroding, a combination of computer analysis, instrumentation and structural monitoring was needed to solve the problem of tendon replacement. Over a period of twenty five years, the concrete structure had suffered from the corrosive effects of the humid chlorine environment generated by the swimming pool which the structure houses. However, because of the unique form of construction used for the pool hall, the decision was made to refurbish the building.

The thrust developed by the four hyperbolic-paraboloid thin shell structures, which form the roof, is counteracted by external prestressing cables which join the tops of the four main columns. A preliminary inspection of the ends of the tendons revealed some slight rust staining on the surface of the concrete. Where the steel was visibly exposed to the chlorine environment, they were wrapped in denso-tape which successfully prevented any corrosion. However, within the anchorage zones, voids were found and the cables were corroding. This may not have caused concern if it was merely superficial and there had been a degree of redundancy in the design. However, the possible occurrence of stress corrosion cracking and the risk of a catastrophic failure made it necessary to remove and replace the cables.

The thin shell roof structure was made from 75mm thick lightweight reinforced concrete cast in situ onto asbestos sprayed wood wool tiles. The first phase of the refurbishment required that these tiles were removed. However, once the insulation layer was removed, it was found that leaching of water and fines had occurred at the interface with the concrete and large voids had formed. In a large number of positions the reinforcement was visible and corroded. This added a further dimension to the cable removal, since the behaviour of the roof during removal of the tendons could not be accurately predicted. However, some estimate of the behaviour had to be made prior to dismantling.

Figure 3. Hyperbolic-paraboloid shell roof.

The complexity of the structure was such that a finite element analysis of the roof structure was required to determine the actions of dead weight, prestress and temperature. The computer analysis was used to estimate the stresses which would be induced in the roof during each stage of removal and replacement of the tendons and the possible shock loading that would occur if a tendon failed in an uncontrolled manner. The stresses induced in the roof due to the removal of the cables were then added to those produced by the marked temperature change which occurred once the heating was switched off. It was found that the stress levels determined would have been sufficient to crack the concrete. Therefore, methods of preventing the stress concentrations had to be investigated.

Consideration was given to the installation of bird-cage scaffolding, props beneath of the edge beams and ties between the column heads as possible temporary support systems during cable replacement. The use of prestressed ties to the tops of the columns was considered the best solution, as it allowed balancing of load between the existing prestressing cables being removed and that applied to the temporary ties. Unfortunately, the tops of the columns were unable to resist the full design prestressing forces in the original cables. Since it was not possible to determine the level of existing prestress prior to cable removal, an unknown tensile stress would be induced in the shell roof. Therefore, to minimise the stresses and damage to the shell structure, a combination of ties and propping of the central edge beams provided a satisfactory solution.

The removal of the existing tendons required a framework, comprising two concrete beams and four Macalloy bars, constructed around each post-tensioning cable. The strands in each tendon were then cut incrementally in turn and the load transferred into the Macalloy bars. As these bars were slackened, stress was applied to a secondary system of temporary ties which was positioned below the intersection of the ring beams and the main columns, and below the springing points of the roof. This load transferal was carried out in a balanced fashion in order to minimise the deflections in the roof.

Gauges were applied to different parts of the structure to determine the effects of load transfer and measure the existing levels of stress in the post-tensioning cables. Vibrating wire strain gauges were positioned on the steel columns, at the ends of the cantilevers, and on selected props forming the central tower. Demec gauges, 100mm long, were used for measuring the strain in the Macalloy bars. The load applied to the temporary ties and the existing levels of stress in the cables being removed were measured with 50mm long Demec gauges. Deflection of the cantilever tips was measured using standard surveying techniques.

The introduction of new permanent cables into the roof required a reversal of the removal process. The stress levels for the new tendons were derived from strain measurements on the removed cables and the framework bars, which showed that approximately 25% losses had occurred in the prestressed cables over a period of 25 years.

PREMATURE COLLAPSE OF A WATER TOWER

The 30m tall tower, shown in Figure 4, consisted of a central circular shaft, post-tensioned by eight "Freyssi" cables, and a circular water tank. The tank also contained a number of post-tensioned elements including two ring beams, 24 columns and 24 radial beams. Unfortunately, the inherent flexibility of the tank structure meant that it was never water tight and so remained unused for 30 years prior to its demolition. It's premature collapse during demolition provided an opportunity to examine the structure fully to determine the causes of failure.

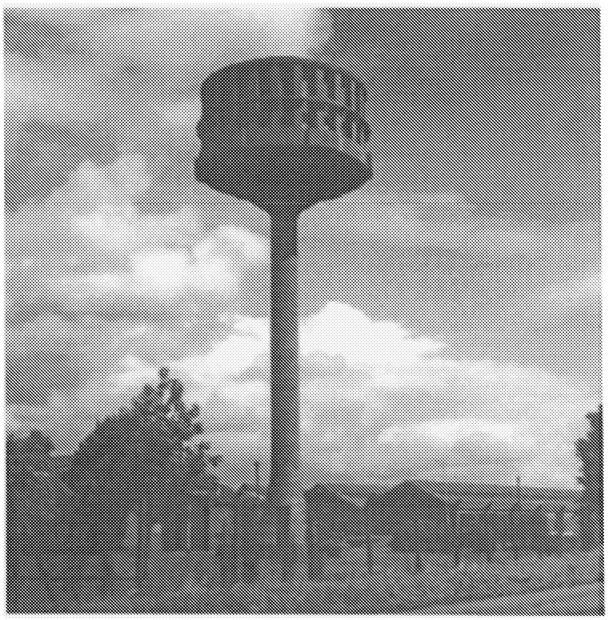


Figure 4. Post-tensioned concrete water tower

An initial inspection of the tower revealed a series of cracks around the base of the shaft and it was considered possible that there had been a significant reduction in prestress. In situ stress levels were determined using coring techniques[3] around the base of the shaft. These tests showed the stress levels to be very low at the base of the shaft and relatively insensitive to variations in prestressing levels, since the overall axial stress within the structure was dominated by self-weight . Horizontal cracks in the thickened sections at the base of the shaft had opened and the residual level of compressive stress was insufficient to prevent tension developing under extreme wind load conditions. Since the condition of the prestressing tendons was unknown and the structural integrity of the shaft could not be guaranteed, it was recommended that the disused structure should be demolished. In view of the general condition of the structure at the base, it was concluded that a progressive failure mechanism could occur which would cause an instantaneous collapse with no prior visual warning. Therefore, demolition was advised.

The proposed method of demolition of the water tower relied upon a hydrodynamic shock wave created by explosive charges suspended within the hollow shaft. In order to ensure a uniform bursting force, it was necessary to completely fill the shaft with water prior to fixing the charges. The anticipated form of collapse was a symmetrical outward bursting of the shell walls and vertical collapse of the tank onto the base. Calculations made to check the maximum tensile hoop stresses in the shaft had indicated that water pressure would be insufficient to break the concrete and it was anticipated that a significant explosive charge would be needed to shatter the entire shaft. However, the evening prior to the day of blowdown, the hollow shaft collapsed under the hydraulic pressure. The tank fell vertically onto the base, exactly as intended.

The subsequent inspection of the debris showed the in situ joints between concrete pours to be cold joints which were very smooth. Consequently, the prestressed shaft was in fact behaving in a similar manner to a precast concrete segmental structure, with no tensile strength across the joints and very little shear resistance. In the upper sections of the shaft this presented no problem since the stress levels were sufficient to ensure monolithic behaviour. However, in the thicker section at the base, the low axial stress allowed water to enter the horizontal joints immediately above the top of the door and drastically reduced the remaining shear resistance of the concrete rings making up the shaft.

At the base of the tower the bottom two concrete rings above the doorway had completely sheared apart. Previous inspections had identified vertical cracks on the surface on each side of the lower construction joints. However, these cracks generally penetrated less than 100mm into the concrete sections, which were some 500-1000mm thick. Immediately above the doorway, a vertical crack had developed previously due to the stress concentrations around the door. For this crack to propagate and the concrete ring above the doorway to split, the prestressing tendons had to be sheared outwards and broken in tension.

From the previous in situ stress measurements, the prestressing tendons were expected to be stressed to less than 50% of their tensile strength. However, examination of the tendons revealed they had failed in the classic "cup and cone" arrangement associated with a tensile failure. The cause was immediately apparent, since the inside of the prestressing ducts showed little evidence of cement grouting and extensive areas of rusting. Many wires were severely pitted and some had withered away in the oxygen starved atmosphere, producing the characteristic black oxide of iron. This is particularly difficult to detect inside a structure since the chemical reaction produces virtually no expansion and no concrete cracks are likely to develop. The complete and instantaneous failure of the prestressing wires demonstrated the importance of cement grout in post-tensioned concrete construction and the need to establish the condition of existing tendons prior to any form of structural alteration or demolition.

CONCLUSIONS

The investigation of failures in actual structures has demonstrated that designers should not follow standard Codes of Practice and National Specification documents, without considering the particular circumstances and local conditions surrounding a structure. In addition, although an apparent degree of redundancy may be built into the structure, this may not apply to the most critical elements.

The selection of materials and timing of construction events are two crucial items that are often left to the contractor to decide, without reference to the original designer. It is vital that the engineers responsible for initiating a design should oversee the construction process and be involved in subsequent maintenance and repairs. In this manner, designers and contractors alike may learn from the experience and avoid the types of failures illustrated in this paper.

REFERENCES

1. BRITISH STANDARDS INSTITUTION. The Structural Use of Prestressed Concrete in Buildings. CP115: Part 2: 1959.
2. BRITISH STANDARDS INSTITUTION. Code of Practice for Design of Concrete Bridges. BS 5400: Part 4: 1990.
3. Buchner, S.H. "Full-scale testing of prestressed concrete structures". Ph.D. thesis, University of Surrey, 1989.

Averting catastrophic failure using forensic engineering techniques

PROFESSOR B.L. KARIHALOO,
Forensic Engineering Group, School of Engineering, Cardiff University, UK

ABSTRACT
This paper will demonstrate on several large concrete structures the application of fracture mechanics as a forensic engineering tool. It will be used for an appraisal of the safety of mass concrete structures that have developed large cracks and for the design of effective strategies for repairing them.

INTRODUCTION
Mass concrete structures with minimal or no reinforcement, such as large containment structures, plinths of bridge piers are full of microcracks which can grow under thermal and/or mechanical loading and coalesce to form large, visible cracks. The growth may be further enhanced by creep of concrete, temperature fluctuations, and water pressure between the crack faces. The important question to answer is whether these cracks pose an immediate or delayed threat to the safety of the structure. A related question is how to repair the structure so as to prevent the opening and growth of the cracks in the future.

These two questions are of particular concern in older structures which are still in service but which were designed without regard to the formation and growth of cracks (Karihaloo 1995). It should be noted *en passant* that this philosophy is still followed today for the design of all concrete structures and not just the large structures under consideration in this paper. The current concrete structural design practice is still based on elasticity or plasticity concepts (i.e. strength criteria) without regard to the formation and propagation of large cracking zones through the structure. This has the undesirable effect of reducing the safety margin as the size of the structure increases. For the same reason, the efficacy of measures undertaken to repair large cracks in structures is doubtful. In fact, because these measures also follow the same design concepts without a knowledge of how the cracks are going to evolve in time, they are often of a temporary nature, requiring repeated and costly repairs.

In this paper, we will present several examples where a lack of understanding of when and how cracks grow in large concrete structures has led to superficial repairs which have not only been costly, but in one instance have had fatal consequences. We shall demonstrate on the same examples how an energy failure criterion based on simple fracture mechanics can be gainfully employed for an appraisal of the safety of mass concrete structures with large cracks and for the design of effective repair strategies, in order to avert catastrophic failure. We shall first describe briefly the concepts of linear elastic fracture mechanics and of a non-linear fracture theory appropriate to concrete.

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 69–76

LINEAR ELASTIC FRACTURE MECHANICS, LEFM

Griffith (1920) was the first to prove that the real tensile strength of a brittle material was significantly lower than its theoretically possible value because it contained cracks with high stresses near their tips. He derived the tensile strength (fracture stress) by equating the energy accumulated in a large thin plate of the material containing a central slit-like crack of length $2a$ under the action of a remote tensile stress σ applied normal to the crack to the energy necessary for rupturing the bonds ahead of the crack tips. The result is the celebrated Griffith energy criterion for fracture

$$\sigma\sqrt{\pi a} = \sqrt{2E\gamma} = \text{Const} \tag{1}$$

where E is the Young modulus of the material and γ its surface energy per unit area, i.e. the energy required to create a unit crack surface in the material. Griffith noted that the crack tips where the stresses are high (theoretically approaching infinity) are the main regions of fracture process.

This observation led to the formulation of an alternative fracture criterion by Irwin (1957). He showed that a sharp crack in a brittle material will grow unstably when the stress intensity factor K_I at its tip reaches a critical value for the material, denoted K_{Ic}

$$\sigma\sqrt{\pi a} = K_{Ic} \tag{2}$$

The local fracture criterion (2) at the crack tip where the fracture process is taking place is exactly identical to the global energy criterion (1), provided

$$K_{Ic}^2 = EG_c \tag{3}$$

where $G_c = 2\gamma$ is the Griffith surface energy density because fracture creates two new traction-free (open) crack surfaces. The notation G_c (after Griffith) was introduced by Irwin. G_c is called the toughness of the brittle material and K_{Ic} its fracture toughness. The parameter K_{Ic}^2/E is sometimes referred to as the critical 'force' necessary for driving a crack.

The fracture criteria (1) and (2) have been derived on the assumption that the fracture process is concentrated at a point (the crack tip) which is physically impossible in a real brittle material because it implies an infinite stress there. Irwin (1958) recognised this drawback and assumed that the fracture process takes place over a finite though small zone near the crack tip – the so-called fracture process zone (FPZ). He obtained a rough estimate of its size l_p by limiting the transverse normal stress in the fracture criterion (2) to the tensile strength f_t' of the brittle material. From (2) and (3) it then follows that

$$l_p = K_{Ic}^2/(\pi f_t'^2) = (EG_c)/(\pi f_t'^2) \tag{4}$$

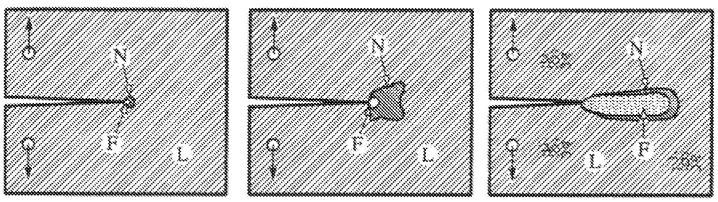
We shall not dwell upon the techniques for the determination of the fracture toughness K_{Ic} of a brittle material from notched test specimens.

A NON-LINEAR FRACTURE THEORY FOR CONCRETE

As concrete was thought to be a brittle material many attempts were made since 1950s to apply the LEFM criteria (1) and (2) to it. It was however found that its fracture behaviour deviated from that predicted by the LEFM, the more so the coarser the microstructure of the mix. The primary reason for this is now known to be the formation of an extensive FPZ in which the material progressively softens due to microcracking.

The Irwin formula (4) can again be used to obtain a rough estimate of its size. Gettu and Shah (1992) calculated l_p for typical cementitious materials using this formula. They found the l_p ranged between 5 and 15 mm for hardened cement paste, 100 – 200 mm for mortar, 150 – 300 mm for high strength concrete (50 – 100 MPa), 200 – 500 for normal concrete, and up to 700 mm for concrete with coarser aggregate (maximum size up to 38 mm). In general, the larger the l_p, the more ductile the mix response. l_p is determined by the microstructure of the mix, in particular the maximum size of the coarse aggregate used.

It was therefore found necessary to develop a non-linear theory of fracture for concrete, which was however different from the non-linear theories available for ductile metallic materials. This is because in the latter the FPZ is small and surrounded by a large plastic zone, whereas in concrete the FPZ is large and occupies nearly the entire zone of non-linear deformation (Figure 1).



(a) Linear elastic (b) Nonlinear plastic (c) Nonlinear quasi-brittle

Figure 1. Distinguishing features of fracture in (a) a linear elastic, (b) a ductile, (c) a quasi-brittle material. L=linear, N=non-linear, F=FPZ (after Karihaloo, 1995).

The first non-linear theory of fracture for concrete was proposed by Hillerborg et al. (1976). It includes the FPZ as a fictitious extension of the real traction-free crack. The term fictitious is used to underline the fact that this extension cannot be continuous with full separation of its faces, as in a real crack, but that it is capable of transmitting residual stresses across its faces depending upon their relative separation, as shown in Figure 2. The fracture of concrete cannot therefore be described by a single parameter, such as K_{Ic} or G_c, as in the case of a brittle material. For this description at least two parameters are required. In the fictitious crack model (FCM) of Hillerborg et al. (1976), these two parameters are (i) the $\sigma(w)$ relation in the FPZ, and (ii) the area under the $\sigma(w)$ curve. This area gives the true specific fracture energy G_F (Figure 2).

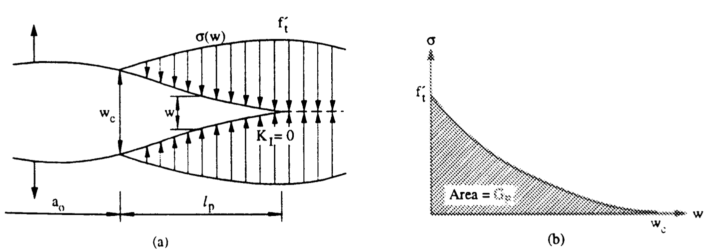


Figure 2. A real traction-free crack a_0 terminating in a fictitious crack with residual stress transmission capacity $\sigma(w)$ whose faces close smoothly near its tip ($K_I = 0$).

As the FPZ is not continuous, nor does it necessarily develop in a narrow discrete region in line with the continuous open crack, it was argued by Bažant (1976) that the $\sigma(w)$ relation can be equally well approximated by a stress-strain softening relation $\sigma(\varepsilon)$. The inelastic strain ε is related to the inelastic crack face separation w and the specific fracture energy G_F through a gauge length h (Figure 3). The damage in the FPZ is thus smeared over a band of width h – hence also the name smeared crack or crack band model (CBM).

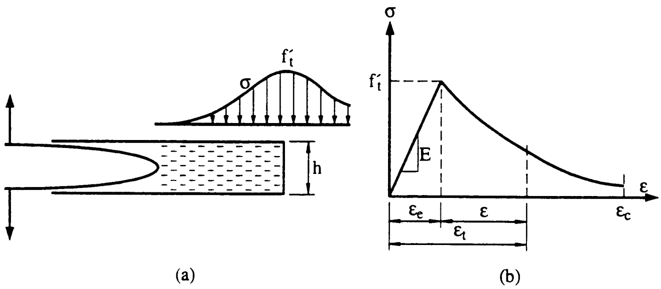


Figure 3. Microcracking smeared over a band of width h and the inelastic strain.

Material and Structural Size Effects

For the analysis of the large cracked structures under consideration, we need no more details of the above two non-linear fracture theories for concrete. This is because the response of a cracked concrete structure is governed not only by the concrete mix used, but also by its size. As mentioned above, the ductility of the mix is defined by size of its FPZ, or by its characteristic length l_{ch}, which is proportional to l_p,

$$l_{ch} = EG_F/f_t'^2. \tag{5}$$

However it is well known that two concrete structures made from the same mix but having different sizes exhibit different failure response. Thus, for example a small concrete structure made from, say normal concrete behaves in a ductile manner, whereas a large structure made from the same concrete behaves in a brittle manner. This transition in response – the so-called structural size effect – follows the scaling law

$$\beta = l_{ch}/W \tag{6}$$

where W is a characteristic dimension of the structure. The smaller the number β, the more brittle the response. Thus, although the concrete structures under consideration are made from mixes with l_{ch} ranging from 200 to 700 mm, their response will still be brittle because of their size (W ranging from tens to hundreds of metres). We can therefore describe their response adequately by the LEFM theory, requiring only the knowledge of K_{Ic} or G_c (3).

LEFM AS A FORENSIC TOOL FOR LARGE CONCRETE STRUCTURES

We shall now demonstrate on several large concrete structures that have suffered major cracking how the LEFM can be applied to appraise their safety and/or to suggest effective strategies for their repair, in order to prevent the cracks from opening and/or growing after the repair.

Schoharie Creek Bridge

Pier 3 of the Schoharie Creek bridge (Figure 4) on the major Interstate Highway in the

New York State collapsed, resulting in the loss of several lives. The failure of the bridge also caused huge financial losses to the State, because of the closure of the Highway for the inspection of scores of bridges of the same design. Investigations revealed that the failure was a result of the fracture of the large concrete plinth that had initiated at its connection with one of the two columns (Figure 4). It was also found that contrary to the design specifications the piles supporting the footing had not been driven to the bedrock, so that flood-induced scour easily eroded the footing support. Investigators were also of the opinion that cracks must have appeared in the plinth during construction, for the builders had reinforced it by adding a tie between the columns. However the tie had not been anchored in the columns, thus leaving slots at either end. It was from one of these slots that the fatal fracture initiated.

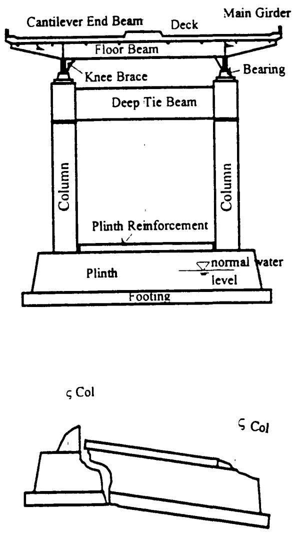
The remaining bridges of similar design were retrofitted by post-tensioning the plinth. The post-tensioning force was calculated by requiring any cracks at potential critical sites (the centre of plinth and near the columns) would never open and grow under superimposed dead and live loads or during grouting.

Fontana Gravity Dam

The construction of Fontana gravity dam operated by the Tennessee Valley Authority (USA) was completed in 1944 (Figure 5) using 1.5–3 m lifts in vertical blocks which were cooled by circulating cold water through coils placed atop each lift to minimise thermal cracking. A large crack was discovered in the downstream face of the dam in 1972 during routine inspection. A thorough investigation was begun to determine the cause of cracking and to undertake necessary interim measures to ensure the safety of the dam. It revealed that the cracked downstream monoliths reached temperatures of up to 55^0C during sunny days, while the upstream face remained at 10–26^0C. However three-dimensional finite element calculations showed that this thermal gradient through the monolith could not be the cause of cracking, for the tensile stresses it generated in the downstream monoliths were only a fraction of the tensile strength of concrete used in the dam.

A series of surveys of the crest movement over the life of the dam had revealed a monotonically increasing movement of the upstream face. This was found to be a result of thermally-driven alkali-silica reaction in the concrete. A peak irreversible upstream movement of over 50 mm was recorded, in addition to the cyclic and reversible thermal expansion mentioned above. A total upstream movement of 100 mm at the crest of the central monolith was found to generate tensile stresses in the downstream face of the cracked monoliths in excess of the concrete tensile strength.

The interim repair measures included the installation of post-tensioned tendons in the cracked monoliths (Figure 5) and the grouting of the crack itself. The efficacy of these measures was evaluated by LEFM. The crack was loaded with a simulated grout pressure of about 140 kPa. The pressure induced a K_I at the tip of the crack which was less than a tenth of the K_{Ic} of the concrete used in the dam, so that the crack should have remained closed during grouting. In fact, no dam movement or crack opening was noticed during repair. The profile of crack growth from its point of initiation to its intersection with the inspection gallery was also calculated with LEFM. It matched with the several locations identified by exploratory drilling. Chappell and Ingraffea (1981) coupled the surveyed crest movements and their effect on the stresses with the long-term behaviour of the tendons using LEFM. They predicted that (i) the crack had started at about the time



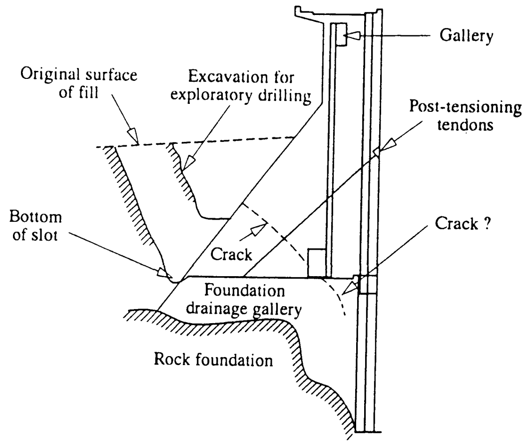
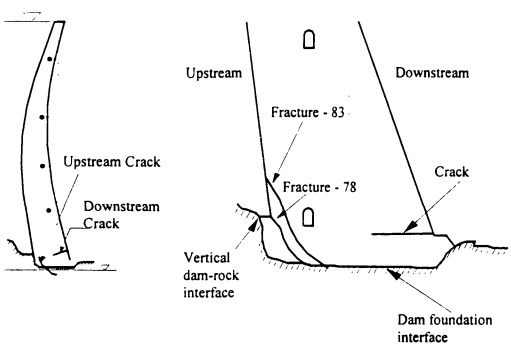


Figure 4 (left) Schoharie Creek bridge pier, showing the fractured plinth.
Figure 5 (right) Cross-section of one of the cracked monoliths of Fontana dam, showing approximate crack trajectory.



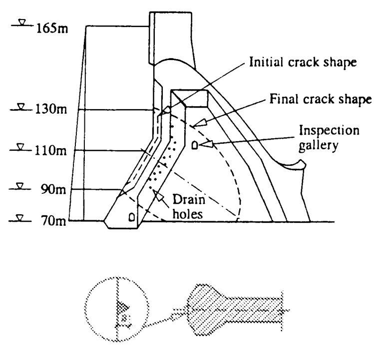


Figure 6 (left) Kölnbrein dam cross-section and details of upstream cracking revealed in 1978 and 1983 and of the toe crack.
Figure 7 (right) Cross-section of the cracked diamond-head buttress of Zhexi dam, showing the approximate locations of crack when construction was completed and after 8 years.

it was first noticed (late 1972), and (ii) the continued upstream movement would open the crack and strain the tendons to rupture by about mid-1980. Recognising that the repair measures were not a long-term solution, the Tennessee Valley Authority isolated each cracked monolith from the rest of the dam in 1977 by cutting a slot through nearly its entire height which was subsequently gasketted (Figure 5).

Kölnbrein Arch Dam

The Kölnbrein (Austria) doubly curved arch dam with an overall height of 200 m (Linsbauer 1991) was constructed between 1973 and 1979 but the reservoir was progressively filled during the construction to meet electricity demand. When the reservoir was filled to a level of 40 m below the crest, increasing uplift pressure and water loss were noticed. Investigations revealed well-developed crack systems both at the toe and the heel of the dam (Figure 6) and established the cause of the cracking at the toe; it was caused by a combination of dead load with high grouting pressure used to fill the vertical construction joints and of inelastic deformations in the foundation region.

In order to assess the risk posed by the downstream crack system an LEFM analysis was conducted by Baustaedter and Widmann (1985) using a K_{Ic} value of 2MPa $m^{\frac{1}{2}}$ appropriate for the concrete used in the dam. This analysis showed that the crack initiation site was not at the toe itself but at a level of about 13.5 m above it. What is more, when this crack was allowed to grow a second crack initiated about 6 m above it. It is interesting to note that the locations of these cracks matched the measurements made by the investigative team. At the time the analysis was made (in 1985), it was found that the first crack would have fully arrested but the second crack would still be growing unstably.

Zhexi Buttress Dam

Zhexi diamond-head buttress dam is one of the largest concrete dams in the Hunan Province of China. There are eight buttresses in all. Concreting began in 1959 and was completed at the end of 1960. Between elevations 92 and 126 m (Figure 7) concrete was placed during the period March–August 1960. Surface cracks were observed in all concrete sections between these elevations, presumably caused by thermal shrinkage. There were nearly 120 cracks in the upstream face which were almost symmetrical with respect to the centrelines of the buttresses. There were also some horizontal cracks. The longest vertical crack was about 20–30 m with a width of 0.1–0.2 mm (Figure 7). The depth of the cracks was estimated to be in the range 20–100 mm. Before the reservoir was impounded, the cracks were repaired by cutting grooves along them which were then grouted. In some instances, wire mesh was placed in the grooves before grouting.

In mid-1969, more than 8 years after the completion of construction, water was noticed spurting through a crack into the inspection gallery of one of the buttresses. Core drilling indicated that a crack nearly 42 m long (along the height of the dam) had penetrated about 47 m into the buttress and almost reached the foundation, thus giving a cracked area of about 2000 m^2 or about 45% of the buttress section (for details, see Yu and Zhang 1986). Measures were taken to prevent further crack growth.

Zhang and Karihaloo (1992) undertook to find why the rather shallow cracks that had been repaired in 1961 had grown to such an alarming size in just 8 years. They extended the FCM non-linear fracture model for concrete to include the effect of creep, in order calculate how deep an initial crack had to be for it to have extended to 47 m in 8 years under the hydrostatic forces between its faces. Using the elastic, creep and fracture properties appropriate to the concrete used in in Zhexi dam, they found that the crack (in the sense of the FCM, i.e. open crack plus the length of FPZ) should have been 1.95 m deep in 1961. It will be recalled that when first noticed, the cracks were estimated to be only 20–100 mm deep. It is clear that this estimate included only the visible, open portion of the crack, but not its discontinuous extension, i.e. the FPZ. Thus the initial repairs were incomplete and proved to be ineffective. Limitations of space do not allow the details of these calculations to be included here, but these will be given during the presentation.

CONCLUSION

Fracture mechanics has been shown to be a powerful forensic tool for the appraisal of the safety of large concrete structures that have suffered major cracking. It has been demonstrated to be equally powerful for the development of effective strategies for repairing these cracks, in order to prevent their opening and growth, thus averting catastrophic failure.

REFERENCES

1. Baustaedter, K and Widmann, R (1985) The behaviour of Kölnbrein arch dam, In *Proc 15th Int Cong Large Dams (ICOLD)*, Lausanne, **2**, 633–651.

2. Bažant, Z P (1976) Instability, ductility and size effect in strain-softening materials, *ASCE J Eng Mech*, **102**, 331–344.

3. Chappell, J F and Ingraffea, A R (1981) A fracture mechanics investigation of the cracking of Fontana dam, *Report 81–7*, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY.

4. Gettu, R and Shah S P (1992) Fracture mechanics and high-strength concrete, In *High Performance Concrete and Applications*, eds. Shah, S P and Ahmad, S H, Edward Arnold, Seven Oaks, UK, 1–75.

5. Griffith, A A (1920) The phenomena of rupture and flow in solids, *Phil Trans Roy Soc Lond*, **A221**, 163–198.

6. Hillerborg, A, Modéer, M and Petersson, P E (1976) Analysis of crack formation and crack growth by means of fracture mechanics and finite elements, *Cem Concr Res*, **6**, 773–782.

7. Irwin, G R (1957) Analysis of stresses and strains near the end of a crack traversing a plate, *ASME J Appl Mech*, **24**, 361–364.

8. Irwin, G R (1958) Fracture, In *Handbuch der Physik*, **VI**, Springer-Verlag, Berlin, 551–590.

9. Karihaloo, B L (1995) *Fracture Mechanics and Structural Concrete*, Addison Wesley Longman, UK, p 330+xiv

10. Linsbauer, H N (1991) Design and construction of concrete dams under consideration of fracture mechanics, In *Analysis of Concrete Structures by Fracture Mechanics*, eds. Elfgren, L and Shah, S P, Chapman and Hall, London, 160–168.

11. Yu, Y Z and Zhang, Y Q (1986) Stability analysis of vertical cracks on upstream face of diamond head buttress dam at Zhexi hydropower station, In *Fracture Toughness and Fracture Energy of Concrete*, ed Wittmann, F H, Elsevier, Amsterdam, 597–606.

12. Zhang, C and Karihaloo, B L (1992) Stability of a crack in a large concrete dam, *Civ Eng Trans Inst Engrs Aust*, **CE34**, 369–375.

Field investigations following natural catastrophe damage

PROFESSOR R. SHEPHERD
President, Earthquake Damage Analysis Corporation, Big Bear Lake, California, USA

ABSTRACT
Two recent natural catastrophes causing very large economic losses in the United States were the 1992 Hurricane (Andrew) and the 1994 Earthquake (Northridge). In both cases significant damage to constructed facilities prompted extensive field investigations. In this paper the salient aspects of the forensic investigations of building structures following these two events are summarised.

HURRICANE ANDREW

Hurricane Andrew hit the shores of Dode County, Florida, on August 24, 1992. The flood damage was small but the wind damage was widespread. A Category 4 storm, such as Hurricane Andrew, has expected sustained wind speeds of 210 to 250 km/h and one anemometer recorded 227 km/h before it failed (1).

The South Florida building code contains both detailed prescriptive and performance levels. Although it appears that, in some areas, the wind speeds associated with Hurricane Andrew exceeded those prescribed in the code, when factors of safety required by the code were taken into account, it was concluded that properly designed and constructed buildings should have suffered many fewer storm related damages than were actually experienced.

The majority of building types could be categorised as one or two story light wood frame, masonry wall, combination masonry ground floor with light wood frame upper level, wood-frame modular or manufactured (wood framed) homes. The primary structural systems providing resistance to horizontal and vertical loads were typically the foundation, the exterior walls and the floor and the roof structure diaphragms. The integrity of each building was dependent not only on the strength of these components, but on the adequacy of the connections between them. Field observations indicated that where a breakdown of the load transfer path at the connections had occurred, damage ranged from extensive to total.

Lessons from Hurricane Andrew

Forensic analyses determined that building failures were primarily a result of negative pressure and /or induced internal pressure overloading the building envelope. The absence, or improper installation, of framing connections, load transfer straps and bracing from non-bearing walls to roofs and walls was noted. The wood-frame gable ends of roof structures were found to have been particularly vulnerable. Inadequacy of gable end braces resulted in the absence of adequate load paths to transfer the wind loads experienced by the gables. Reliance on plywood sheathing to provide diaphragm action presupposed that the

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 77–84

connection of the plywood to the roof trusses would be satisfactory to maintain the integrity of the structure. When the plywood separated, as it did frequently when the staples used to connect it were found inadequate to resist the withdrawal loads applied, a "domino" effect was initiated. Flying debris then contributed to the destruction as many case of structural damage due to impact were noted.

As a result of the investigations undertaken following Hurricane Andrew it became apparent that the quality of local construction workmanship must be improved. Improved training of tradespersons, supervisors and inspectors coupled with the inclusion in the design code prescriptive details of design elements for lateral load transfer have been suggested as a means of achieving this.

THE NORTHRIDGE EARTHQUAKE

The January 17, 1994 earthquake in southern California (2) produced a disproportionately large amount of structural damage (3). Although a moderate event in seismic terms, the fact that its shallow epicenter was immediately beneath a major urban area resulted in a thousands of buildings being subjected to accelerations larger than those anticipated by the Uniform Building Code and an even greater number experiencing shaking of a lower intensity (4).

A large proportion of the most severe damage to residential buildings was experienced by condominium buildings. Typically of the order of five thousand square meters in footprint and having one level of basement or sub-basement garage, with three levels of residential accommodation above, these buildings have contributed to the development of relatively high density population areas compared with the tracts of more traditional single family detached house that were previously more common.

The parking level is usually constructed either as timber framed walls, open at one end at least, or, has concrete perimeter walls and interior columns supporting a two way structural concrete slab. The upper levels are almost invariably timber framed with stucco exterior cladding and drywall lining. Lateral load resistance is provided by the in-plane shear resistance of the walls which typically incorporate diagonal braces or nailed-on sheathing. During the Northridge earthquake many hundreds of these buildings situated in the most severely shaken areas suffered severe structural damage and the largest single incidence of fatalities ascribed to the event occurred in one such building, the Northridge Meadows Apartments.

Although no record was made on an actual condominium structure, a large number of strong motion records were obtained from nearby sites and from these it can be inferred that many of the damaged structures close to the epicenter experienced an effective peak acceleration in both the vertical and horizontal directions of between 0.25 and 0.30g. Undoubtedly some were subjected to larger accelerations than these.

Almost all of the damaged condominium buildings were designed at different times within the last thirty years hence each would have been subject to the design codes in effect at the particular time that the structure was conceived (5). In broad terms, a base shear coefficient of 0.06 for the earliest structures ranging up to 0.18 for the most recent ones probably formed the basis for the working stress seismic design (6). Implicit in the codes was the assumption that post-working-stress response would provide energy absorption capacity to survive larger imposed accelerations with significant damage but without collapse.

Consequently a building designed to the 1985 Uniform Building Code could be expected to survive an earthquake characterised by a 0.40g peak acceleration. The progressive development of awareness of ductility provision techniques and the introduction of appropriate detailing requirements into the building codes has resulted in a stock of buildings having very variable post-working-stress limit resistance capabilities. Furthermore the capacity of many structures has been eroded by construction practices which decrease the nominal seismic resistance (7).

A particularly interesting aspect of the behaviour of the condominium buildings in the Northridge earthquake is that many structures clearly experienced a seismic demand that approximated very nearly the available capacity. As a consequence much response was beyond the working stress limit of the components and the connections with inevitable widespread damage, including many collapses, being suffered. However, with the exception of the Northridge Meadows Apartment Building, no collapse caused loss of life.

Although every building is unique, a typical structure is described. The fifty-four unit condominium has footprint 89 m x 37 m at ground level. The sub-basement garage, continuous under the residential units has 212 mm thick, poured-in-place concrete perimeter walls and a 308 mm thick, reinforced concrete, two-way structural slab supporting the upper three levels of conventional timber framed construction. Fifty seven 371 mm diameter concrete columns, approximately 2.5 m long, provide internal vertical load support to the slab which spans 8.6 m across the drive aisles and 5.1 m elsewhere. The timber framing is braced by 25.4 mm. thick let-in braces, by drywall on the inner faces and by lath plaster forming a stucco outside surface. The plywood panel flat roof supports various service units such as air conditioners and hot water heaters.

The building outlined is representative of one of the two main condominium configurations. The second, exemplified by the Northridge Meadows, has timber framed carports at ground level, with the residential units above and no structural concrete other than footings for the timber structure. Whereas in the case of the buildings with concrete basement garages the weak plane relative to seismic shear tends to develop immediately above the structural slab over the parking garage, in the second category a soft story is almost unavoidable at the carport level. This is particularly vulnerable as the necessary access for vehicles results in the absence of walls in at least one side of the building's footprint.

Lessons from the Northridge earthquake

Post earthquake inspections revealed a consistent pattern of seismic weakness. In the case of buildings with timber framed carports or garages, overloading of the perimeter walls was a common observation. The soft story, coupled with lack of torsion balance planwise, prompted excessive sidesway, frequently leading to collapse under the effect of the vertical loads. Vertical earthquake generated forces appeared to have exacerbated the cracking experienced by reinforced concrete structural slabs supported on concrete columns and led to concern lest the punching shear failure mode may have been close to being triggered. In-plane failures of stucco and drywall clad walls, as a result of their being called upon to resist greater shear forces than their capacity, were found frequently.

Framing failures were very common. They included cracking of vertical studs, splitting of sill plates and tension failures of let-in braces. The unreinforced lightweight concrete which is frequently used as an insulating slab on top of the plywood upper floors was often many locations resulting in the exterior stucco face hanging loosely on the sid building. The usual construction defects, including the failure to install shear down units correctly, and the cutting away of vital sections of the framing to a service lines, were evident far too frequently.

Damage sustained by the representative building included shear cracking of th concrete walls, shear and flexural cracking of the soffit of the structural slab, internal blocked drywall and exterior stucco surfaces, split vertical studs and b diagonal braces. Overturning of inadequately restrained water heaters resulted damage from leaked water. Permanent racking of walls made the closing of d difficult or impossible and the building had to be evacuated. Unlike the "panc of the typical soft story carport configuration, the concrete garage area was rel undamaged with the result that it was useable.

Structural Concrete Slabs

A particular, and somewhat novel, aspect of the diagnosis of the damage expe some condominiums focussed on the cracking of the parking garage elevated s slabs over and around the top of the support columns. This is described belov

A common evaluation procedure (8) was adopted with the objective of determ safety of the structure, the extent of the damage and the presence of deficienci the slab. Additionally, where the investigation indicated that the condition of benign, the homeowners reoccupying the building were reassured. For the pu survey, damage was interpreted as a material non-trivial change in safety, serv appearance or repairability. The detection of earthquake damage calls for exp several areas. These include the interpretation of the results of inspection of t load path, including the elevated slab, of measurement of the profile of the sla evidence of previous accommodation for slab deflections. Crack examination both visual assessment and petrographic analysis.

The relative contributions of earthquake loading and other causes to the slab d shape had to be apportioned since the early pulling of shores and the effect of known to be possible contributors to significant distortions in condominium fl of which are sparsely designed by comparison with ACI standards (9). Additi use of low strength concrete and the incorrect placing of the rebar can contrib excessive cracking unrelated to earthquake loading. Conversely, the relatively vertical accelerations experienced in the Northridge earthquake undoubtedly re significant changes in the loads transferred from the flat slabs to the tops of th possibly activating a punching shear failure mode.

The slab deformation measurements involved a differential elevation survey o underside of the slab using standard survey techniques to determine the deflec the slab. Data sampling was at a minimum of 1.6 m intervals along column l midspan between columns, in each orthogonal direction. Where a distinct cha or stepwise discontinuity occurs, additional data was collected. When the top the slab was accessible, a limited differential survey was performed in areas w largest differential deflections were detected from the soffit measurements. B points and 15 mm elevation contours were overlaid on plans of the slabs. Wh plans were not available, it was necessary to create footprint drawing records of each building.

A crack survey of the accessible top and bottom surfaces of the elevated slab, the columns, the capitals, the slab on grade and the garage walls was made and recorded in the form of maps containing indications of the crack width, condition and age. Pachometer examination of the slab was also undertaken to locate the reinforcing steel. In selected positions, particularly over the tops of chosen columns, chipping was used to expose the rebar to allow measurement of the size and cover.

Concrete coring was undertaken to provide specimens for mechanical and petrographic testing. The locations of those cores intended for strength measurement was chosen to provide cores free of cracks whereas those intended for petrographic analysis are taken through representative cracks. The core strength included determination of modulus of elasticity and Poisson's ratio whereas petrographic analysis included determination of the age of the crack, proportion of unhydrated cement, estimate of the water/cement ratio, identification of aggregate type and indications of any deleterious reactions that might affect slab performance.

The protocol required that in situations when the slab deflection exceeds L/120, a survey of the condition of the doors in the upper timber framed structure shall be undertaken to assist in resolving whether the profile distortion predated the January 17, 1994 earthquake.

The information assembled was used in analyses to determine the expected behavior of the slab under actual gravity loads. This expected behavior was then compared to the observed situation in order to explain the crack deflection patterns and magnitudes.

That concern for the possible deterioration of column/slab connections was warranted can be verified by a simplistic load and resistance assessment based on typical values. For a three story framed superstructure, the factored dead load on the slab is within one percent of the factored (allowable) shear strength. The closeness of these values suggests that the margin of capacity over applied loads could be small enough to be absorbed by a significant earthquake induced vertical acceleration.

Improvements resulting from post-earthquake investigations

Improved seismic performance of the condominium type structure can be expected if a few basic design considerations are modified and complementary changes made to construction process. In the case of the carport or garage configuration having open ends to allow vehicular access, an effective portal frame should be provided around the opening. This frame should possess strength and stiffness equivalent to that of the parallel wall at the opposite end of the parking space, thus greatly enhancing the structure's ability to resist seismic generated movement across the opening. By eliminating the bulk of the rotational response from which the present layout suffers, the better balanced structure will be much less vulnerable to the P/delta effect. Also prohibition of reliance on drywall clad shear walls at the garage level would avoid the brittle collapse which is a feature of overloads on these elements. The reinforced concrete parking garage configuration could be vastly improved if the tendency for these structures to fail within the shear resisting elements at the level immediately above the elevated structural slab was overcome. This could be achieved by the provision of considerably greater strength in the bottom story of the timber framed structure. Again reliance should not be made on the in-plane shear strength of drywall clad panels but rather correctly installed plywood should be used to create shear walls.

A second aspect of improvement relates to the evident breakdown in communication between building designers and site construction crews. This typically leads to such omissions as failure to install correctly either the bottom sill holding down bolts or the steel angle clips between floor joists and wall plate. The effect is failure to supply continuity of reliable load paths throughout the structure. It appears that many building contractors do not understand that there are well founded justifications for such details being called out. Also as long as it is tacitly understood that subcontractors such as electricians and plumbers are required to cut and drill through timber framing in order to complete their work, some provision for control of these trades should be made to prevent substantial degradation of structural strength occurring as a result of their activities.

Alternative Configuration of Condominium Buildings

Although almost all of the multi-family condominium and apartment buildings damaged in the Northridge earthquake are of the form described above, a small number of structures of a different configuration do exist in the area effected by the Northridge earthquake. These are basically high-rise, welded steel moment resistant joint frames. Condominium or apartment buildings form only a small proportion of the stock of several hundred structures, most often office buildings, that rely of the integrity of welded steel moment resistant frames.

Much concern exists regarding the damage sustained by these structures. Whereas for decades prior to the Northridge earthquake structural steel moment resistant frames were considered to be amongst the safest form of earthquake resistant structures, the damage experienced on January 17, 1994 prompted revision of this opinion. In particular, fractures in the column portions of the beam/column joints and in the base plates occurred unexpectedly, shedding doubt on the design and fabrication techniques used. One result of the uncertainties both with respect to the appropriate repairs to be made to existing details and to the design and construction criteria which should be applied to new work, is the $M11 SAC Joint Venture program. This is arguably the largest civil engineering forensic project under current investigation.

THE SAC PROGRAM

The Joint Venture partnership (SAC) between the Structural Engineers Association of California, the Applied Technology Council and CUREe (California Universities for Earthquake Engineering Research) was established in 1994 with the object of solving the welded steel moment resistant frame problems and in particular to focus on the development of standards for the repair, retrofit, and design of steel moment resisting frame buildings, so that they will provide reliable, cost-effective performance in future earthquakes (10). Phase I of the SAC Program, costing around two million United States dollars and extending over one year, was concluded in 1995 with the publication of Interim Guidelines for the evaluation, repair, modification and design of welded steel moment frame structures (11). Phase II, with a budget of about nine million dollars and extending over three years, is also being coordinated by the SAC Joint Venture.

The problems facing those involved in the SAC program may be summarized in four categories. It is necessary to identify those connections in existing steel frame buildings which are potentially defective. Those connections which have suffered earthquake-induced damage must be found. An acceptable repair or retrofit technique must be developed and applied to all appropriate connections. Finally, if faith in this form of earthquake resistant structural configuration is to be restored, a modified approach to the design and construction of new moment resisting steel frames must be developed.

Results of the first stage of the program included publication of the Interim Guidelines (11) including identification and classification of Northridge earthquake welded moment resistant steel frame damage, establishment of a consistent inspection program, development of post-earthquake repair and modification techniques, coordination of the experimental testing of a variety of welded beam-column joints and correlation of proposals for the design of new structures, together with consideration of the relevant metallurgical and welding factors including quality assurance.

The objectives of Phase II of the program are:
* To determine the causes of damage to steel moment frame buildings resulting from the Northridge earthquake
* To develop non-destructive testing techniques to identify damaged buildings
* To develop design and analysis procedures which will assure satisfactory steel moment frame performance during earthquakes
* To establish construction and inspection procedures to assure satisfactory steel moment frame performance during earthquakes
* To verify the techniques and procedures of the above elements through a coordinated testing program
* To develop a consensus-backed resource document for the repair and rehabilitation of existing steel buildings and the construction of new steel buildings, and
* To assess the economic, social and political costs of implementing the recommendations in this resource document.

Significant progress with many of the tasks necessary to achieve these objectives has been made (12) consistent with the fact that until certain tasks are completed, others cannot proceed.

It is planned that the SAC Phase II program will culminate, at the end of 1999, with a set of major products namely:
* A revision of the Phase I Guidelines to reflect new information regarding identification and inspection of damaged steel frame buildings, evaluation of the current safety of such buildings for a life-safety performance level, and life-safety repair and retrofitting techniques
* Procedures to be used for determining to what extent a building has suffered damage in an earthquake, and for inspecting with a view to making repair or other recommendations
* Recommendations for construction of new steel frame buildings as well as rehabilitation of existing ones
* Evaluations of computer software useful in executing designs in conformation with the Design Criteria and
* Resource documents summarising knowledge related to steel frame construction, behaviour under earthquake loads and the changes in design and construction recommended to improve expected performance.

FORENSIC IMPLICATIONS

The forensic issues most frequently raised following a natural catastrophe are related to causation and responsibility. The establishment of a positive relationship between damaged sustained and a particular event may be relatively simple if reliable evidence of the pre- and post-event condition of a building is available. In the more usual situation where such information is incomplete, the establishment of a certain link between event and response can necessitate a great deal of field observation, testing and analysis. The skills of the forensic engineer can contribute meaningfully to the resolution of what could otherwise remain an uncertainty. On the one hand property owners are frequently ill prepared for the difficulties they experience in substantiating insurance claims whereas insurance companies can be subjected to claims that are unjustified; a result of either innocent or devious behaviour. In many case when damage is identified immediately after a catastrophe, the question is raised whether any original defects may have contributed to the unsatisfactory performance by weakening the structure and thereby increasing its vulnerability. An engineer experienced in construction standards can factor into his/her consideration the inevitable imperfections in a building structure and can make a reliable judgement regarding the contributions, if any, that they may have made to the overall damage.

REFERENCES

(1) Federal Insurance Administration (1992), Building Performance: Hurricane Andrew in Florida, FIA-22.

(2) Moehle, Jack B. et al (1994), Preliminary Report of the Seismological and Engineering Aspects of the January 17, 1994 Northridge Earthquake: University of California, Berkeley, Report UCB/EERC 94-01.

(3) Hall, John F. et al (1994), Northridge Earthquake, January 1994, Preliminary Reconnaissance Report: Earthquake Research Engineering Institute, Report 94-01.

(4) Shackal, A.M. et al (1994), Strong Motion Records from the Northridge, California Earthquake of 17 January 1994: California Strong Motion Instrument Program, OSMS, Report 94-07.

(5) Shepherd, R. (1988), Earthquake Induced Building Damage, a Continuing Problem: INTERCIENCIA, Journal Science Technology America, 13 (4), 183-191.

(6) Wall, William D. (1994), Uniform Building Code Seismic Provisions: Past and Future: Building Standards, May/June 1994, 7-9.

(7) Shepherd, R. (1993), Earthquake Damage Lessons from the Big Bear Lake Earthquake, 1992: Journal of Performance of Constructed Facilities, ASCE 7 (4), 234-248.

(8) -----(1994), A Framework for Post-Earthquake Evaluation of Elevated Concrete Slabs, Failure Analysis Associates, Inc., Menlo Park, California.

(9) -----(1989), Building Code Requirements for Reinforced Concrete, (ACI 318-89), American Concrete Institute, Detroit.

(10) ---- (1994), Program to Reduce Earthquake Hazards in Steel Moment Frame Structures, Formulated by the SAC Joint Venture Partnership, Structural Engineers Association of California, Sacramento, California.

(11) ---- (1995), (SAC 95-02), Interim Guidelines: Evaluation, Repair, Modification, and Design of Welded Steel Moment Frame Structures, FEMA-267 (SAC 95-02), 215p.

(12) Shepherd,R. (1997), Progress with the SAC Joint Venture Program for the Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures, Innovation in Engineering for Seismic Regions, Proceedings, Mouchel Centenary Conference,, Civil-Comp Press, 21-26.

Supporting the Legal Process: Legal Aspects

VIVIAN RAMSEY QC,
Keating Chambers, London, UK

INTRODUCTION

The English legal process is strongly adversarial. Each party presents its case to the Court or Arbitrator by making Submissions and calling factual and opinion evidence. It challenges the other party's evidence by cross-examination. The Judge or Arbitrator then has to decide between the cases presented. It is in this context that expert opinion evidence is given. Perhaps not surprisingly, the expert opinion evidence is generally supportive of the case which a party wishes to present.

THE ROLE OF EXPERT EVIDENCE

The role of expert evidence is to give assistance to the Court in issues which arise in a case and raise matters which require expertise in particular subjects in order to resolve those issues.

In Shell v Pell Frishmann (1987) 3 Const. LJ 57 Judge Newey reviewed the development of the role of expert evidence:

"It would appear that from an early stage in the development of the common law witnesses were required to state facts and were not allowed to intrude upon the role of judges or juries by expressing opinions. To this, however, there soon arose an exception, namely when the Court required assistance in order to understand the facts. In Buckley v Rice Thomas (1554) Plowden 118, Court of Common Bench, Saunders J said at p.124:

> *"... if matters arise in our law which concern other sciences of faculties, we commonly apply for the aid of that science of faculty which it concerns. Which is an honourable and commendable thing in our law. For thereby it appears that we don't dispute all other sciences but our own, but we approve of them and encourage them as things worthy of commendation."*

The learned Judge went on to mention cases in which expert evidence had been received from a civil lawyer, surgeons, a canon lawyer and a grammarian. Later decisions of the courts were similar, including that of Lord Mansfield in Folkes v Chadd (1782) 3 Douglas 157, Court of King's Bench, in which an engineer had been called by the plaintiffs to give evidence as to the effect of the erection of an artificial bank upon the choking up of a harbour. From the sixteenth

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 85–91

century until the Evidence Act 1851, there was no possibility of parties themselves being able to give expert evidence, since they were not allowed to give any evidence at all.

The official referees' courts would seem to have been the first regularly to require parties to exchange reports of experts before trial, although in Chadd's case the defendants complained of surprise because the engineer's report had not been disclosed in advance. Gradually it became the practice in the Queen's Bench Division and in County Courts to require exchange before trial, particularly of doctors' and surveyors' reports. In 1970 the seventeenth report of the Law Reform Committee dealt with evidence of opinion and experts' reports."

THE ROLE OF THE EXPERT

Various phrases are used to describe the role of an expert such as *"Independence"* or *"Impartiality"*. In reality an expert must do no more or less than give his honest opinion on the issue which comes within his expertise. A party usually instructs as its expert a person who has no connection with that party. This is because the expert's view is more likely to be and be seen to be his honest opinion if he is independent of a party. That independence will also, in principle, ensure that the expert does not have a pre-disposition or bias in favour of one party's case: to that extent he will be impartial.

There is no rule precluding an expert from giving opinion evidence if he is not independent. However, in such cases it will be necessary to establish that any lack of independence does not taint the expert's ability to give an honest opinion.

The Duties to the Court

In a number of cases Judges have described the approach to be adopted by those giving opinion evidence. In the Ikarian Reefer [1993] 2 Ll.R 68 at 81 Cresswell J described the role of an expert as follows:

"The duties and responsibilities of expert witnesses in civil cases include the following:

1. *Expert evidence presented to the Court should be, and should be sen to be, the independent product of the expert uninfluenced as to form or content by the exigencies of litigation (Whitehouse v Jordan [1981] 1 W.L.R. 246 at p.256, per Lord Wilberforce).*

2. *An expert witness should provide independent assistance to the Court by way of objective unbiased opinion in relation to matters within his expertise (see Polivitte Ltd. v Commercial Union Assurance Co. Plc [1987] 1 Lloyd's Rep. 379 at p.386 per Mr. Justice Garland and Re. J. [1990] F.C.R. 193 per Mr. Justice Cazalet). An expert witness in the High Court should never assume the role of an advocate.*

3. *An expert witness should state the facts or assumption upon which his opinion is based. He should not omit to consider material facts which could detract from his concluded opinion (Re J sup).*

4. *An expert witness should make it clear when a particular question or issue falls outside his expertise.*

5. *If an expert's opinion is not properly researched because he considers that insufficient data is available, then this must be stated with an indication that the opinion is no more than a provisional one (Re J sup.). In cases where an expert witness who has prepared a report could not assert that the report contained the truth, the whole truth and nothing but the truth without some qualification, that qualification should be stated in the report (Derby & Co. Ltd. and Others v. Weldon and Others, The Times, Nov. 9, 1990 per Lord Justice Staughton).*

6. *If, after exchange of reports, an expert witness changes his view on a material matter having read the other side's expert's report or for any reason, such change of view should be communicated (through legal representatives) to the other side without delay and when appropriate to the Court.*

7. *Where expert evidence refers to photographs, plans, calculations, analyses, measurements, survey reports or other similar documents, these must be provided to the opposite party at the same time as the exchange of reports (see 15.5 of the Guide to Commercial Court Practice)."*

In University of Glasgow v Whitfield 42 BLR 1 Garland J. said this of expert evidence:

"The nature of the expert evidence in this action and the manner of its introduction prompts me to make some general observations which I hope may in the future assist in the saving of time and costs and also lead to a more precise definition of issues particularly where experts from a number of different but overlapping disciplines are involved.

First, the role of the expert. It appeared to me that some (but by no means all) of the experts in this case tended to enter into the arena in order to advocate their client's case. This led to perfectly proper cross-examination on the basis:

> *"You have assembled evidence and advanced explanations which you consider most likely to assist your client's case."*

It is much to be regretted that this had to be so. In their closing speeches counsel felt it necessary to challenge not only the reliability but also the credibility of experts with unadorned attacks on their veracity. This simply should not happen where the court is called upon to decide complex scientific or technical issues. To a large extent this excessively adversarial approach to expert evidence could have been avoided if experts who had at various times expressed contrary or inconsistent views had dealt with this in their reports giving any necessary explanations. Similarly, where experts alter their views at a late stage or introduce a wholly new theory or interpretation, the new approach should be reduced to writing and furnished to the other parties at the earliest possible opportunity so that all the relevant experts can give the matter due consideration and, in a proper case, meet in order to define what is common ground and where they differ. I acknowledge that the timing of exchange of reports and the omission to provide for the exchange of reports in reply contributed to the difficulties in this case and I deal with that topic below.

It is in my view salutary to recall the observations of Lord Wilberforce in Whitehouse v Jordan [1981] 1 WLR 246 at page 256:

> *"It is necessary that expert evidence presented to the court should be, and should be seen to be, the independent product of the expert, uninfluenced as to form or content by the exigencies of litigation. To the extent that it is not, the evidence is likely to be nor only incorrect but self-defeating."*

Second, this was a case, as I have said, where structural engineering, architecture and expertise in the chemical and physical properties of ceramic tiles, of cementitious materials and of epoxy resins, overlapped. We also had an excursion into the proper statistical basis for sampling. More than one report contained the expertise of two or more experts. In some instances the non-signatory expert was not acknowledged let alone identified. This led to situations in cross-examination where the witness was constrained to say: "This was the conclusion of Mr. X" or "Mr. Y supplied this information". If Mr. X and Mr. Y are not called, both opposing counsel an the court are in some difficulty, particularly if the evidence is prima facie credible.

It seems to me that if a report contains evidence or expertise contributed by some person other than the apparent author, then that person and his contribution should be identified so that at the very least he can be tendered for cross-examination. Of course, this situation should not be confused with that of the leader of a team of investigators or of laboratory research assistants under his direction and control."

The expert has a duty both to the Court and to the party for whom he gives evidence to ensure that, at all times, that evidence is his honest opinion. That requires the expert to have given proper consideration to the issue on which he provides his evidence and to keep his opinion under review as, inevitably, the case develops.

Two particular aspects of the expert's involvement in the adversarial process are experts' meetings and experts' reports.

Experts' Meetings

Under Order 38, rules 35 to 44 of the Rules of the Supreme Court there are various rules which deal with expert evidence. One of these rules concerns Meeting of Experts (r.38). That provides:

"In any cause or matter the Court may, if it thinks fit, direct that there be a meeting "without prejudice" of such experts within such periods before or after disclosure of their reports as the Court may specify, for the purpose of identifying those parts of their evidence which are in issue. Where such a meeting takes place the experts may prepare a joint statement indicating those parts of their evidence on which they are, and those on which they are not in agreement"

The purpose of that rule is to achieve a consensus, so far as is possible, so that the Court only has to deal with opinion evidence on issues which are disputed. The meetings are conducted on a *"without prejudice"* basis so that the experts can have a fair opportunity to discuss issues without being bound by what is said. Once a joint statement is made then the precise role of that statement is uncertain. One view is that it remains *"without prejudice"* until it is accepted by the parties. Another view is that the statement is not subject to *"without prejudice"* protection. Whilst there is much to be said for the second view, I consider that the first view is correct. To avoid any difficulty, the parties should agree the procedure for the production of the joint statement. Whilst the expert should be free to state his honest opinion, the phrasing of it can contain pitfalls for the unwary expert.

Experts' Reports

These may be produced either before or after the experts' meeting and sometimes preliminary reports are ordered before the meeting with final reports afterwards. Equally there are frequently supplementary reports to deal with the other expert's evidence.

The experts' report must contain a statement of the qualifications of the expert, any matters which may affect his *"independence"*, the scope of the material which he has considered and the view the expert expresses on the issues.

Very often expert reports are weighed down by pages of recital of the facts of the case which are irrelevant to the issues. Equally, when the issues are dealt with they are often treated summarily without any detail or reasoning. In answering most issues, the expert will have to make assumptions as to background facts or as to other relevant matters. These are frequently omitted but are essential to the foundation of an expert opinion.

It must be remembered, too, that most Solicitors, Barristers and Judges do not have familiarity with technical concepts or the other matters which are the subject of the opinion evidence. Indeed, it is partly for that reason that opinion evidence is necessary. The report must therefore not assume that abbreviations or terms of art are known. A introduction or appendix containing some of the basic principles of the subject is often of assistance.

APPOINTING AN EXPERT

When looking for an expert the first enquiry is inevitably related to expertise. Often cases involve a combination of issues or novel developments in materials or techniques. It is therefore essential that experts are frank about their knowledge and expertise.

Experts must then consider any conflicts of interest. With the worldwide nature of engineering projects and mobility of personnel, it is essential that experts confirm that they or their firm have not been involved in some aspect of the case or project and that, so far as they are aware, they have no close connection with those involved in the project. These matters will not always preclude an expert from giving evidence but a party should know about them before making its choice of expert.

An expert must be articulate. He must be able to put forward complex subjects in terms which are comprehensible. He must be able to justify his views, in particular, under cross-examination.

Finally, an expert must have time to decide to read background documents so that he can make an informed view. Whilst some work can be delegated, it often becomes obvious where an expert has not himself reviewed the detail of the case. If an expert is relying on an assistant that should be clearly stated and the other party may apply to cross-examine that person.

EXPERT'S ASSISTANCE TO A PARTY

Whilst an expert must maintain his independence and not become biased, he has a role to play in advising the party who instructs him.

It is essential that the legal team understands the expert's evidence. This means that expert reports both in draft and final form must be reviewed. The draft must be checked to ensure that it does not contain inaccuracies of fact and that it is written so that it is comprehensible. In addition loose wording can create a wholly false impression. It is also legitimate for the party to *"cross-examine"* their appointed expert to test the firmness of that expert's views and whether they are justified. What is not permissible is the situation which occurred in Whitehouse v Jordan where the legal team wrote the expert's report.

The expert also has a role in assisting in commenting on the other party's expert reports and suggesting lines of cross-examination.

In many cases it is essential that the expert is present at the opening of the case and during the factual evidence. This allows the expert to understand the context of the issues and to confirm his assumptions based on the evidence. It also permits the expert to make sure the party appointing him can be briefed on any points which arise.

Inevitably, experts who are to present important evidence will participate in discussions which may include strategy or factual considerations. They must not identify themselves with those aspects or change their approach or their opinion to suit. This can lead to the expert's role being confused with the advocate's. Often it is sensible to exclude experts from such discussions

UNPROFESSIONAL CONDUCT

The most frequent danger of expert evidence is that the expert loses the ability to provide an honest opinion on the issues within that expert's expertise. Often this shows itself in advocacy within reports or when giving evidence, in evasive or biased expression of views. In some cases experts have deliberately excluded data which did not support his case. Whilst it is true that in certain respects the lawyers are to blame for this, an expert must restrain any inclination to express views merely because they will support the client's case.

Another problem is lack of time or competence. Thess problems can mean that the expert is unable to produce a comprehensible view on the issues which are to be considered. Often this means that the expert only realises the full situation at or near the trial and then performs a volte face, sometimes only when giving evidence under cross-examination.

CONCLUSION

The role of an expert in giving opinion evidence is an essential point of the adversarial process. However it demands a high calibre of professional to perform that role, combining the ability to give a party and the Court confidence in expertise whilst avoiding the pressures to lose the impartiality which is essential to the role.

Technical evidence to support enforcement

A. MAITRA
Health and Safety Executive

INTRODUCTION

Health and Safety Executive [HSE] Specialist Inspectors have investigated thousands of accidents on construction and other sites, ranging from simple component failures to complex structural collapses, eg, the Ramsgate Ro-Ro jetty. Regardless of the complexity of the case, the investigative process is the same - evidence is gathered, statements taken and calculations carried out, to establish the cause of the accident, determine whose actions caused it and whether it was foreseeable. If a decision is taken to prosecute, the evidence has to be presented in court, in a way that can be understood. And, since a breach of Health and Safety law creates a criminal offence, the HSE has to prove its allegations beyond reasonable doubt.

Consequently, the case presented by the HSE has to be irrefutable and has, therefore, to be built up meticulously, with constant reference to the evidence which is available. If an expert's opinion cannot be supported by facts, his own experience or knowledge of accepted practise, it should not be given. It is imperative that the technical evidence is based on these principles.

This paper explains how an accident investigation is carried out, concentrating on:

- the types of technical evidence available to the Inspector and the information which can be abstracted/deduced from it;
- the importance of foreseeability;
- the role of testing;
- the role of design and assessment standards in investigating accidents;
- presenting the evidence in court.

Each point is illustrated by case-studies of accidents involving temporary and demountable structures.

FORMS OF EVIDENCE

There are two important forms of technical evidence which, for the purpose of this paper, will be called *primary* and *secondary* technical evidence. Both forms are important in building up the case - one complements the other.

Primary evidence is collected at the site. It is what the investigator and his assistants observe at the scene and usually comprises notes, sketches and photographs.

At the accident site, it is difficult to know what primary evidence is relevant. Realistically, until opinions are formed, nothing can be ignored. It is important to form some initial opinions about the reasons for the accident, soon after visiting the site. In this way, investigative effort is concentrated where it matters. Engineering knowledge, intuition and past experience play an important part at this stage as illustrated by two scaffold collapses

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 92–100

Case study 1 : Collapse of a 30m scaffold

This resulted in a mass of tangled steel tubes and timber boards, as shown in figure . Two important things were noted :

(1) the collapse was in a 20m section of a scaffold 60m long;

(2) the debris occupied an area not much beyond the footprint of the scaffold.

figure 1- *the debris was localised*

Two important conclusions could be drawn :

- from (1) : the failure could be attributed to some form of localised "overload"; and
- from (2) : the collapse mode was predominantly vertical, indicating a buckling failure.

Thereafter the investigation concentrated on finding the source of the overload and other factors which would initiate buckling.

Clues about the reason for the overload started to emerge from the witness statements. These provided information that the scaffold had collapsed during dismantling and dismantled components had been stored in the area that had collapsed, which explained the presence of excess, unconnected tubes in the debris. In addition, an inventory of the boards removed from within the collapsed area revealed that dismantled boards were stacked on the scaffold.

Ties connecting the scaffold to the facade had pulled out when the scaffold collapsed. An examination of these ties showed that some of the anchor inserts had hardly expanded. This observation led to a fuller examination revealing that several ties had been installed in oversize holes in a stone feature only 40 mm thick, and would not have been effective as buckling restraints as they had little or no resistance to pull-out.

Consequently, the investigation concentrated on checking the sections of unrestrained scaffold against the extra loads imposed by the stacking of dismantled components. These calculations showed that the unrestrained scaffold could not support the extra loads applied by the dismantled components stacked on it.

Case study 2 - overturning of a mobile access tower [MAT]
The MAT was being used by a person painting the gable of a house. It had overturned causing the painter to fall 6m to his death. There were no eye-witnesses to the accident and the MAT had been dismantled.

The following primary evidence was noted :

(1) there was fresh paint at the gable end apex;
(2) it was measured as being approximately 7m above ground;
(3) there were vertical drag marks on the gable wall, starting just below the fresh paint;
(4) there were enough components to erect a MAT 4m high;
(5) no outrigger components were found;
(6) an extending aluminium ladder was lying under where the person had been working;
(7) An inspection of the end of the ladder showed that the edge of the plastic insert, sealing the end of the styal, had been abraded off. When this plastic was rubbed hard against the wall, it left a mark similar in colour to the marks observed (3).

From the primary evidence (1)&(2) it could be concluded that an area 7m above the ground had been painted from a MAT only 4m high (4). From (7) it could be concluded that the marks on the gable were caused by the ladder slipping down the wall. Therefore, the ladder must have been used to gain the extra height and must have been footed on the MAT. In addition (5) indicated that the MAT must have been used without outriggers.

Calculations showed that the horizontal force the ladder applied to the toe-board was sufficient to overturn the MAT.

Secondary Evidence
Is based on observations made/information supplied by other people. It can be abstracted from many sources, including : eye-witness statement, a manufacturer' instruction, a set of test results, a paper in a journal, standards and codes of practice. Generally, it is used to support the primary evidence and any conclusions which can be drawn from it.

The following case-study illustrates the importance of secondary evidence :

Case-study 3 : Collapse of a 36m high scaffold
A tangled pile of steel tubes, timber boards and concrete blocks - see figure 2 - lay where the scaffold had been. The wreckage was concentrated in a small area. Site photographs indicated a well constructed and adequately tied scaffold with ties generally at 6.0 m intervals.

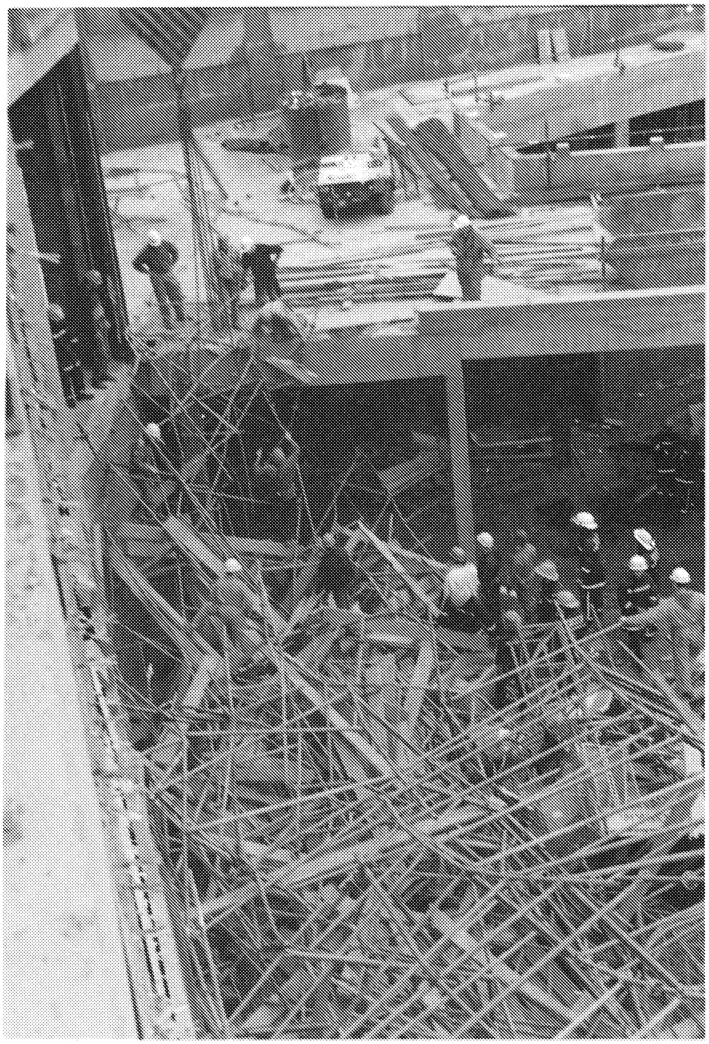


figure 2 - *A tangled pile of tubes lay where the scaffold had been*

The primary evidence alluded to the following :

(1) the collapse initiated at a particular standard;
(2) the collapse mode had been vertically downwards;
(3) concrete blocks had been stacked on several of the lifts simultaneously;
(4) the total weight of blocks exceeded the load a single standard could support and must have been distributed along the platform;
(5) tying had been inadequate over the bottom section of the scaffold; and,
(6) the foundation failed under one standard.

But it was not sufficient to show why the scaffold collapsed. There were two important unknowns - the distribution of the blocks and where the collapse started.

The missing information was provided by the secondary evidence, in the form of :
(a) eye-witness statements : which supported the opinion that the collapse was vertical and had been initiated at a particular standard. They also confirmed that the blocks had been distributed, in discrete piles, along platforms at several levels . Additionally, they were able to quantify the numbers of blocks tacked adjacent to each standard, which verified the loads used in the calculation.
(b) scaffold working drawing : confirmed the inadequacy of ties at the lower levels (5)

Nevertheless, the loads calculated were insufficient to show a collapse of the suspected standard. However, an examination of the statements showed that at the time of the collapse, five people had been standing at, or, close to, the standard The missing load was found and it was possible to prove a mechanism for the collapse.

THE ROLE OF TESTING

Testing also plays an important part in proving a case beyond reasonable doubt. While it is possible to make certain presumptions, eg, $g = 9.81\ m/s^2$, because they are universally accepted as being true, testing may be the only way to prove other assertions. This is especially true when the only explanation for a failure could be a micro-defect, eg, weld porosity. The point is illustrated by the following example :

Case-study 4 : collapse of an aluminium alloy suspended platform

A platform collapsed when 50 kg of load fell 1.5m onto it, near a suspension point. While collecting primary evidence, it was noted that the welds appeared to be porous. Because of this observation, the fractured joint and several others were sent for metallurgical examination, which showed that :

- all the welds exhibited porosity. Generally, the degree of porosity was 30%, but in some welds it was as much as 50% - see figure 3;
- there was a general lack of penetration in all of the welds; and
- there were cracks in the weld that failed.

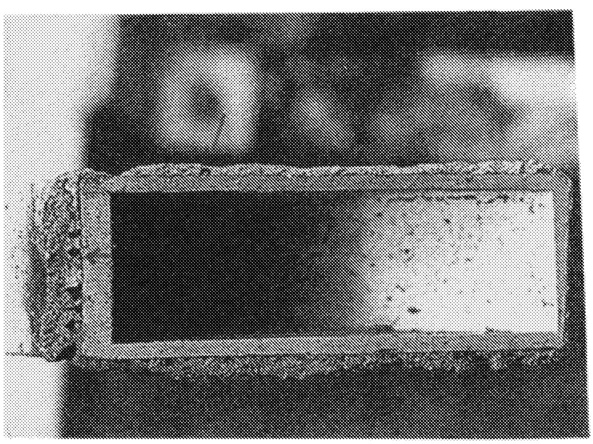


figure 3 - *porosity in the welds*

On this and other secondary evidence, provided by a recognised specialist organisation, an investigation into the manufacturing process was carried out. This proved that the process of welding the joints was not adequately controlled, because welders were not aware of the difficulties in welding aluminium.

FORESEEABILITY

An accident is an unexpected event, ie, it could not have been foreseen. Therefore, a part of the HSE expert's investigation will concentrate on determining whether the consequences of an action could have been foreseen.

In deciding about foreseeability, the expert will have to take into account what was acknowledged as accepted good practise and levels of competence, at the time of the accident. For example, digging a trench close to the foundations of a structure could cause collapse of the trench sides and ultimately the whole structure, a foreseeable consequence. Conversely, the presence of an uncharted drain under the foundations of a structure may not, with the information to hand, have been foreseen. But the issue is not always so simple.

THE USE OF DESIGN STANDARDS

Before discussing their application in accident investigations, it is useful to understand that design standards play a specific role in civil and structural engineering; they provide an assurance that a structure has complied with some minimum requirements. This compliance is usually equated with structural safety and serviceability.

This assurance comes from the knowledge that a structural element designed in accordance with a standard will have a sufficient factor of safety [FoS] between the loads applied to it and its capacity. It follows that a structure which is made up of these individual elements will also have a similar FoS. Although, interaction between individual elements, means that the overall FoS in the structure is often greater than for its individual elements. Additionally, design standards contain advice which errs on the side of safety and do not permit failure of any member in any part of a structure, ie, no part of it is allowed to reach a limiting stress and only the extreme fibres are checked. While one could argue that the FoS that standards provide are too great, there is no doubt that this is a sensible way to design buildings.

But it creates a problem for the accident investigator. It means that it may not be sufficient to show that the load in an element was in excess of its published capacity. For example, for a continuous steel beam to collapse, the load must be sufficient to cause either lateral buckling or the formation of three plastic hinges. An accident investigator has to prove that one or other of the loads was obtained and then show that this failure was the most likely trigger for the collapse of the whole structure.

Therefore, it is often necessary for the investigator to go back to first principles. When analysing a structural failure he will have to :

- identify the structural form, the material and its mechanical properties;
- identify, as far as possible, the loads that were present at the time of collapse;
- identify the load path for such loads;
- **check whether the members in the load path were overstressed;** and,
- check what effect local overstress had on overall stability.

Design standards may only be applicable at the stage highlighted.

PRESENTING THE EVIDENCE IN COURT

Presenting the evidence in court is the culmination of the process of gathering the evidence. It is essential to note that a HSE expert is there to help the court with technical matters and to offer a professional opinion, based on his technical knowledge and experience of safe methods of work, about why an accident happened. His evidence must be fair and balanced otherwise it would jeopardise the privilege that the courts bestow upon him. Other people carry out the prosecution.

The HSE expert will have to justify his opinions to people who will not have much understanding of the engineering principles relevant to the case. In proving that there is no reasonable doubt about his conclusions, the inspector may have to help these people to understand complex engineering principles. It is, therefore, important to minimise the amount of technical evidence. Irrelevant evidence must never be presented.

Beyond reasonable doubt [the "could ....." question]

In cross-examination, HSE specialists may be asked questions intended to show that there is some doubt about his conclusions. Therefore, their answers must show that at every point in their investigations the defendant has been given the benefit of any doubt, and that they are seen to have looked at all the possibilities, ie, no causation had been dismissed too soon. Not to do so would make them vulnerable to the " could..." question. This is an important point illustrated by the following examples :

- If the evidence given was that an element was overloaded, the HSE specialist must, in answer to "*could* the load you have assumed have been lower ?", be able to show that the load used in a calculation was the lowest credible one;
- If the evidence given was that the method of work was unsafe, then in answer to "*could* they have done it differently ?", the HSE engineer must be able to provide an alternative, reasonably practicable, method.

Explaining engineering principles

If the outcome of a case hinges on a technical issue, then explaining this issues to lay-persons, without confusing or boring them, is <u>the</u> problem facing technical experts.

Consider the following :

In the elastic zone, up to first yield stress, load is proportional to extension and Young's modulus for the material is defined as the slope of the load-extension line. Beyond first yield stress, the material exhibits a ductile plateau up to the point where the strain is approximately 10-15 times the strain at yield, at which point strain-hardening sets in and there is, once again, a degree of proportionality between load and extension. This pseudo-proportional behaviour is exhibited upto the ultimate stress.

To an engineer this is a description of the tensile test curve for steel. But it may mean nothing to the people hearing the case. If a case relies on this point being understood, it is likely to be lost. The same applies to all the terms that engineers take for granted .

So, how can engineering principles be presented in a way that non-engineers can understand ? On the presumption that a picture saves a thousand words, a good way is to use models, props and sketches. Where it is not possible to provide a model, familiar parallels will do. Needless to say, this type of evidence should be accompanied by explanations in simple English.

Models and props
Very simple props can be used to illustrate engineering principles. I have seen a plastic ring-binder used to demonstrate tension and compression in a beam, a paper clip to demonstrate the elastic to plastic transition, a plastic ruler to demonstrate that buckling always occurs about a less stiff axis.

Familiar parallels
A good example of a familiar parallel was in an explanation of cohesion in c-ϕ materials : it was explained as "......the reason why we can make sand castles".

While this type of approach may be simplistic and offend the purists, it gets the message across.

Omitting irrelevant technical evidence
To a non-technical person, technical evidence is difficult enough to understand, without having to listen to too much. Therefore, unless a technical point is absolutely relevant to the case, it should not be presented.

When presenting the evidence for why a column buckled, it may be sufficient to explain that the pressure [compressive stress] you calculated exceeded the capacity of the column. There is no need to say that you checked the stresses on an effective length of Xm, based on an analysis of the effectiveness of the lateral restraints, the end conditions, the inherent imperfections etc. The additional information should be available, but only in case there are questions about it.

DISCUSSION

The outcome of every legal action is decided by the quality and credibility of the evidence presented. In criminal cases in England, an allegation must be proved *beyond reasonable doubt* otherwise the defendant will be found not guilty. In order to satisfy this requirement for "certainty", prosecutors are turning, increasingly, to the evidence that science can, credibly, provide, eg, ballistic tests. Health and Safety prosecutors are no exception.

The case-studies show that the collection of primary evidence is not easy for HSE specialists; faced, as they often are, with collecting what evidence they can from a confusing wreckage, in the aftermath of an accident. Intuition, experience of previous accidents and engineering knowledge play an important immediate part in deciding what evidence is not really relevant.

As HSE specialists rarely witness the accident, they have to rely on other peoples observations, to supplement their own - secondary evidence. This is quite acceptable, as long as such evidence is not used selectively. Where secondary evidence is based on advice given in standards or other technical papers, it is important to be aware of any assumptions incorporated in the advice. Secondary evidence may also provide corroboration for the primary evidence.

Primary and secondary evidence provides the facts which allow technical conclusions to be drawn about why the accident happened and whose actions provided the trigger for it.

The expert may also have to show that the consequences of an action were foreseeable. Not to do so may indicate that a dangerous occurrence was indeed an accident.

In addition, HSE specialists have to contend with the added complication of always having to "err" on the side of the defendant. Not to do so would provide the defence with a way of showing that there are grounds for doubting what is being alleged, simply because an alternative, credible, scenario had not been investigated.

Each of the processes summarised above contributes to the credibility of the technical evidence to be presented in support of a prosecution.

Of all the stages in the process of investigating an accident, presenting the conclusions in court, is the most important. A prosecution will flounder, in spite of the excellence of any forensic work, if the principles behind the conclusions cannot be understood by the jury. Technical experts must, therefore, develop methods by which they can explain relevant engineering principles simply.

CONCLUSIONS

1. Some health and safety prosecutions hinge on the credibility of the technical evidence and on how such evidence is presented in court.

2. Credibility for technical evidence can be gained by ensuring that :

   - any evidence collected is , as far as possible, corroborated;
   - opinions which cannot be validated are not offered; and
   - any analysis is always weighted in favour of the defendant.

3. Presentation of the technical findings must be in a form that the people who will hear it can understand and are not overloaded by it. This can be helped by :

   - using simple English - minimising jargon;
   - using aids, eg, models, familiar parallels etc., to illustrate important principles; and
   - presenting only the relevant issues.

Micro-biological attack on concrete – a threat to concrete infrastructure

NAYSAN KHOYLOU EMAMI, Ph.D., DIC, Engineer, principal author [1]
ANDREW NICHOLSON, Ph.D., Senior Geo-chemist, principal geo-chemist [2]
JON WREN, Ph.D., P.E., Managing Engineer, project coordinator [3]
PIOTR D. MONCARZ, Ph.D., P.E., Vice President, leading investigator [4]

[1, 3, 4] Exponent Failure Analysis Associates, Menlo Park, California, USA
[2] Exponent Environmental Group, Boulder, Colorado, USA

ABSTRACT
Bio-corrosion of concrete is one of the least understood phenomena by practicing civil engineers. This paper shows how low-iron, organic-rich sediments may trigger sulfate degradation of concrete, even when standard pre-construction chemical analyses indicate only a moderate sulfate level. A pile foundation in the United States was driven into marine channel sediments and sediment-derived fill material. The concrete piles lost their structural integrity due to secondary ettringite formation and depletion of iron in the cement paste. Disintegration of concrete occurred only where it contacted superficial marine sediments and sediment-derived fill material. Concrete in direct contact with sea water or native sand and silt materials appeared to be sound. Sediments in contact with the degraded concrete were highly anoxic and had a history of sewage contamination, contained low concentrations of total iron (<2%), Fe(III) (<0.3%) and moderate levels of sulfate (1500ppm), and exhibited high bacterial activity. This environment resulted in the microbial dissolution of Fe(III)-rich ferrite in hardened cement paste. Iron depletion in the cement paste had made the concrete vulnerable to degradation by sulfate, even at moderate levels of sulfate concentrations in the sediments.

INTRODUCTION
The case study relates to a multi-story structure on the East Coast of the United States that was demolished due to extreme deterioration of its concrete pile foundation system. The building was designed and constructed in the early 1980s. The footprint of the building, illustrated in Figure 1, extended over a seawall into an inland marine channel. Ninety-one concrete piles in twenty-nine clusters supported the building. The concrete piles were pre-stressed and pre-cast. The concrete used for the manufacturing of the piles was made from Type III cement and was of high quality, high density and steam-cured. It contained a high cement content of 418kg/m^3 and had a nominal strength of 34.5MPa. The concrete mix also contained an admixture for enhancing the strength and reducing the permeability. The group of piles within each cluster were encased by a pile skirt.

After approximately ten years in service, the building showed signs of significant settlement exhibited through damage to the facade and interior finishes. The total measured settlement at one corner of the building had reached 216mm. In an emergency investigation, some piles were found to be deteriorated to a degree of total disintegration. No significant prestressing and reinforcing steel corrosion was found. The building was then declared unsafe and dangerous by the local municipal authorities and was ordered to be demolished. Figure 2 shows pictures of some of the excavated piles after demolition of the building.

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 101–108

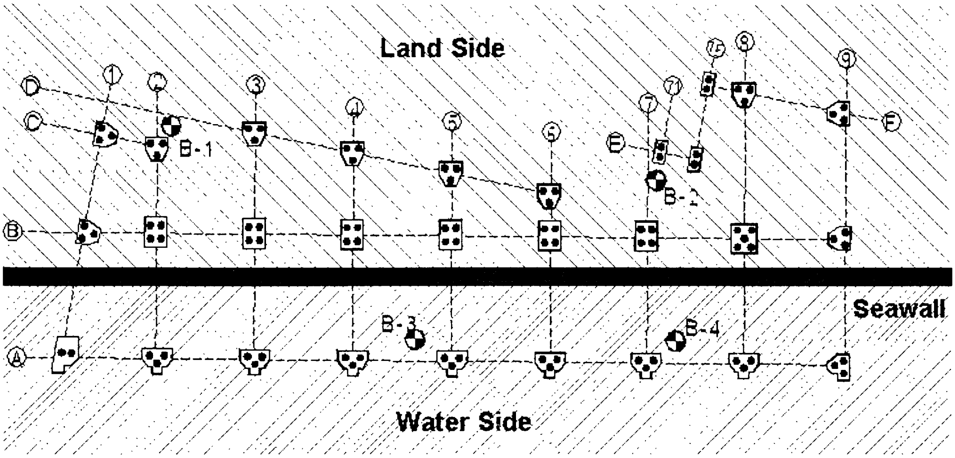
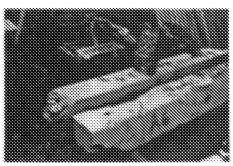
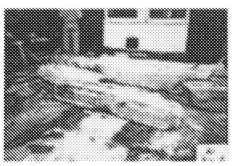
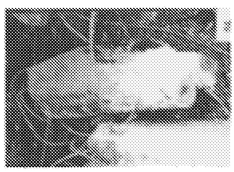
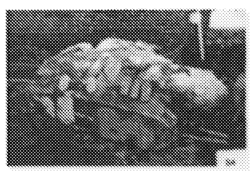


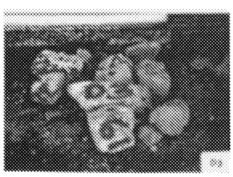
Figure 1. Footprint of the building

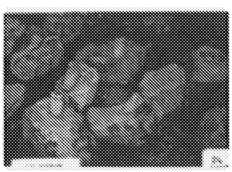

Clusters A4 and A6

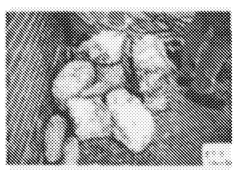

Cluster A1


Cluster B2


Cluster B4


Cluster D3


Cluster D6


Cluster E7.5

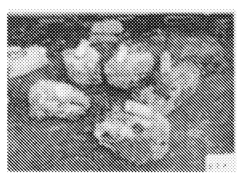

ClusterE7.5

Figure 2. Excavated piles

Examination of the excavated piles revealed that the deterioration of the piles at the water-side was bounded within a narrow region of bottom sediment. On the land-side, deterioration was limited to the sediment-derived fill region and generally worsened further away from the tidal washed area adjacent to the seawall. The pile deterioration characteristics are schematically illustrated in Figure 3.

The allegation that the concrete was self-destructing (Alkali Silica Reaction) and highly vulnerable to sulfate attack (Type III cement) was found erroneous as the deterioration was found to be caused by the specific environment of the sediment layer through which the piles were penetrating. The findings of the investigation and analysis revealed that the piles were subjected to a bio-corrosion process that can be a threat to any conventional concrete infrastructure exposed to similar conditions.

EVIDENCE OF DETERIORATION AND DEGRADATION OF CONCRETE

From the nature and pattern of the pile deterioration, it was evident that the degradation of concrete had initiated from the outside surface of the piles, gradually progressing into the pile center. There was no evidence of interior deterioration propagating outward. Also, there were large segments of piles that were not deteriorated. Thus, it was clear the attack was not inherent to the material and had been driven by external elements.

Petrographic analysis of concrete samples taken from the deteriorated areas of the piles showed that most of the cracks, micro-cracks, aggregate sockets and air-voids were filled or lined with ettringite. Although ettringite formation is a characteristic of sulfate attack, the sulfate content of the site did not conform with the extent of damage to the concrete.

The pattern of pile deterioration across the footprint of the building provided insight into the mechanism of deterioration. The degradation of concrete was only evident where it was in contact with sediments and sediment-derived fill material. Concrete in direct contact with sea water or native sand and silt materials was sound. Therefore, it was clear that an external factor intrinsic to the sediments was governing the extent of sulfate attack on concrete.

SITE HISTORY

According to historical records, prior to the construction of the seawall this area of the city was under water or marshland. The construction of the seawall along the channel started over a hundred years ago and took almost three years to complete. The project was then followed by dredging parts of the channel and filling behind the seawall. The fill material that today forms the land side portion of the site is partly from the dredged sediments from the channel. Undisturbed native sediments from the harbor, including organic poor sands and silts, underlies the fill material. After filling behind the seawall, the original development of the site was completed. The site was then mainly used for warehouses and docking of the ships.

SITE CHEMISTRY

A soil and sediment sampling and analysis program was carried out to document the geochemical variations across the site. Soil samples were collected using continuous split-spoon sampling from a hollow-stem auger drill rig, while sediment samples were collected using a barge-mounted vibracore. The soil and sediment samples were analyzed to determine the sulfate concentration, the iron content and the organic content at the site.

Sulfate concentrations in sediments and soils were not found to be particularly high. Approximately, 92% of the samples exhibited sulfate concentrations below 1500ppm. Thus, the exposure conditions at the site were moderate according to the classifications by ACI 201.2R-10.[1] The iron concentrations were generally low (less than 2% in 87% of the samples). More than 75% of the total iron content was in the form of Fe(II) associated with pyrite.

The sediments were found to contain a high quantity of Total Organic Carbon (>2% in the majority of the samples), greater than most marine sediments which typically contain less than 1.5 percent organic carbon.[2] The high organic content of the sediments and the fill were related to the urban runoff and sewage overflow that the channel had been receiving for many years. This input continues to the present, as combined sewage overflow enters the channel area during storms.

The samples were also examined for bacterial activities. Visual microscopic identification indicated that the bacteria present in the samples were primarily from the genera *Desulfovibrio* and *Clostridium*. These species are the most common sulfate-reducing microorganism under anaerobic conditions.[3] The number of bacteria (Most Probable Number, MPN, organism/gram) in the samples taken from upper layers of the sediments was very high (in the order of 10^5) and consistent with published data on MPN of sulfate-reducing bacteria in highly polluted and aggressive soils. MPN in the soil samples ranged from 10 to 10^4. According to published data, the MPN should be less than 100 for water and soil to be considered innocuous.[3]

CONCRETE DEGRADATION MECHANISM

The susceptibility of concrete to sulfate attack is governed by its physical and chemical nature. Low permeability concrete is less vulnerable to sulfate attack due to the limited ingress of destructive agents into the concrete mass.[6,7] Significant improvements in sulfate resistance of concrete are achieved by changing the chemical composition of the cement by partially replacing the C_3A (tricalcium aluminate) content of the cement with C_4AF (tetracalcium alumino-ferrite).[6,8] To date, the connection between the sulfate resistance of concrete and its C_3A content is very well understood and documented. What is not yet entirely clear is the connection between the sulfate resistance of concrete and the other compounds within the hardened cement paste.

It has been shown that C_4AF is more resistant to sulfate attack than C_3A,[6] although when exposed to sulfates, C_4AF is theoretically capable of undergoing similar expansive reactions leading to the formation of calcium sulfoaluminate and/or corresponding sulfoferrites. The explanation may lie in the work of Cirilli.[4,5] He demonstrated that when hydrated cement is exposed to calcium sulfate solution, the amount of sulfate taken up by the paste is directly related to the ratio of Al_2O_3/Fe_2O_3 in the cement; the higher the aluminum to iron oxide ratio the higher the rate of sulfate attack.[6] In other terms, at a constant aluminum oxide content, reducing the iron oxide content within the paste increases the susceptibility of hardened concrete to sulfate attack.

The environmental investigations at the site had revealed that the sediments in contact with the degraded concrete had a history of sewage contamination, contained low concentrations of total iron (<2%) and Fe(III) (<0.3%), and moderate levels of sulfate (1500ppm). The sediments exhibited high sulfate-reducing bacterial activity.

In sediments, bacteria oxidize and use the organic matter as a source of energy to support their metabolism. Generally, oxygen is the preferred oxidizing agent (terminal electron acceptor) by bacterial communities as it provides the most energy. However, under anaerobic conditions where oxygen is depleted, the absence of oxygen forces the bacteria to utilize other oxidizing agents such as manganese, iron, and sulfate. Microorganisms preferentially consume the oxidizing compound that provides them with the most energy. Therefore, the oxidizing agents in the sediments are used by the bacteria in a specific order, illustrated in Figure 4,[9] based on their oxidation potential.

Of all oxidizing agents in the sediment, iron and sulfur control the diagenetic chemistry of most marine sediments because of their redox sensitivity and great abundance. Sulfate is present at high concentrations, 2711mg/L, in seawater [10] and diffuses rapidly into the sediments.

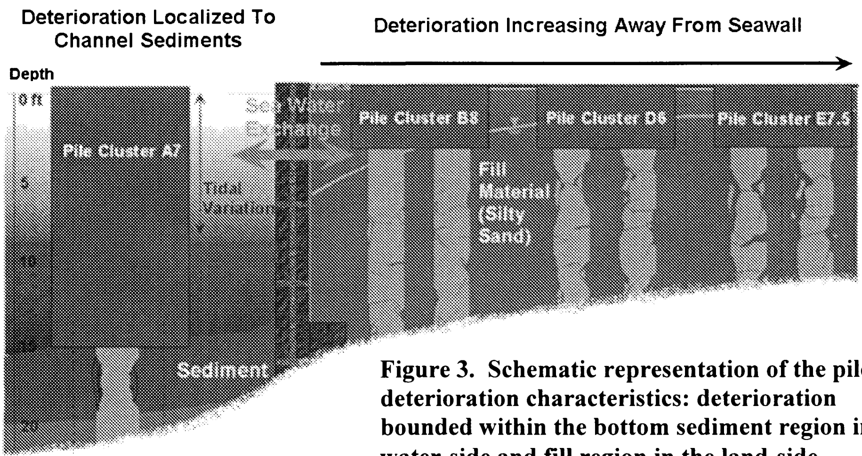


Figure 3. Schematic representation of the pile deterioration characteristics: deterioration bounded within the bottom sediment region in the water-side and fill region in the land-side

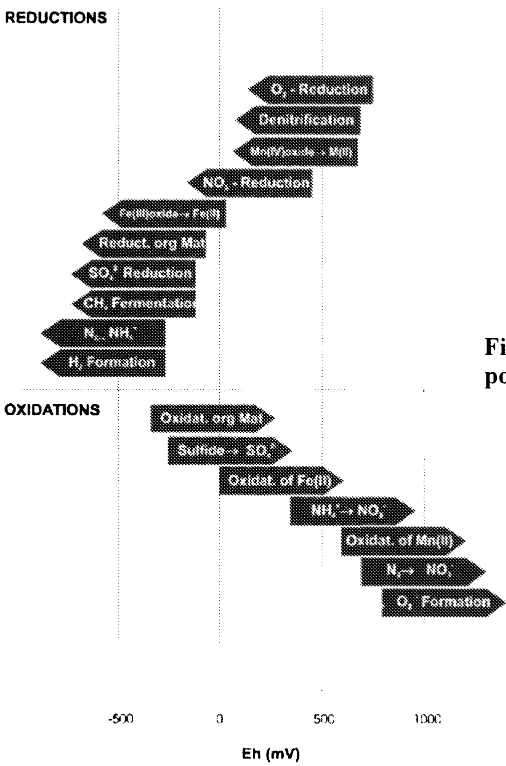


Figure 4. Order of oxidation potentials in soils and sediments[9]

Accordingly, marine sediments generally have high sulfate contents that decrease with depth due to the activity of sulfate-reducing bacteria.[2] Oxidized iron [Fe(III)] is another common component in the sediments, simply because of its abundance in the earth's crust and its oxidation during weathering and erosion.

The sulfate-reducing bacteria uses sulfate, SO_4^{2-}, to oxidize organic matter, resulting in the release of energy and the formation of hydrogen sulfide (H_2S) and carbon dioxide (CO_2). As shown in Figure 4, iron-reduction by iron-reducing bacteria can occur prior to sulfate reduction as iron has a higher oxidation potential than sulfate. The iron-reducing bacteria directly reduce ferric iron, Fe(III), to ferrous iron, Fe(II), producing siderite or dissolved Fe^{2+}. Siderite and Fe^{2+} are unstable in the presence of H_2S [11,12] and are therefore readily converted to the mineral pyrite (FeS_2). Dusolfovibrio bacteria can reduce both iron and sulfate under anaerobic conditions.[12]

In the sedimentary environment, different iron minerals respond differently to the reducing environment.[13] In organic-rich sediments with little iron, almost all the iron in the sediment will react with sulfide, since the sulfide production is not the limiting factor.[14,15] The extent of iron-sulfide reaction is measured through Degree Of Pyritization, DOP, which is an indicator of how reducing an environment is.

Laboratory testing of the sediments had shown that more than 75% of their total iron content were in the form of pyrite (FeS_2). High DOP of the sediment was indicative that: a) bacterial activities within the sediment were high, and b) Fe(III) content within the sediment was low. Since Fe(III) is the preferred oxidizing agent, in the absence of sufficient Fe(III) in the sediment, the bacteria will actively attack the iron content of the hardened cement paste consuming it as an oxidizing agent and reducing it to Fe(II). This bio-process will result in dissolution of Fe(III) compounds of the cement paste and reprecipitation of iron as iron-sulfide or siderite minerals.

As previously discussed, when the iron content of hardened cement reduces (increasing the Al_2O_3/Fe_2O_3), the amount of sulfate taken up by the cement paste increases.[6] Sulfates react with the calcium aluminate hydrate forming calcium sulfoaluminate within the structure of hydrated cement paste. The increase in the solid volume associated with this reaction results in cracking and gradual disintegration of the paste. The resultant increased permeability creates a positive feedback loop. Faster and easier ingress of deteriorating agents into the concrete structure will lead to more iron depletion, more sulfate attack and thus more damage to the paste.

Bio-corrosion can occur in any conventional concrete infrastructure exposed to anoxic, low iron, organic-rich sediment or fill. Under these favorable site conditions, for the microbial attack to proceed, the anaerobic microorganisms should be present in sufficient numbers.

MICROSCOPIC EVIDENCE OF BIOLOGICAL ATTACK ON CONCRETE

Bio-corrosion of concrete results in a series of changes in the microstructure of concrete, which can be identified by microscopic studies. In hardened concrete, a reduction of pH at the surface and possibly the successive layers by neutralizing effects such as carbonation, creates migration of iron ions (cations, i.e. positive ion charge) from an inside to outward direction. During microbial corrosion, migrating iron ions gradually accumulate and concentrate locally between the corroded and sound concrete. These ions eventually form a very thin iron layer dividing concrete between corroded and sound.[16] Thus, the iron layer can be an indicator of the rate of microbial corrosion of concrete. The SEM-EDX data of the samples from the concrete cores taken from the deteriorated piles showed a high concentration of iron at about 6-7mm away from the surface of the pile, Figure 5. On the other hand, the iron-rich layer could not be identified in the concrete samples taken from the pile within the skirt and below the mudline, Figure 5. The segments of piles within the skirt and below the mudline did not exhibit signs of deterioration.

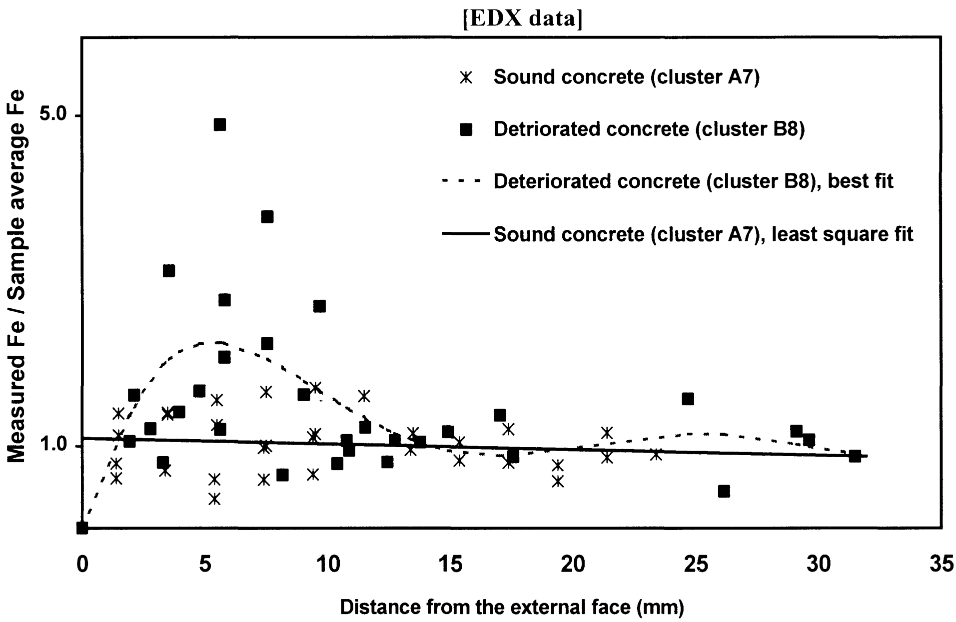


Figure 5. Variation of iron content in samples taken from deteriorated piles (cluster B8) and sound pile segments (cluster A7, within the skirt and below the mudline)

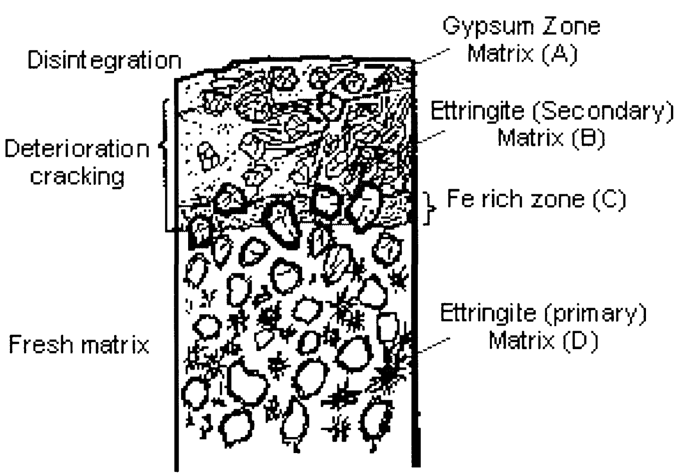


Figure 6. Schematic representation of how corroded mortar specimens zonally form gypsum, Calcite and Barite (A), Secondary Ettringite (B), Iron Oxides (C), and Primary ettringite (D) [17]

SEM-EDX and petrography data also showed the formation of secondary ettringite in the corroded region. These lath-shaped crystalline materials were secondarily produced under high alkaline conditions after exposure to sulfates. The secondary ettringite had the same chemistry as the primary ettringite but exhibited a different morphology. It was formed from small lath-shaped crystals of less than 10μm. Formation of secondary ettringite during bio-corrosion process in sewer pipelines has been documented by Mori et al.[17] Figure 6 is a schematic presentation by Mori et al of the different layers identified in the bio-corroded concrete in sewer pipelines. The figure clearly shows the formation of the iron layer and the layer of secondary ettringite.

CONCLUSIONS

Bio-corrosion process is a serious threat to concrete infrastructures exposed to organic-matter rich sediments and fill under the proper conditions. It can increase the susceptibility of concrete to degradation by sulfate attack, even at moderate sulfate concentrations at the site. The bio-corrosion process can be aggressive to any conventional concrete. This emphasizes a great need to thoroughly investigate the environmental conditions when evaluating the potential for degradation of concrete infrastructures.

REFERENCES

1. "*ACI 201.2R-1992, Guide to durable concrete*," ACI Manual of Concrete Practice, Part I: Material and General Properties of Concrete, Detroit, Michigan, 1994, pp.24
2. "*The sulfur cycle*," M.B. Goldhaber, and I.R. Kaplan, The Sea, Vol. 5, Marine Chemistry, Edited by I.D. Goldberg, John Wiley & Sons, Inc., pp. 569-654
3. "*The Microbiology of Corrosion: A review of the action of microbes in the corrosion process, with particular reference to the attack on concrete and underground pipe systems*," C.A. Smith, Anti-Corrosion, Methods and Materials, Vol. 28, No. 1, January 1981, pp. 15-20
4. "*Richerche intornoalla corrosione dei cementi per opera dei solfati*," V. Cirilli, La Ricerca Scienta, Vol. 11, No. 12, 1940, pp.973-977
5. "*I ferriti di calcico idrati, e i complessi che dal ferrito tricalcico prendono origine per associazone con differenti sali di calcico*," G. Malquori and V. Cirilli, La Ricerca Scienta, Vol. 14, No. 2-3, 1943, pp.78-84
6. "*Resistance of Concrete to Destructive Agencies*," M. Eglinton, Lea's Chemistry of Cement and Concrete, Fourth Edition, Edited by, P.C. Hewlett, 1998, pp. 299-343
7. "*Concrete: Structure, Properties, and Materials,*" P.K. Mehta, Prentice-Hall, Inc., 1993, pp. 153
8. "*Properties of concrete*," A.M. Neville, Fourth Edition, John Wiley & Sons, Inc. 1996, pp.76-77
9. "*Aquatic Chemistry*," W. Stumm and J.J. Morgan, An Introduction Emphasizing Equilibria in Natural Waters, John Wiley & Sons, Inc., 1981, pp. 780
10. "*Introduction to geochemistry*," , K.B. Krauskopf, Second Edition, International series in earth and planetary sciences, McGraw-Hill Company, 1979
11. "*Reduction of Fe(III) in Sediments by Sulfate-reducing Bacteria*," M.L. Coleman, D.B. Hedrick, D.R. Lovely, D.C. White, and K. Pye, Nature, Vol. 361, Letters to Nature, pp. 436438
12. "*Enzymatic iron and uranium reduction by sulfate-reducing bacteria*," D.R. Lovely, E.E. Roden, E.J.P. Phillips, and J.C. Woodward, Marine Geology, Vol. 113, 1993, pp. 41-53
13. "*The Reactivity of Sedimentary Iron Minerals Toward Sulfide*," D.E. Canfield, R. Raiswell, and S. Botrell,, American Journal of Science Vol. 292, November 1992, pp. 659-683
14. "*Reactive Iron in Marine Sediments*," D. Canfield, Geochimica et Cosmochimica Acta Vol. 53, pp. 619-632
15. "*Comparison of Methods to Determine Degree of Pyritization*," J. Leventhal, and C. Taylor, Geochimica et Cosmochimica Acta Vol. 54, 1990, pp. 2621-2625
16. "*Significance of Iron Layer as an Indicator to Determine the Microbial Corrosion of Concretes*," T. Nonaka, N. Ismail, K. Tazaki, and T. Mori, Journal of Construction Management and Engineering No. 474/VI-20, September 1993, pp. 125-131
17. "*Interactions of Nutrients, Moisture and pH on Microbial Corrosion of Concrete Sewer Pipes*," T. Mori, T. Nonaka, K. Tazaki, M. Koga, Y. Hikosaka, and S. Noda, Water Research Vol. 26, No. 1, 1991, pp. 29-37

The technical investigation of failure – a view from the marine industry

J.S. CARLTON and J.R. MAGUIRE
Lloyd's Register, London

Synopsis
Lloyd's Register's Technical Investigation Department has for the last fifty years been invited to investigate the technical reasons for many different types of failure and mal-performance in the marine, land-based and offshore engineering industries. These investigations have mostly been made at full scale and, frequently, in less than ideal conditions using a combination of trial measurement, metallurgical investigation, theoretical analysis and engineering judgement. In some instances the use of model tests has also been required in order to augment these other investigation techniques.

Following a brief outline of the work and capabilities of the Department, the philosophy applied to failure investigations is discussed after which some illustrative examples of recent investigations are presented. The paper then considers, in general terms, the more common failure modes encountered in the marine industry. The paper finally draws certain conclusions about the basic causes of failure in marine engineering situations and the qualities necessary for engineers to minimise the occurrence of failure. Conversely, some commentary is also offered on the qualities necessary in investigation engineers.

1. INTRODUCTION

The Technical Investigation Department (TID) of Lloyd's Register (LR), since its formation fifty years ago, has been invited to investigate some of the more difficult engineering problems posed by the marine and other industries that Lloyd's Register serves. More recently, this subject area of engineering failure investigation has become fashionably known as forensic engineering.

Within TID, investigations have been accomplished by a combination of trial measurement, metallurgical investigation, theoretical analysis and engineering judgement based on the Department's accumulated experience of over 5000 investigations. **Table 1** shows an analysis of the distribution of investigation types that have been undertaken in each of the marine, land based and offshore industry sectors. This experience has embraced a wide range of failure and mal-performance based engineering problems. Furthermore, LR's Technical Investigation Department archives bear adequate testament to the cyclic nature of failure problems. Indeed, in TID's experience, it is a general characteristic that investigations tend to be grouped into particular technical subject areas for discrete time intervals which then re-occur periodically.

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 109–126

MARINE	%	LAND BASED INDUSTRIES	%	OFFSHORE	%
Hull/Mach. Vibration	25.8	Petro-Chem/ Indust	21.7	Platforms	58.3
Shafting	24.1	Power Stations	20.3	Miscellaneous	33.3
Diesel Engines	14.1	Miscellaneous	18.5	Pipelines	8.4
Gearing	9.1	Buildings	17.0		
Power Absorption	5.8	Nuclear	14.5		
Noise	2.7	Docks and Harbours	4.7		
Turbines	2.5	Bridges	3.3		
Electrical	2.4				
Propellers	2.1				
Auxiliary Machinery	2.0				
Condition Monitoring	1.9				
Boilers	1.6				
Couplings/ Clutches	1.5				
Ship Structural Failure	1.2				
Rudders	1.1				
Environment	0.9				
Miscellaneous	0.8				
Pipelines	0.4				

Table 1 Primary Classification of Investigations

To address these problems TID comprises a multi-disciplinary group of engineers and scientists which includes mechanical, marine, civil and structural engineers, naval architects, physicists, electrical and electronic engineers, mathematicians, computer scientists and statisticians. The talents of this relatively unique group of highly qualified engineers and scientists are combined to provide a high quality, rapid response, technical consultancy and advisory service to the marine industry, the other industries that LR serves and to LR itself. These activities are supported by fully equipped instrumentation and material investigation laboratories.

The Department also conducts medium and long term marine engineering research and development to equip LR, in keeping with its divisional strategies, with the necessary capabilities to meet future requirements based on a continuing review of technological development and achievement. Clearly, by the nature of the Department's primary work, many of the research initiatives derive directly from the failure scenarios presented to TID.

2. PHILOSOPHY OF INVESTIGATION

The diagnosis of engineering failure is an art that has to be acquired over many years by investigation engineers; indeed, it is a process that is honed throughout an engineer's working life. As such, the most senior and experienced investigation engineers are those who have devoted considerable portions of their lives to this area of technology. This, however, is not to devalue the contributions of engineers and scientists who have spent lesser amounts of time in this field of endeavour before moving on into the other branches of technology with a considerably enhanced experience.

In their essentials, however, the principles of investigations are no different from the fundamental diagnosis techniques learnt by medical practitioners. The pre-requisite for diagnosis is to enter an investigation with an open mind no matter how many apparently similar exercises have been undertaken in the past. Minor changes in environmental circumstances, loading, manufacturing or design detail can bring entirely new perspectives and subtle twists to an otherwise familiar failure scene. Nevertheless, initial impressions, indications and signs, provided that they are ultimately rigorously challenged in the hypothesis testing procedure, can be extremely valuable in the initial stages of an investigation.

Most diagnosis situations start with the formulation of an hypothesis about the cause of a failure against which the various facts of the case are eventually tested. If one fact is found not to fit, then either the hypothesis is rejected or modified. As such, failure diagnosis is an iterative process. The initial working hypothesis is formulated from various sources:

- Accounts of the failure by the owners of the problem and those close to it. This clearly is essential evidence, however, it is usually also filtered evidence in which the features considered to be important by the reporter are presented or accentuated. Clearly, each of the symptoms highlighted need to be probed in order to reveal their true significance or, indeed, reveal further symptoms and avenues of exploration. Considerable skill is required at this stage of the investigation on the part of the investigator if the correct path or paths are to be followed at the start of the investigation.

- A viewing of the failure evidence either at first hand, which is the most preferable, or by photographs and logged accounts where the evidence is inaccessible is essential. The examination of failure evidence needs to be undertaken in the most thorough way possible if crucial evidence is not to be lost. In many cases a 're-construction' of the failed parts can prove a most helpful and revealing exercise. Photographic evidence is frequently difficult to assess effectively since photographers are, by their training, often most concerned with producing pictures having considerable artistic rather than scientific merit. Equally, images of submerged failures are frequently incomplete and unclear due to the constraints under which they are obtained, however, it must be recognised that considerable progress in this area has been made in recent years.

- A consideration of the engineering and environmental principles likely to be applicable to the problem in terms of, for example, the ambient conditions, the corrosiveness or otherwise of the environment, the likely static and dynamic load paths through the item under consideration. By way of illustration, in this latter context, a most useful basic technique in a ship vibration investigation, prior to undertaking an in-depth exploration of the problem, is to *walk the ship* using the soles of one's feet or a very simple portable instrument in order to understand the various global characteristics of the problem before considering the detail. The importance in an investigation of global understanding of the engineering interactions is considerable prior to concentrating on the detailed aspects.

- The service records and how these relate to similar types of components or systems. In particular, whether there has been a previous history of failures or indications of a growing problem in the time leading up to the failure being investigated.

- The investigator's experience of previous case histories.

From an initial working hypothesis, a suitable instrumentation fit and trials programme may be prepared; sometimes in the form of a pilot or exploratory investigation. Alternatively, a theoretical model may be derived to test the validity of the hypothesis. In either case, if it is a failure investigation, a metallurgical investigation of the failed component usually proceeds in parallel with information gained from the other various lines of enquiry as they become available. The metallurgical investigation aims at establishing the material chemical composition, structure, failure mode and the position of the origin and the presence of foreign bodies, voids, corrosion products and so on. In this respect the keeping of the failed specimens, which may be of considerable size, free from contamination after the failure event is of the utmost importance.

In the case of an investigation involving a measurement programme, following the full scale trials stages of the investigation, an analytical or numerical model may be formulated in order, first to obtain correlation with the quantitative trials data set and then, secondly to extend this domain so as to formulate proposals for appropriate remedial action or gain a deeper understanding of the failure processes. Typical of such a situation may be where measurements are constrained for some operational reason to be taken in, say, a ballast condition for a ship fitted with a fixed pitch propeller and data are, therefore, unavailable for the deep loaded conditions.

Alternatively, analytical models are frequently used to complement measured trials data in terms, for example, of general validity and identifying mode shapes of vibration. For theoretically biased investigations, a similar procedure applies but without the benefit of measured data, the correlation being undertaken by comparing the predictions with the observed qualitative behaviour and other known standard test cases. In these cases significant demands are placed on the selected analytical or numerical procedures which, in turn, require that the chosen methods are well correlated and that their predictions can be generally supported by less detailed methods or heuristic insights into the appropriate behaviour. The essential feature, however, of any computational method, whether used in association with field trial measurements or in isolation, is that it has been properly validated and correlated with the results of model or full scale experience. By way of example of the divergence that can occur between the results of computations obtained from reputable organisations, **Figure 1** shows the propeller blade stresses calculated using finite element methods for a highly skewed propeller blade [1]: the experimental values for which were obtained from work carried out in TID using a 254 mm model of a 72 degree biased skew propeller under the action of point loading. An alternative example of reasonable correlation is seen in **Figure 2** which shows a comparison between the results of finite element and boundary element computations and the results of three dimensional photo-elastic experiments. This exercise formed a precursor to an investigation on the integrity of some nuclear pressure vessels.

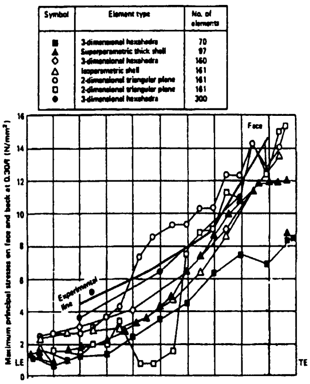


Figure 1 - Comparison of Different Propeller Blade Stress Calculations with Experiment

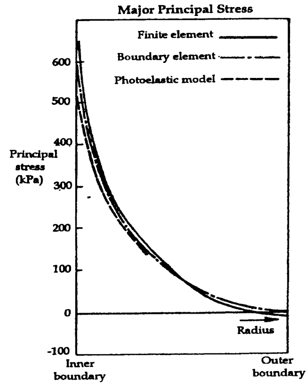


Figure 2 - Comparison of Finite Element, Boundary Element and Photo-Elastic Experiments for a Nuclear Vessel.

For any of the investigation scenarios described above the accumulated experience of past failures, and the factors involved in their manifestation, are an essential ingredient. Using these techniques a number of iterations are performed until all of the known facts of the case can be supported from the evidence gathered or derived. Consequently, a unique blend of field measurement, metallurgical investigation, theoretical analysis and engineering judgement combined with a sound historical knowledge of failure situations are required to satisfactorily execute an investigation. Within this process, however, the more complex measurement tasks are engineering projects in their own right, requiring design, manufacturing and installation phases which must fit with other technical requirements and production or repair schedules.

When undertaking investigations of failure situations it is important to recognise that the failure may not be attributable to a single cause. Frequently, two or more contributory factors may be involved, the combined effects of which have resulted in producing the conditions for failure. The approach taken, therefore, to an investigation must always allow for this possibility which in practice frequently occurs. In this context the investigator must always endeavour to understand the underlying causes of the problem because if this is not done, then proper judgement cannot be exercised on whether palliative or fundamental changes to the system are required.

3. TWO CASE STUDIES

In order to illustrate the diversity of investigation scenarios the following two studies are cited. The first outlines a relatively straightforward investigation, although not trivial, of a diesel engine failure involving a reconstruction of events. The second involves two apparently similar cases but requiring major instrumentation exercises, extensive field trials, theoretical studies, metallurgical investigation and model tests in order to understand the problems involved and ultimately leading to differing causes of the failures experienced.

Loose Crank Bearing Bolt:
TID surveyors are often called upon to attend the site of a mechanical mishap to conduct an investigation into the cause. Sometimes the cause is simple, as in this case of a loose crank bearing bolt.

The engine which suffered damage was an eight cylinder two stroke diesel engine arranged to drive a large alternator. The first indications that it had a problem were loud knocking sounds during normal operation. Unfortunately, before the engine could be brought to a stop, one of its connecting rods had abandoned its relationship with the crank pin and emerged from the crankcase, causing substantial internal and external damage. The final state of the connecting rod can be judged from **Figure 3.**

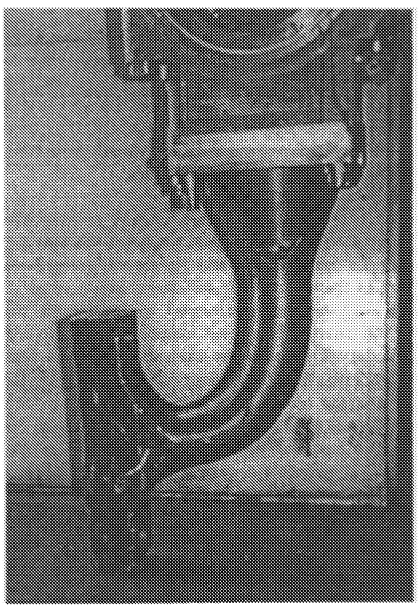


Figure 3 - Damaged Connecting Rod

As the various damaged parts became accessible from the wreckage, possible alternative causes were continually tested for credibility. By this process, attention was increasingly drawn to the need to find the crank bearing bolts, which were not initially accessible. When they were retrieved, one of them was found to be virtually intact, but without its nut. This nut, its locking device and locking screw were all found separately. The nut threads for about one and a half turns nearest to the lower face were seen to have been damaged by axial shear. About one quarter of the first turn, although present, had been separated from the nut around its circumference. The other bolt had broken under severe combined tensile and bending load and its nut with locking device and screw were still present on the broken end. Furthermore, a bolt in a different connecting rod was found to be 1 mm slack with its nut locking device and locking screws correctly fitted.

This evidence clearly showed that the slackening and loss of the intact bolt were the initiating cause of the engine damage. In searching for the reason why the bolt became slack, the effects on the bolt of possible cylinder malfunctions were calculated and physical tests of similar bolts were conducted. The key finding from this work was that if the bolt had been properly tightened, the probability that sufficient torque could have been generated to loosen the nut against the frictional resistance of the threads and of the nut face was minimal. The torque due to tensile load, which normally acts to unscrew a nut, was found to be one eighth of the frictional torque resisting such movement. It was concluded, therefore, that the damage resulted because the bolt had not been properly tightened to the correct tensile load.

The routine maintenance procedures adopted for this installation involved periodic checks of the bolt tension. The method used was to slacken and re-tension the bolts and, as such, this procedure had the potential to introduce error.

Sterntube Bearing Failures in Two Passenger Ships:
These two investigations, which were undertaken within months of each other, illustrate how two apparently similar sets of initial symptoms led to conclusions which, although having much in common, had important differences.

In the first case, at the time of its sea trials the ship experienced, over a period of three to four months, a series of A-bracket bearing failures through overheating. After each failure, modifications to the propulsion line shafting were carried out by the builder which included re-alignment of the shafting, changes to bearing clearances and materials, and so on. Additionally, during the trials following each bearing modification, using data measured from the ship's own standard instrumentation, certain basic correlations between, for example, course changes and bearing overheating were deduced. However, after the fourth bearing failure a full investigation of the problem was commissioned from TID by the shipbuilders.

The investigation commenced with a theoretical analysis, using a vortex lattice model of the propeller operating in a scaled model wake field of the ship. These calculations indicated that the effects of the forces and moments generated by the propeller on the shaft dynamic alignment were likely to be significant in the straight ahead condition. Simultaneously with this computational study, a series of model tests were commissioned to explore the behaviour of the in-plane wake field components at the propeller location when the ship was turning. The data derived in this way were used both to gain an understanding of the importance of the cross flow components during turning and for subsequent theoretical computations for eventual correlation with the results of a full scale measurement exercise, which was also initiated at this time, and directed towards quantifying the shaftline dynamic behaviour. Both of these major experimental tasks within the overall investigation programme were required to be complete within a time frame of around four weeks.

The full scale measurement task required a complex instrumentation fit to be installed on the ship, **Figure 4.** This, in turn, needed custom built instrument housings and fixings to be fabricated and installed, underwater and conventional air-gap telemetry systems to be fitted together with a range of other less complex instruments and a suitably responsive data recording system having an adequate storage capability. In order to fit some of these instruments, principally those to be used outboard of the hull and shaft sealing arrangements, required the ship to be dry-docked. Furthermore, as a part of the investigation the tail shafts were required to be removed from the ship, transported some ten kilometres and checked for concentricity in a suitably sized lathe. During this dry-docking period the stiffness of the ship's A-bracket arrangement was also determined by transversely recording displacements while pulling the bossing of the A-bracket from the dry-dock wall by pneumatically operated chain blocks with a 100 tonne load cell coupled into the system. This sub-component of the trials programme required a civil engineering appraisal of the capability of the ageing dry-dock wall to withstand this treatment. Additionally, a series of viewing windows were cut into the hull above the propellers in order to observe the propeller behaviour, chiefly through its cavitation performance and with the aid of tufts on the hull and appendages, to see if any abnormal flow regimes developed. As such, all of these activities together with their attendant logistical problems of the transport of personnel and equipment over several thousand miles and the customs and importation formalities required to be phased in during the time allotted for the investigation so that not only the planned delivery of the ship could take place, but that delays to other ships wishing to use the dry-dock facilities would not be incurred.

Following the sea trials the detailed analysis of the relevant data gained, all of the data having undergone preliminary analysis by the investigation team at the time of collection, and the correlation with the theoretical predictions of the hydrodynamic and shaftline dynamic models took place. This involved the direct comparison of the data sets involved and the extension and interpretation of the measured data together with the positive identification of shaft vibration mode shapes. The principal findings of the investigation relating to the first ship were that the slopes of the shafts through the bearings were too high due to the dynamic loads generated by the propellers both in the normal ahead and turning conditions. Additionally, a blade order shaft lateral resonance was moved into the running speed range on the inside shaft when turning, due to the change of bearing loads induced by the hydrodynamic loading of the propellers. Of particular importance in this investigation was quantification of the entirely different characteristics of the loading vectors on each shaftline when the ship was turning, their correlation with the observed burning marks on the bearings and the implications for this and future designs.

The second of the two ships cited exhibited very similar initial symptoms to the first and indeed, with the exception of the findings relating to the lateral resonance, the principal conclusions from the first investigation applied in this case. The investigation for the second ship followed very much the same format as in the previous case but without some features such as the model tests, full scale flow visualisation and A-bracket stiffness determinations. One notable difference between this case and the first ship was that the second ship was fitted with water rather than oil lubricated bearings. During the dry-docking period it was noted that craze cracking of the shaft liner material had taken place in way of the bearing retaining rings implying, due to the rapid wear-down of the bearings, that contact between the retaining rings and shaft had taken place. Due to the mix of materials involved this introduced a potential for a grain embrittlement mechanism to take place in the shaft liner. Of additional concern was that a metallurgical analysis of a relatively uniform distribution of metallic particles along the length of the A-bracket and stern tube bearing materials identified the particles as coming from the shaft liner material. The distribution of these particles could not, however, be entirely explained by considerations of the likely water flow paths through the bearings and, as such, their presence raised questions of material incompatibility. The actual mechanisms operating in this case are, as yet, not completely understood and are the subject of a continuing research programme within Lloyd's Register with the full co-operation of the various other parties involved. As a pragmatic measure in order to return the ship to sea the bearing material was changed and the shaft liner dressed to remove the effects of the craze cracking and potential grain embrittlement. To date the ship appears to be working satisfactorily.

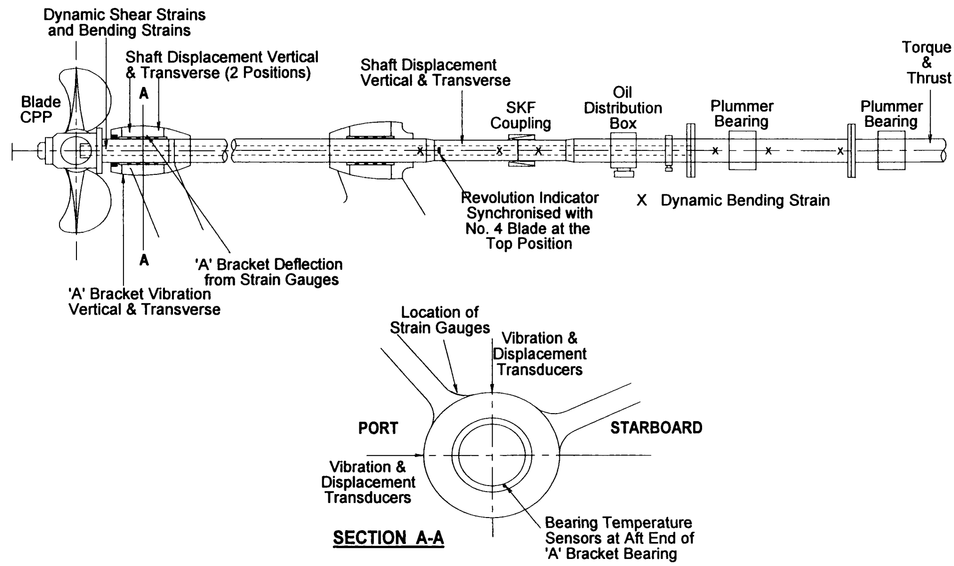


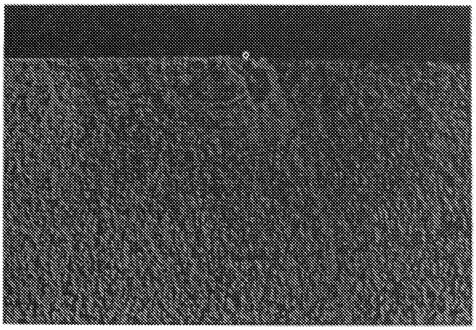
Figure 4 - Shaft Instrumentation for First Ship

4. COMMON FAILURE MODES

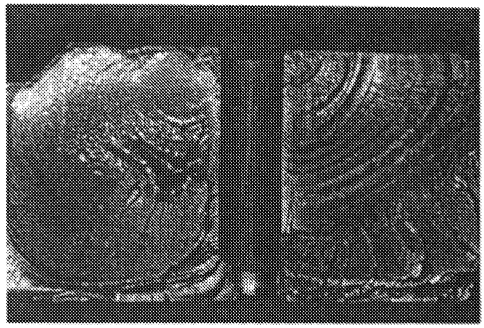
The majority of failure investigations encountered today by TID in the marine industry involve aspects of fatigue. Other failure modes such as brittle failure and creep are less frequently encountered with pure ductile failures being a rare event.

Fatigue Failures:

Fatigue failures require cyclic stresses to be experienced by a discontinuity in the material. Furthermore, the fatigue life of the component will be influenced by the magnitude and nature, compressive or tensile, of any steady mean stresses. The material type, local geometry, mode of manufacture and the environment in which a component operates also affect the fatigue strength.



(a) Typical Propeller Blade Failure



(b) Failure of a Diesel Engine Gudgeon Pin

Figure 5 Typical Fatigue Failure

Fatigue failures are normally characterised by being transcrystalline and occur without significant plastic deformation. Moreover, the general appearance of a fatigue failure, as distinct from its orientation, will be similar for most modes of loading, for example, whether the failure has been induced by axial, bending or torsional loading or a combination of these. **Figure 5** shows two typical fatigue failures, one on a marine propeller blade and the other on a diesel engine gudgeon pin. Fatigue failures are normally considered to progress as three distinct phases in ductile materials. The first phase, *Stage I*, is strongly influenced by the slip characteristics of the material, the applied stress level, the extent of crack tip plasticity and the characteristic microstructural dimensions of the material. Where cracks are initiated in ductile materials it is generally considered that the cracks grow cyclically by the deformation in the slip bands near the crack tip which leads to the creation of new crack surfaces by the mechanism of shear de-cohesion. In components with relatively small flaws it has been found that cracks can spend a considerable time in this mode of the development. Typically, for a propeller blade this stage might account for some 80 to 90% of the crack life. The second stage in the development of a fatigue crack, termed *Stage II*, is where the plastic zone at the crack tip extends over many grains due to the higher stress intensities. This is in contrast to the *Stage I* mechanism which embraces only a few grains at a time and is essentially a single shear type of mechanism in the direction of the primary slip system. For *Stage II* crack growth the process involves simultaneous or alternating flow along two slip systems in the material. This duplex slip mechanism results in a planar crack path which is normal to the far-field tensile strain direction and hence defines the orientation of the crack face. For components or structures where there are significant initial flaws the major part of the fatigue life is spent while the crack is growing in this mode. Consequently, for welded structures *Stage II* crack growth laws and codes are especially applicable. One frequent characteristic of a *Stage II* fatigue failure is the presence of striations in the fracture surface the spacing of which, within the applicability of the Paris Law regime of crack growth, has been shown to correlate with the measured average rate of crack growth per cycle. **Figure 6** shows a set of striations relating to a fatigue failure in the tooth of a gear wheel of an ice breaker. Of particular interest is the relatively coarse nature of some of the striations in relation to the normally observed magnifications of around 1000 to 4000 for this type of marine component. However, it is important to note that striations are not always present and it has been shown that environmental effects can influence their development. In air, for example, striations are clearly seen in pure metals, some ductile alloys and in many engineering polymers, but this is not always the case in steels and they can often be indistinct in cold worked alloys. In a vacuum, striations are not seen in a number of alloys which would normally be expected to exhibit them in air, furthermore, crack growth rates can be an order of magnitude slower. The final phase of fatigue crack growth is *Stage III* and this is where the crack has grown to a sufficient size where the component can no longer withstand the mechanical loads imposed upon it and, therefore, it fails by another mode. This final phase in the fatigue crack life is normally very short, of the order of microseconds for most dynamic situations.

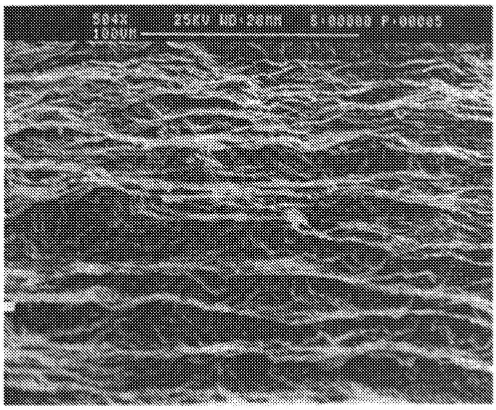


Figure 6 - Fatigue Crack Striations on a Gear Tooth Failure (x500)

Striations should not be confused with beach marks which are often clearly visible on fatigue fracture surfaces **Figure 5.** Beach marks are normally associated with periods of crack arrest whereas striations can be thought of as being due to the plastic blunting of the crack trip upon each cyclic application of tensile stress.

The propensity for crack growth is influenced by the environment due to the deleterious effect of corrosion when combined with stress. If the stresses are sensibly constant, as for example in a pressure vessel, the corresponding failure mechanism is usually termed stress corrosion cracking whereas the term corrosion fatigue is usually applicable when cyclic stresses are predominant. In practice, such clear distinctions are unusual because most components experience some stress fluctuations and significant residual tensile stresses can be induced by manufacturing processes. All environments are corrosive to some degree, even air and pure water, and it is interesting to note that the fatigue strength of samples is increased if they are tested in a vacuum. The crucial function of the corrosive action is its contribution in overcoming the stronger microstructural barriers during the early stages of crack growth. Such action is a chemical function (fluid composition, pH value and electropotential) and is consequently time dependent which helps explain why there is no conventional cyclic stress limit for corrosion fatigue conditions. Furthermore, fatigue life is not related solely to the number of stress cycles and the results of corrosion fatigue tests are influenced by the frequency of the applied loads. Corrosive agents include both acidic and alkaline embrittlement mediums: chlorine, sodium and sulphur are commonly encountered in marine and industrial failures which are caused by corrosion assisted cracking.

Fatigue research has more recently concentrated on short cracks and it has been shown that the growth rates of small flaws can be significantly greater than those for long flaws when considered in terms of the same nominal driving force. **Figure 7** shows in schematic form the typical fatigue crack growth behaviour of long and small cracks at constant values of imposed cyclic range and load ratio. In this context small flaws are considered in terms of one of four classifications [2]:

- *Microstructurally small;* Those where the crack size is comparable to characteristic microstructural dimensions.
- *Mechanically small;* Cracks where the near-tip plasticity is comparable to the crack size or which is encompassed by the plastic strain field of a notch.
- *Physically small;* Cracks typically less than about 2 mm in length.
- *Chemically small;* Cracks which would normally be amenable to linear elastic fracture mechanics but exhibit anomalies in growth rates below a certain size as a consequence of corrosion fatigue effects.

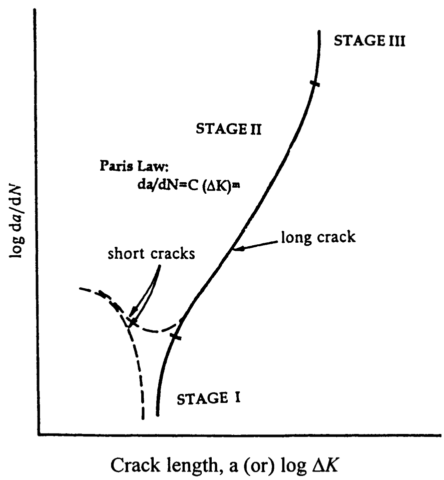


Figure 7 - Fatigue Crack Growth

Indeed, while each of these classifications present some difficulties from an engineering standpoint, the behaviour of *physically small* flaws can be the most difficult to quantify because it has been demonstrated that these types of cracks can grow appreciably faster than long cracks subjected to the same nominal stress intensity range. The studies of short crack behaviour and non-propagating cracks mean that fatigue failures now have the potential to be explained in terms of crack growth throughout the process from the first strain cycle to final rupture using fracture mechanics principles. Additionally, it seems likely that many familiar classical techniques and empirical factors used to estimate fatigue strength will be superseded in the future; for example, the treatment of multiaxial stress states, notch sensitivity, stress-strain cycle counting and strain hardening or softening characteristics.

A good illustration of this change of thinking is that the fatigue limit was considered previously to be identified only by a stress value. A better concept, however, is *the ability of a crack, whatever its length, to propagate to failure* because the fatigue limit refers to the stress level required to overcome the strongest barrier to crack growth which will be represented by a microstructural distance.

Apart from the greater susceptibility of soft whitemetal bearing materials to crack, the effects of temperature on the fatigue strength of most engineering materials are not serious until about 400°C when all mechanical properties are progressively impaired. Temperature fluctuations can, however, cause severe thermally induced cyclic stress gradients which in turn induce fatigue damage which is manifested as crazed cracking. Typical examples are the overheating of diesel engine bearings and consequent damage to crankpins and journals and the impingement of water on the bore surfaces of superheated steam pipes.

Fretting fatigue is a special case of fatigue action which results from a combined mechanical and chemical action and in which three fundamental conditions are necessary for the failure mechanism to develop. These are, the ability of two surfaces to move relative to each other, albeit by a small amount; points of asperity on the surfaces which make contact and the presence of sufficiently high stresses in the vicinity of the contacting points to cause surface cracking. Typical engineering situations giving rise to the conditions promoting fretting action are flat contacting faces such as flanges where shear loads across the faces may exist and the normal forces may permit some degree of slippage between them. Alternatively, holes which, for example, may house bolt shanks or rivets and be subjected to interface sliding and varying interface pressures. Further situations include key and keyway interfaces, leaf springs, splines and contacting strands in wire ropes.

When surfaces are permitted to rub together under the fretting conditions described, scars on the surface tend to form relatively rapidly and these often have a roughened appearance. In cases of fretting in steel the scars contain a reddish-brown oxide, often in the form of a powdery deposit although in some cases this may form a glaze. Alternatively, if the action is between aluminium surfaces then the deposit is black in colour. Research into the fretting fatigue mechanism has suggested that the nucleation of fatigue can result from one of a number of causes; typically these are an abrasive pit-digging mechanism, asperity-contact microcrack initiation, friction generated cyclic stresses that lead to the formation of microcracks and subsurface cyclic stresses that lead to surface de-lamination in the fretted region. It has also been shown that compressive stress between the members can have a beneficial effect on the suppression of fretting fatigue. Much research effort is, however, needed in the subject of fretting fatigue.

Figure 8 shows an example of a failure caused by fretting initiated torsional fatigue. This failure was induced by fretting which occurred at the interface between a drive shaft and fluid coupling due to an inadequate compression fit on a 1:10 taper. This fretting action induced over one hundred separate fatigue crack initiation sites on the shaft. In this case the function of the key was to provide a reserve safety factor to the design. The lack of compression fit was induced partly because of the high taper and in part due to the original design not taking due account of the restricted conditions under which the required compression fit had to be achieved during construction or maintenance in the ship.

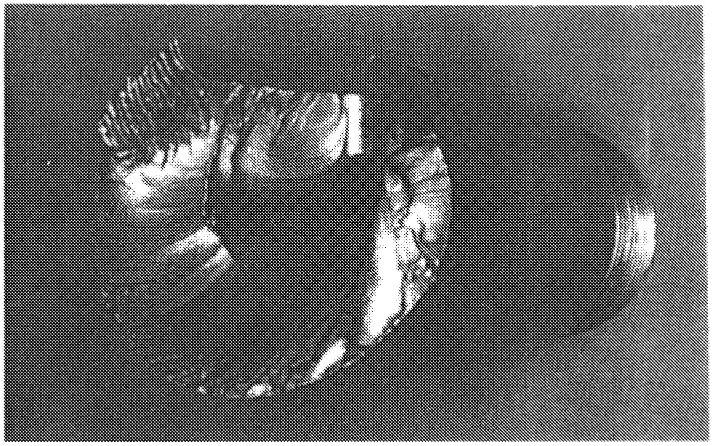


Figure 8 - Fretting Fatigue of a Tapered Shaft

Brittle Failure:
True brittle fracture occurs without significant gross deformation. This fracture mechanism manifests itself in a plane normal to the applied stress and is essentially a fracture mechanism which occurs through the grains of the material. When viewed under the microscope the fracture face is seen to contain a large number of facets together with a branching pattern of cracks. In plate sections a pattern of *chevron* markings is normally seen, the direction of which points to the origin of the failure, **Figure 9**. While brittle fracture is not a commonly encountered type of failure today, a recent example of its appearance is the failure of some 38 mm bolts shown in **Figure 10**, from a steering gear hydraulic ram stopper pedestal. These bolts were manufactured from a 0.35% C, 1.48% Mn steel. Material tests showed them to have a ratio of the 0.2% proof to ultimate strength of 98% and an elongation of only 9%. The bolts had failed at the underhead position in way of a 0.45 mm radius by brittle fracture. Also around the circumference of the failed section is a small, 5 mm deep region of fatigue propagation from multiple origins.

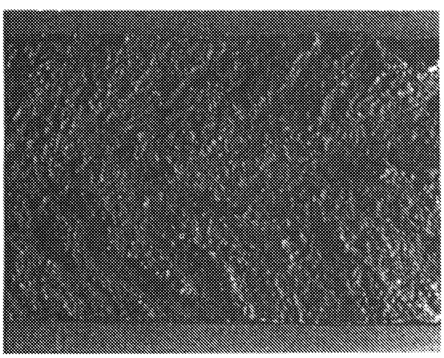


Figure 9 - Chevron Markings on a Brittle Fracture of a Plate

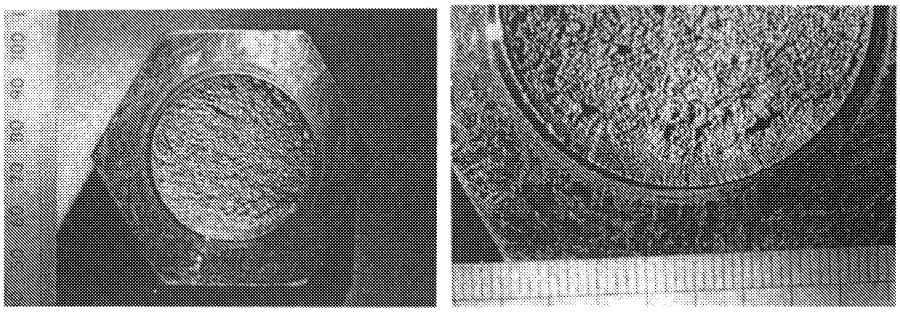


Figure 10 - Brittle Fracture of a Bolt

Ductile Failures Types:
Pure ductile failures are rarely encountered today in the marine industry, however, a variant of this mechanism is occasionally seen. This is the lamellar tearing mechanism which is known to sometimes occur in the parent plate beneath welds in the through thickness direction. **Figure 11** shows a classical example in a cruciform joint. In this type of tearing mechanism the presence of non-metallic inclusions has a significant affect on its development. Another example has recently been found in a fractured fuel injector. The injector was made from a medium carbon sulphur bearing steel with a significant quantity of manganese sulphide inclusions elongated in the axial direction. The holder had cracked longitudinally due to the action of lamellar tearing caused by high hoop stresses and an unfavourable microstructure of the material; **Figure 12**.

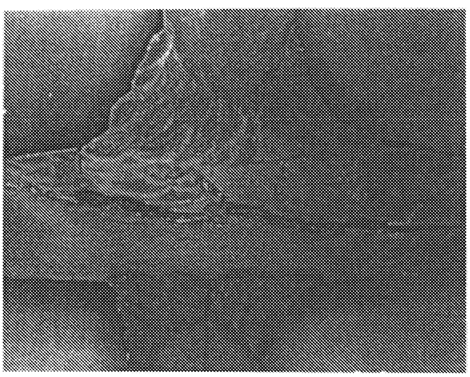
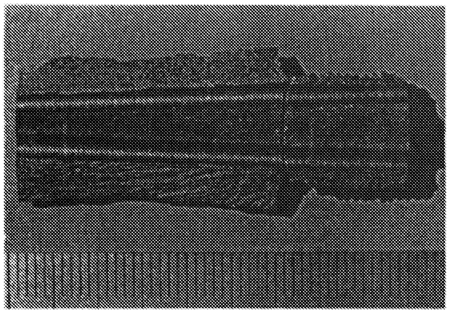
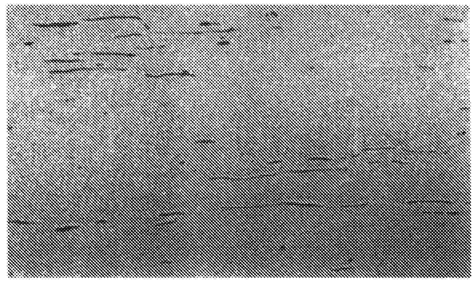


Figure 11 - Lamellar Tear on a Cruciform Joint



(a) Axial Fracture Face



(b) Manganese Sulphide inclusions in the Material

Figure 12 Failure of an Injector

5. SOME LESSONS LEARNT FROM FAILURE INVESTIGATIONS

There are a great many lessons that can be learnt from the failure investigation activities of the Technical Investigation Department of Lloyd's Register. Some are specific to certain areas of engineering application while others are more general in their nature. The underlying general lessons can be summarised as follows:

- When undertaking engineering design it is essential to *stand back* from the detail of the design and look at the whole engineering problem. From such an exercise it is possible, for suitably experienced engineers, to identify the weak points in the design.

- Today the investigator, or designer for that matter, has a range of analytical and experimental capabilities at his disposal. In most engineering situations these capabilities only give a partial picture of the problem and, as such, they are aids and not a substitute for sound engineering judgement.

- The Department's data base shows that in a great many instances problems continue to reoccur on a periodic basis. Whether this is due to technology moving on in other areas which then reintroduces problems of a similar type in a later age or the lessons of the past not being effectively passed on to new generations of engineers are unclear, perhaps a combination of the two causes.

- A great many failures are caused by a lack of attention to the detail design of individual components. Moreover, problems frequently arise when similar care is not exercised in the integration of components into an engineering product or system; especially when different manufacturing sources are involved.

- Similarly, installation, maintenance and operational procedures in relation to the design philosophy are critical if failures are to be avoided.

- Investigators must always attempt to identify and understand the prime cause of the problem so that proper judgement can be exercised in deciding whether fundamental changes are needed or if palliative countermeasures will be sufficient.

- The training of engineers in the detailed practical and theoretical skills of engineering is fundamentally important, but more critical is the combining of these skills into a unified professional engineering knowledge and instinct. Furthermore, within this concept engineers must gain an in depth knowledge and appreciation of the materials with which they work.

- Continuing professional development is an essential ingredient of any engineer's training. It must, however, be implemented rigorously and honestly on the part of the individual concerned and the learned institutions.

The quality of a design, or an investigation, is directly dependent on the quality and motivation of the people employed in that function. As such, the rewards given to the individuals in terms of creativity, job satisfaction and of course remuneration must be such so as to attract the correct calibre of person. These rewards, however, need to be set within a proper framework of responsibility and accountability.

6. CONCLUDING REMARKS

The investigation of failure in engineering situations relies for its success on the quality of the people involved in the activity together with a combination of skills and technologies. The basic technical skills are those of field measurement and study, metallurgical investigation and theoretical and computational analysis; each providing a part of the solution or extending the knowledge gained from one of the other approaches. Equally important, however, are the engineering and diagnostic skills of the investigator. These latter skills, while relying on a sound knowledge of engineering theory and practice, derive more from the application of logical analysis and reasoning to a problem. In addition, an extensive database of previous failure histories is essential.

7. ACKNOWLEDGEMENTS
The Author wishes to thank the Committee of Lloyd's Register for permission to publish this paper. Additionally, the experience and knowledge of a group such as TID can only be built up by much careful and hard work from the Department's technical and administrative staff over the years. Consequently, thanks are due to the Author's many colleagues, both past and present, who have contributed to and developed the various investigation techniques and without whom, the Department would not exist with its present capabilities.

8. REFERENCES

1. Proc. 18th ITTC - Report of the Propulsor Committee, Kobe 1987.

2. Suresh, S. and Ritchie, R.O. *Propagation of Short Fatigue Cracks.* Int. Metals Rev. 29, p445-76, 1984

Incident reconstruction - Piper Alpha case study

ROD SYLVESTER-EVANS
RSE Consultants Limited, Edinburgh, UK

ABSTRACT
The Piper Alpha disaster in which 167 men lost their lives occurred on 6th July 1988. At about 22.00 hours an explosion occurred within the platform and within seconds a major crude oil fire developed and all but the lower parts of the platform and wellhead area were engulfed in black smoke. Twenty minutes into the fire, a major failure of a riser occurred creating a fireball in excess of 150 metres in diameter. Subsequent fires and explosions caused the eventual collapse of the platform during the next few hours. By the morning only the wellhead module remained standing.

Investigators were faced with two major problems. Firstly, all the potentially relevant physical evidence was at the bottom of the sea and it was deemed impracticable to recover the equipment for forensic examination. Secondly, no eyewitness to the fuel/air cloud which created the initial explosion survived. The investigators were left with a mystery to solve on the basis of circumstantial evidence. This paper shares the experience of the investigative process required to reconstruct the events of the night and then refining, presenting and testing that reconstruction at a Public Inquiry lasting 180 days.

GENERAL BACKGROUND
The Piper Field was discovered in January 1973 and is some 120 miles north east of Aberdeen. The water depth is 140 metres and at the time the Piper Alpha platform represented a major step in both the development of the U.K. offshore resources and technology. Production of oil started in December 1976 and during its early life the platform proved extremely productive, the oil being pumped to the onshore terminal at Flotta on Orkney.

Close by, the Claymore Field had been discovered approximately a year after the Piper Field and the Claymore platform, which was a similar design to that of Piper, came onstream in November 1977. The oil produced from the Claymore Field was also exported to Flotta through the same subsea pipeline. As the offshore fields were developed it became possible to export gas produced at the Piper Alpha Platform, together with gas from the nearby Tartan A Platform, to the nearby compression platform, MCP-01 which formed part of the gas export system from the Frigg Field. In addition a gas line was installed linking Claymore to Piper. The Piper Alpha Platform thus became the focal point for network of oil and gas pipelines. The inventory associated with these pipelines was large with the main oil line to Flotta containing some 70,000 tonnes of oil whilst the three gas pipelines linking Piper to other platforms contained almost 2,000 tonnes of high pressure gas.

The west and east elevations of the top sides of the Piper Alpha Platform are shown in Figures 2 and 3. The production deck at the 84' level comprised four modules, A, B, C and D. The general layout is seen in Figure 4. Module A, the wellhead module, was

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 127–137

considered to be the most hazardous and, accordingly, the production modules were arranged so as to provide the maximum separation from Module A and Module D which contained the various utilities, with accommodation areas located above. Module B was a production module where the separation of oil from other fluids took place and where the oil was pumped into the main oil line for transmission to Flotta. Module C contained the original gas compression equipment whereby gas from the production separators was compressed for export ashore via MCP-01. In the 1980's, a gas conservation module (GCM) had been installed at the 107' level above, but at the time of the disaster this module was under maintenance and, therefore, gas was being processed and compressed only in Module C. As part of this process, heavier components from the gas, known as condensate, were removed by reducing the pressure and temperature of the gas. The condensate so collected accumulated in a vessel which was located beneath Module C at the 68' level. (See Figure 5). The condensate was then pumped back into the main oil line for export to Flotta by use of a booster and a condensate injection pump, of which there were two pairs, one normally on standby.

Modules A, B, C and D were separated by firewalls which were not rated for explosion overpressure. The firewall between Modules C and D were specified for 6 hour fire rating while those between Modules B/C and A/B were specified as a fire barrier for 4.5 hours. At the time of the disaster the hydrocarbon inventory within the production modules was approximately 80 tonnes, mainly in Module B and, in particular, within the two production separators. In addition, there was about 160 tonnes of diesel located in tanks above Module C. Thus the hydrocarbon inventory onboard the platform was small in comparison with that contained in the oil and gas pipelines.

SUBSEQUENT HISTORY/EVENTS

At the time of the disaster in July 1988 the operation and safety of the U.K. offshore oil and gas installations was under the control of the Department of Energy. The Secretary of State for Energy appointed Lord Cullen to hold a Public Inquiry to establish the cause and circumstances of the disaster. The Inquiry sat for 180 days, heard evidence from some 260 witnesses who spoke in excess of 6 million words of evidence. The Public Inquiry was divided into two parts. Part 1 concentrated on determining the cause and circumstances while Part 2 concentrated on the *'lessons to be learned'*.

Lord Cullen's Report was published in November 1990 and contained some 106 recommendations. In implementation of Part 2 of his remit, he recommended that the Department of Energy be relieved of the responsibilities for offshore safety and that these should be transferred to the U.K. Health & Safety Executive. Further, he recommended a complete revamp of the offshore regulations from a prescriptive to an objective style regime; the cornerstone of this approach was the concept of a Safety Case for offshore installations. Lord Cullen believed that the safety case should be prepared by the operators to demonstrate that (a) the safety management system (SMS) is adequate to ensure the design and operation of the installation's equipment are safe, (b) the potential major hazards of the installation and its risks to personnel had been identified and appropriate controls provided and (c) appropriate provision is made ensuring a temporary safe refuge and safe and full evacuation, escape and rescue for personnel onboard in the event of a major emergency. Subsequent to Lord Cullen's Report there has been a major revamp of the offshore regulations, the Piper B Platform has been constructed and is now operating and the estimated cost for safety-related modifications and follow-up work for the offshore industry has exceeded £5 billion.

As to the cause of the disaster, as we shall see, Lord Cullen found it established on the balance of probabilities (being the required test) that the initial explosion occurred as a result of a release of condensate from a blind flange assembly at the site of PSV-504 which was not leak tight (Ref. 1). Consideration will now be given as to how Lord Cullen was able to reach that conclusion given the circumstantial nature of the evidence with which he was presented.

THE INVESTIGATION - DATA SOURCES

As Technical Consultants to the Crown the initial work was to investigate the potential cause of the explosion and the escalation of the disaster and to ensure that all aspects were identified fully and examined by the Inquiry. A team of specialists were assembled covering such diverse areas as explosion modelling, fire dynamics, compressor design, hydrate formation, thermodynamic predictions, gas detection, wind tunnel modelling, noise predictions, leak rate and pipeline mass-balance analysis, to name but a few. In all, some sixty organisations and companies had to be co-ordinated to provide either specialist analysis using often *'state-of-the-art'* technology, or reports which were submitted to the Inquiry.

As already indicated, the unusual feature of this disaster was the total destruction of the platform and the loss of much of the forensic evidence. The *'scene of the accident'* no longer existed. The recovery of hardware was extremely limited and comprised loose items which *'fell'* free of the main structure such as containers and structural debris. No process equipment could be recovered, except for the methanol pump. What remained of pipework and vessels was in a tangled heap of steel 150' deep on the seabed. Whilst video recordings of subsea debris was possible to a limited extent, recovery of equipment and the missing bodies of the deceased were deemed impracticable.

Having been unable to gain access to the plant and machinery itself to solve the mystery, the investigation team looked at what data was available to them. In attempting to establish the cause and circumstances of the disaster a wide variety of sources of data were relied upon. These included eyewitness accounts from the survivors; from persons on neighbouring vessels; data from nearby platforms; the recovery of the deceased; recovery of debris and documentation from the seabed; documentation available ashore; statements from the *'back to back personnel'* who had recently left the platform and from management; third party inspections etc.

It had proved possible to recover from the seabed two accommodation units which proved to be a valuable source of information both as a result of examination of their physical condition and the documents which were found within the unit. They required detailed forensic examination to determine the cause of smoke and flame ingress and fire development within the units. This was achieved by, for example, examination of metal fittings to determine external temperatures, paint layers to determine internal/external temperatures, analysis of smoke deposits to determine hydrocarbon sources and means of ingress and movement of smoke. Further, a large quantity of documents including daily logs and reports were recovered and these had to be dried out, sifted, prioritised and preserved after having been in the water for 100 days.

In addition, 135 bodies were recovered and only 4 indicated death by burning. The vast majority died from inhalation of smoke and gas. The remainder died from injuries sustained from jumping into the sea from heights of up to 174'. A total of 79 bodies were found in the larger of the two accommodation units recovered.

Further sources of vital information were the accounts of 61 survivors from the platform which proved crucial to establishing the cause. There was the vital evidence from the control room operator, who received the series of gas alarms from Module C shortly before the explosion. The movement and timing of personnel also required careful analysis, particularly what they did, and did not, hear, see, smell and feel prior to and immediately following the explosion. Mapping of their evidence provided a surprisingly high corroboration of what were clearly independent accounts as to the movement and timings of various activities.

From the survivors' evidence it was established that no major problems had been encountered with the process on the day of the disaster until some 15 minutes, or so, before the explosion, when a condensate injection pump, located at the 68' level tripped. Process operators went to investigate the situation; the second condensate injection pump was under maintenance at the time. Attempts to restart the tripped pump failed and it was established that there was the intention and opportunity to recommission the second pump.

It was also established from the survivors' accounts that, shortly before the initial explosion, the control room operator responded to a number of gas alarms and trips of equipment. Some 2 to 3 minutes before the explosion there was a low gas alarm associated with a centrifugal compressor at the east end of Module C. This was followed by a tripping of several centrifugal compressors. Seconds before the explosion there was a flurry of gas alarms at the east end of Module C with one high gas alarm occurring at a centrifugal compressor. At about this time the third and final centrifugal compressor tripped.

As described above, just prior to the explosion there was activity associated with the condensate system at the 68' level. In addition, an operator had left that area, and went upstairs to Module C to investigate the cause of the initial low gas alarm. Further, some 10 minutes before the explosion high flaring rates were noticed by many survivors and eyewitnesses which tended to subside until several minutes before the explosion when there was a further increase seen in the flaring.

The explosion occurred at or about 22.00 hours. It appeared that the initial explosion originated in Module C and affected Module B and C, this being consistent with the initiation of gas alarms before the explosion.

Also of crucial importance, were the eyewitness accounts of personnel of nearby vessels who helped to piece together the early fire development that occurred so quickly after the initial explosion. They also provided a wealth of photographic and video data. In analysing this offplatform data it was most important to establish precisely how people became aware of the incident and their immediate actions prior to their first observations of the platform. For many eyewitnesses, the first phenomenon which they saw was a fire, of various proportions, in Module B, but it was clear from their account that this sighting always followed as a response to some initial noise (such as a thump), vibration or tannoy message which alerted them to a problem. All the survivor and eyewitness evidence was available to the investigation team on the police computer (Holmes) which allowed for an initial sifting of eyewitness accounts to prioritise the most important observations.

It transpired that only one eyewitness observed the combustion phenomena associated with the initial explosion, namely the Master of a nearby vessel. The stern of the vessel was located about 25 metres from the south west corner of the platform and he was looking directly at the west face of the platform at the time of the explosion. He observed a blue flash, which appeared to come from Module C, expand at low level across the west face of the production deck and retracted back into Module C. Thereafter, immediately he felt the effects of the explosion and witnessed what appeared to be a major vibration associated with the platform. Other eyewitnesses who heard, or felt the effects of the explosion, and had an immediate view of the platform observed smoke coming from Module C initially prior to any events occurring in Module B.

These sources of data indicate the nature and extent of the factual *'jigsaw'* that had to be fitted together so as to determine the cause and circumstances of the disaster. Whilst it did appear from these data that the initial explosion originated in Module C, there were a number of potentially puzzling features which required further testing of this hypothesis, namely:-

- The rapid development of a fire and a dense smoke plume in Module B within seconds of the initial explosion.
- A fireball emanating from the west face of Module B some 15 seconds after the initial explosion.
- The rapid development of a crude oil fire in Module B which continued to burn for a period which could not have been sustained from the platform hydrocarbon inventory.
- A fire seen on the north face of the platform that appeared to be connected in some way with the fire in Module B.
- The early failure of the Tartan riser at 22.20 hours.
- Prolonged flaring of gas for some 50 minutes after the initial explosion which could not be sustained from the platform hydrocarbon inventory.

These features of course related to the escalation of the fires and subsequent explosions which eventually caused the loss of 165 lives, out of the total of 226 persons onboard, and 2 crew members of a fast rescue craft (FRC) who were engulfed in a fireball caused when the MCP-01 riser failed catastrophically.

EXPLOSION LOCATION AND ESCALATION

As discussed earlier the location of the gas alarms prior to the explosion suggested that the explosion was centred at the east end of Module C. Broad estimates suggested that the maximum overpressure generated, had the explosion been in Module C, was of the order of 0.3 to 0.7 bar. Further, the explosion effects on personnel were wholly consistent with the explosion originating in Module C. The strength of the firewalls was an important parameter that needed to be examined closely. The firewalls comprised a bolted latticed-work structure and were not designed as blast walls. However, the A/B firewall was seen by survivors to be intact following the initial explosion. The explosion effects on certain personnel, together with the movement of smoke and photographic evidence suggested that there was major disruption to both the B/C and C/D firewalls. A series of calculations were performed to determine the strength of the firewalls and how they would break up when subject to an explosion overpressure. The mathematical modelling varied from hand calculations through to finite element analysis. The calculations showed that there was sufficient overpressure generated by the explosion to cause failure and break up of the firewalls. Further the velocity and energies associated with the break-up of the firewall panels were calculated and confirmed that their ejection into Module B could have caused pipework failure with a major release of oil and condensate and a rapid fire development. A vulnerable pipeline in Module B was a 4" diameter condensate pipeline, containing some 75 to 100 kilograms of condensate at the west end of the module. The size and characteristics of the fireball caught in the first photograph taken of the disaster, was shown to be consistent with a release of condensate from this pipeline.

Detailed analysis of the oil and gas pipeline inventories and depressurisation rates were conducted and these suggested that emergency shutdown valves isolating the pipeline from the platform in some cases did not work and in others did not fully close so as to isolate the pipeline inventory. This accounted for the extended fires in Module B and the extended flaring observed.

All the evidence available either pointed exclusively, or was at least fully consistent with an explosion originating at the east end of Module C. There was no evidence that pointed exclusively to Module B. The questions that now needed to be addressed were the hydrocarbon source that fuelled the explosion and what flammable mass was required.

POTENTIAL FUEL SOURCES

A number of the observations pointed to the fuel source being *heavier-than-air* located in the eastern half of Module C. These observations were the low lying characteristics of the blue flash seen at the west face; the combustion effects seen in the ceiling above the condensate injection pumps at the 68′ level immediately following the explosion; the heat and lack of heat effects experienced by a number of the survivors in the immediate vicinity of Module C. The only *heavier-than-air* fuel source in the eastern end of Module C was condensate. The explosion experts analysed the explosion damage and believed that the explosion was created by a flammable mass of typically 40 to 60 kilograms of condensate. More complex explosion simulation modelling, using the FLACS Code were conducted. The results showed that sufficient overpressure could be generated from such a small cloud located at the east end of Module C to cause failure and break-up of the firewalls and subsequent failure of the 4" diameter condensate pipeline.

Following the survivors and eyewitness accounts being heard at the Public Inquiry, and as the evidence unfolded, it was decided to conduct wind tunnel tests simulating various types of hydrocarbon releases from various locations within Module C. The aim was to simulate the gas alarm pattern and generate the required flammable mass. The results showed that releases of *'heavier-than-air'* gas, such as condensate, were required to achieve the latter.

DEVELOPING AND REFINING ACCIDENT SCENARIOS

At the outset of the investigation there were two possible accident scenarios that had been developed during the Department of Energy's investigation and recorded in their interim report (Ref. 2). It was most important however not to concentrate solely on just these two possible causes but to ensure an open approach. Therefore a number of additional accident scenarios were developed early on in the investigations. These scenarios were based on typical failure mechanisms associated with items of equipment and piping, historical problems known on the platform and observations and experience of survivors and back-to-back personnel. There had to be a potential reason for their inclusion. As the eyewitness and technical data were assimilated, the accident scenarios were refined. They were presented before the Public Inquiry with the failure mechanisms identified and the circumstances necessary to cause the initial explosion being explained. In this way their reasonableness could be tested by the represented parties.

The wind tunnel simulation proved to be invaluable in showing trends and classes of release that could have caused the pattern of gas alarms witnessed by the control room operator. Of particular importance was the finding that to simulate the gap between the initial gas alarm and the subsequent flurry of gas alarms a two-stage release was required, the first stage being significantly smaller than the second stage. There were relatively few condensate sources in the eastern end of Module C. Of particular interest were the pressure safety valves associated with the condensate injection pumps located at the 68′ level below. The pressure safety valve (PSV-504) associated with the pump out of commission was known to have been removed for certification on the day of the accident and not replaced. The open-ended pipework required blind flanges to be fitted securely. It was known therefore that very shortly before the explosion there was the intent and opportunity to bring back into commission a condensate injection pump which was in an *irregular* condition.

A series of leak rate tests were conducted on various configurations of blind flange assemblies to determine under what conditions of bolt tightness leaks could occur. Further, *'state-of-the-art'* thermodynamic calculations simulating the repressurisation and depressurisation of the condensate injection pump were conducted. These calculations, together with the wind tunnel simulations, showed that, had the recommissioning of the condensate injection pump occurred in two stages (as was possible from the operator movements below at the 68′ level), then condensate released from an insecure blind flange assembly could have caused the pattern of gas alarms witnessed. Further wind tunnel simulations, together with FLACS explosion simulations, demonstrated a scientific consistency linking this accident scenario with the explosion and subsequent escalation. Furthermore, it was confirmed that the actions arising from the initial tripping of the condensate pump fully explained the sequence of alarms/trips and the increased flaring, witnessed before the initial explosion in Module C.

The PSV-504 scenario was the only scenario which could account for each piece of the *'jigsaw'*. No *'piece'* was left unaccounted or was forced to fit. No other accident scenario achieved this. As indicated already, Lord Cullen concluded that on the balance of probabilities the cause of the disaster was a release of condensate from the blind flange assembly at the site of PSV-504 which was not leak tight. (Ref. 1).

OBSERVATIONS AND CONCLUSIONS

The investigative process undertaken for the Public Inquiry followed the basic approach required to develop a technical case. This is shown schematically in Figure 1. (Ref. 3). The basic tasks were the preliminary identification of issues; securing the evidence; witness interviews/analysis; data/document retrieval; development of scenarios and data analysis; retention of experts; technical/scientific analysis and simulations; development of technical propositions; preparation and presentation of expert reports. The central column shown in Figure 1 represents the principal steps taken by the multi-disciplinary team whilst the activities of the experts are shown schematically to the left of the diagram. Whilst the Piper Alpha investigation was significantly more complex and required many iterations, the same principles were adopted. Any technical case must pass the test of *'reasonableness'*, it must be objective, inclusive of all known facts, self-consistent and technically correct.

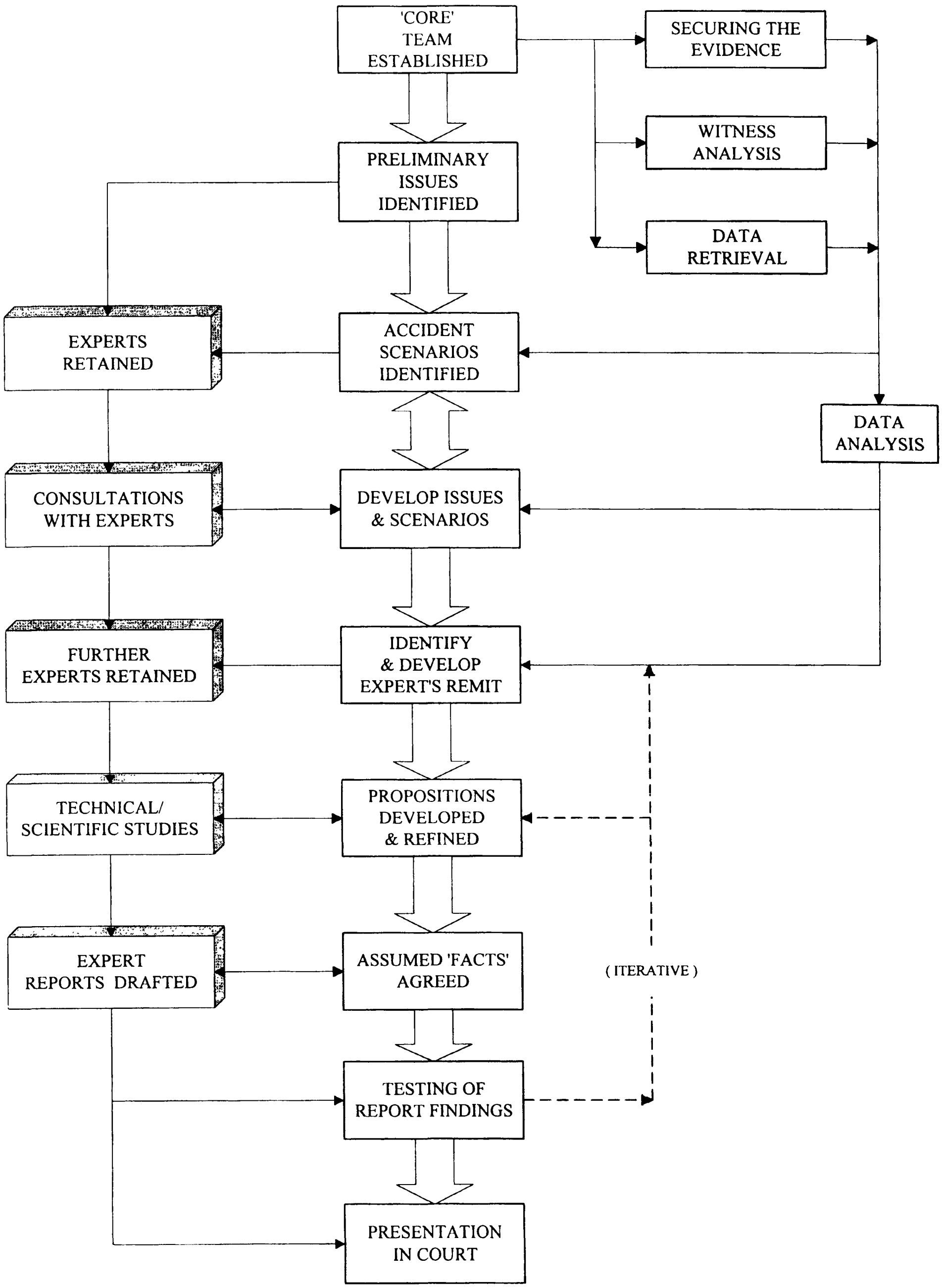


FIGURE 1

FLOWCHART SHOWING THE DEVELOPMENT OF A TECHNICAL CASE.

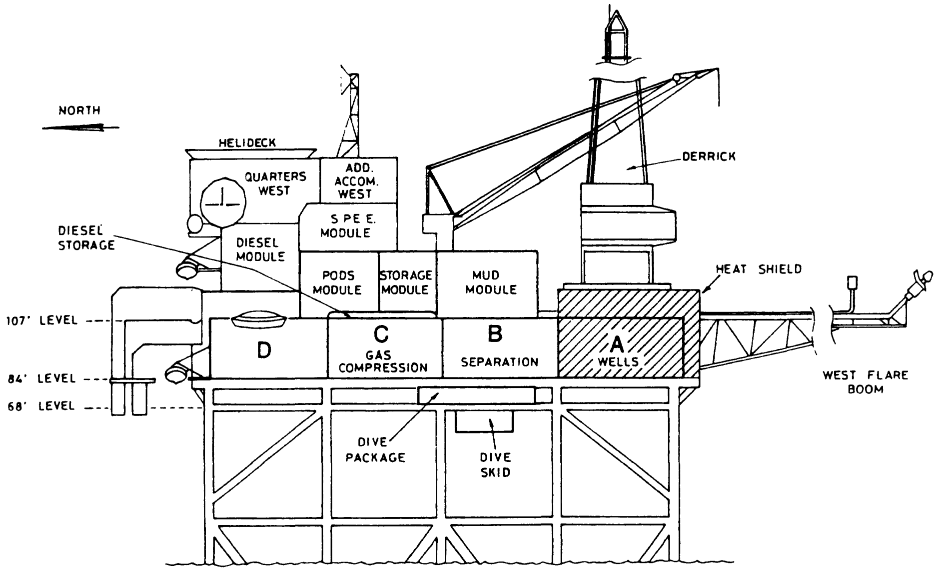


FIGURE 2 PIPER ALPHA - WEST ELEVATION

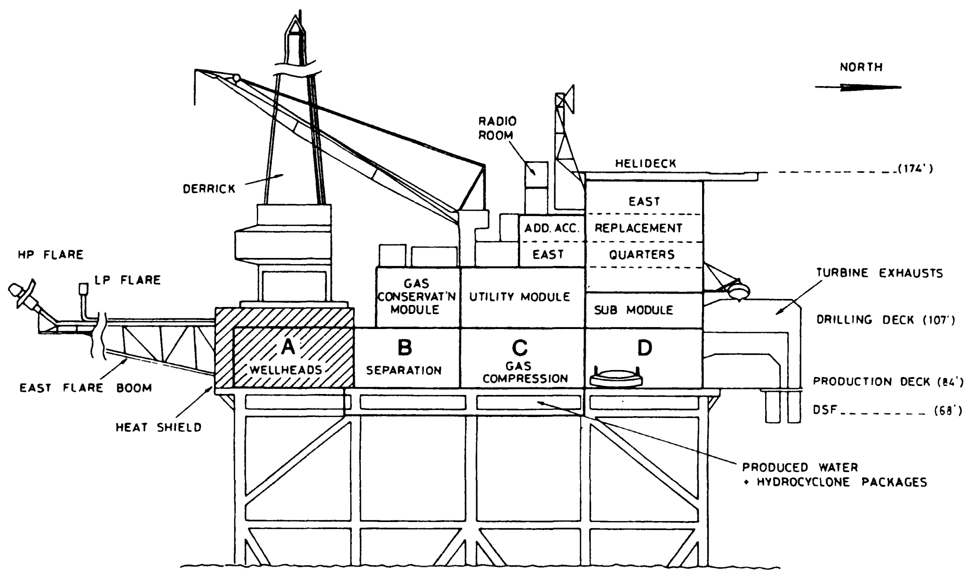


FIGURE 3 PIPER ALPHA - EAST ELEVATION

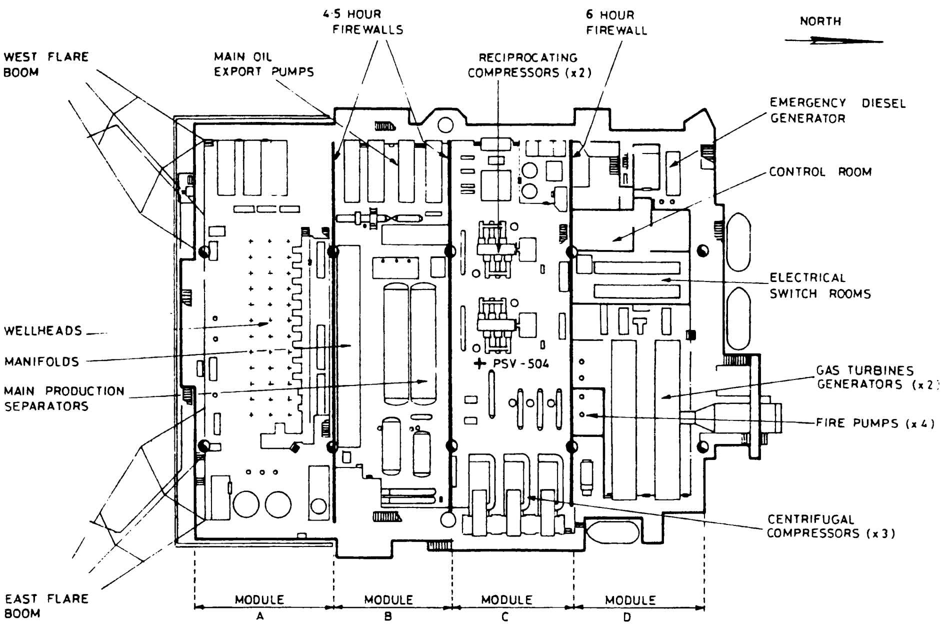


FIGURE 4 PIPER ALPHA – PRODUCTION (84 ft) LEVEL

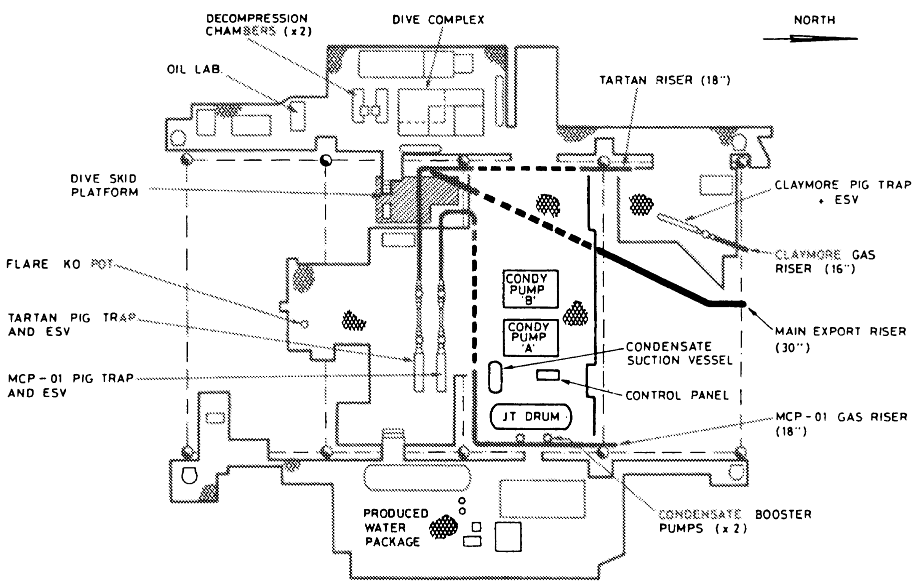


FIGURE 5

PIPER ALPHA – DECK SUPPORT FRAME (68 ft LEVEL)

The following observations, in my opinion, hold true not only in the Piper Alpha investigation but are universally applicable to the subject of forensic engineering and incident reconstruction:-

- It is a process of elimination where flexibility is essential. Jumping to conclusions too early is unacceptable. A multi-disciplinary approach, suitably objective and with a high degree of independence is highly recommended.

- Development of working hypothesis/scenarios encourages open-mindedness.

- Remember that the *'negative'* side can be as important as the *'positive'* side. For example, lack of damage or no observations can be of equal importance.

- Start with simple *'back-of-the-envelope'* calculations and progressively work to more complex analysis techniques when it is deemed necessary. Don't jump into the deep end unnecessarily!

- Where *'state-of-the-art'* technology/simulations are necessary, proceed with caution ensuring models/techniques are validated and pass the *'test of reasonableness'*. Also ensure the legal niceties regarding lodging of material and the presentation in Court are carefully considered well beforehand.

- Development of technical propositions formally identifies the technical/scientific steps that must be proved.

- Ensure that all facts are accounted for and that there are none inconsistent with the scenario being advanced - recognising the difficulties associated with eyewitnesses recollections and particularly timings.

- Whilst the failure mechanism and the consequences arising may be highly technical with a complex chain/interconnection of occurrences, consider the principle of *'Occam's razor'* to see whether the issue can be simplified.

- Remember it is the *'root cause'* of the incident/disaster that is important. A forensic analysis of a failed item forms only part of the overall jigsaw which must also take account of all human activities, management issues and the wider influences, such as regulatory control, design standards and inspections etc.

ACKNOWLEDGEMENTS
I would like to acknowledge the work of all the technical experts and the legal teams who assisted in the investigations for Lord Cullen's Public Inquiry and in the subsequent legal actions arising.

REFERENCES
1. *'The Public Inquiry into the Piper Alpha Disaster'* Lord Cullen, Department of Energy, HMSO. (November 1990).
2. *'Piper Alpha Technical Investigation - Interim report'*, U.K. Department of Energy, HMSO. (September 1988).
3. *'Developing the Technical Case - Experts Beware!'*, R. Sylvester-Evans, 5th IBC Conference entitled *'Emergencies'*. (September 1996).

Bucketwheel Reclaimer Collapse
New South Wales, Australia

DR PETER HO, Bsc. Ph.D., C.P.Eng., REPQ M.I.C.E., M.I.Struct.E., M.I.E.Aust., M.H.K.I.E. and ROBERT LEWIS, M.I.E. Aust., Directors of INCODE Pty Ltd, Forensic Engineers International, Australia

BACKGROUND

At approximately 2am on Tuesday, 22nd July 1986 a rail-mounted bucketwheel reclaimer weighing 680 tonne, which was part of a coal handling and preparation plant in New South Wales, collapsed when the structural boom supporting the counterweight ballast box failed. The ballast box (weighing 250 tonne) fell impacting the rear western side of the bucketwheel reclaimer causing catastrophic structural damage to the unit.

The reclaimer had been commissioned in 1985 and was able to traverse some 350 metres of rail track between two coal stockpiles running east and west and was designed to recover coal by grade and to deliver same via a conveyor running between the two stockpiles to an adjacent rail loading facility. The reclaimer rail bogies supported a base structure that spanned across the conveyor system running between the two stockpiles and supported, in turn, a circular gantry deck on which was constructed a slew mechanism. A tower or pylon had pivoted from its base, the bucketwheel boom, while to the immediate rear was the counterweight box supported by its structural boom. The slew deck which was integral with the base of the pylon had incorporated the switchroom, which housed the Programmable Logic Control (PLC), switchboards and controlling equipment for the unit. The bucketwheel boom was 50 metres in length and the control cabin was mounted on the end of same overlooking the bucketwheel that the unit's operation could be observed at all times.

Supporting connections ran from the top of the pylon to the extremities of the bucketwheel boom and the counterweight boom to complete the unit. The reclaimer boom was able to slew through 330° and luff above or below the horizontal as part of its operation. The reclaimer could be operated manually or through the PLC.

The specification for the unit required that all other necessary field devices for safe and efficient operation were to be included to prevent accidental collision and overload. In addition, the reclaimer had an onboard water system to spray down and clean coal dust build-up on the structure etc.

At the eastern end of the rail track, a storm park was installed and at this location the bucketwheel boom could be lowered onto a structural rest and the unit tied down during high winds and storm conditions. This was also the area where maintenance could be undertaken. The end of the track incorporated concrete based buffers onto which were mounted compressible cellular plastic buffer rubbers some 250mm diameter and 750mm in length.

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 138–147

Complementary buffer rubbers, as above, were mounted on the ends of each of the bucketwheel reclaimer bogies, however, these of the same diameter were only 250mm in length.

Sketches 'A' and 'B' attached outline the buffer installation.

FORENSIC ENGINEERING INVESTIGATIONS

The subsequent forensic engineering investigations into this major loss event confirmed again the importance of three basic forensic engineering principles:

1. The value of accurate and detailed inspection work immediately after the loss event;
2. The need to consider very basic engineering principles in establishing the performance of the reclaimer at the moment of collapse;
3. Acceptance that not all of the circumstances affecting the event will be immediately revealed when the "shock state" of people concerned leaves then unable to convey critical information.

On arriving at the scene of the collapsed unit by aircraft, careful observations were made immediately above the collapsed unit and it was noted that the 225 tonne counterweight box had not collapsed down directly behind the unit, but had rather swung, as it fell, to the side. This is shown on sketch 'C' attached.

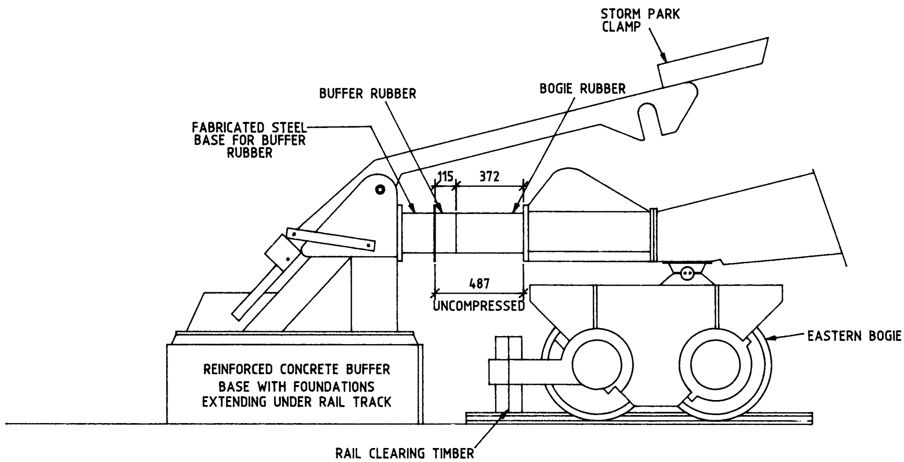
For this displacement of the counterweight box to the side it was immediately apparent that there had to have been one of three conditions applying, or a combination of these at the moment the unit collapsed:

1. *A lateral force applied to the counterweight box; and/or*
2. *A lack of symmetry in the structural adequacy of the K-framed supporting structure or boom to the counterweight box; and/or*
3. *The unit was under a dynamic state at the moment of collapse.*

Following this observation our forensic engineers moved to establish the dynamic condition of the counterweight boom at the moment of collapse. To achieve this, our forensic engineers proceeded to the point where the bucketwheel had been working immediately prior to the collapse. It was noted that the last cut in the coal pile was such that the sides of same were truly vertical and it could therefore be concluded quite positively that the bucketwheel reclaimer was neither slewing or travelling at the moment of collapse. It then became obvious that the failure of the counterweight structure down and to the side had to be the result of:

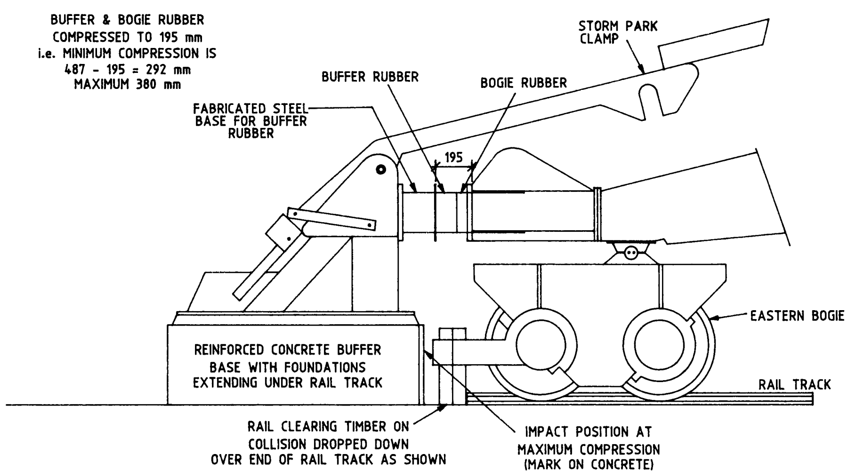
(a) either a lateral force applied to the counterweight or its supporting boom (structure); and/or

(b) an unsymmetrical condition in the K-braced counterweight boom (structure) which supported the counterweight.



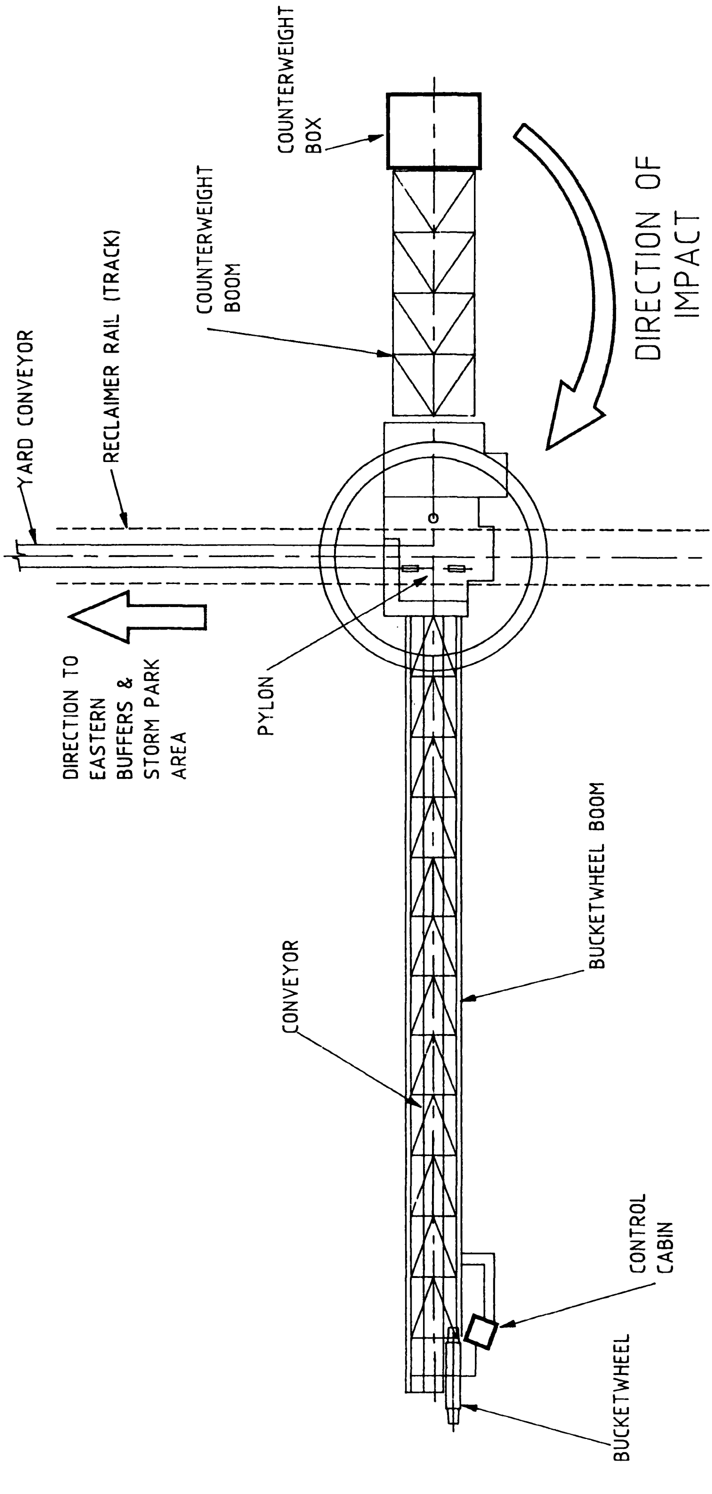
SKETCH 'A': BUFFER & EASTERN BOGIE IN REST POSITION (STORM PARK)

N.T.S.



SKETCH 'B': BUFFER & EASTERN BOGIE AFTER COLLISION 19 JULY 1986

N.T.S.



BUCKETWHEEL RECLAIMER - SKETCH PLAN SKETCH 'C'

N.T.S.

Consideration was given to the question as to whether there had been any collision with the two coal stackers operating adjacent to the bucketwheel reclaimer, however an anti-collision control system had been installed and the reclaimer's bucketwheel boom also incorporated safety crash-wires down either side so that it was clear the unit had not been subject to impact.

As with all major inspections, our forensic engineers moved over the site as quickly as possible, photographically recording the condition of all structures, materials etc. This is essential since it is always possible that evidence will be either deliberately or inadvertently moved or displaced so that conclusions cannot be effectively drawn as to the actual condition applying at the moment of failure or collapse.

A check on weather conditions at the time of the collapse revealed the site was not subject to excessive wind conditions so that the counterweight structure could not have had lateral wind loadings applied. In addition, the design of the unit incorporated controls such that when exposed to winds in excess of 20m/s the operation of the unit automatically stopped.

There was also, obviously, no external force applied to the structure which stood clear and proud in the air and our forensic engineers knew immediately that they had to look critically at the counterweight structure for some unsymmetrical condition which allowed the 225 tonne counterweight bin to fall to the side.

At this point it was reasoned there was one remaining structure which could give rise to unsymmetrical conditions in the counterweight boom and that was the buffers at either end of the rail track on which the unit operated, although the unit was not in the vicinity of either of the buffers when it collapsed.

A careful inspection of the buffer rubbers on the eastern end bogies and on the eastern end buffers revealed signs that these had been exposed to a recent heavy impact evident from the marking of the rubbers and some cellular failure in same. During this inspection, our forensic engineers observed at the eastern buffers two pieces of 150mm x 150mm hardwood timber, each approximately 600mm long, laying on the ground. A photograph of the buffers and these pieces of timber was taken at the time of this inspection. However, the consequence of the pieces of timber was not immediately appreciated.

On the second day of inspection, a helicopter was used to facilitate a more careful inspection of the total structure. The reclaimer had suffered very serious structural damage, the counterweight bin and contents had fallen, as described above, to the rear and to the side of the reclaimer and the electrical control room located at this point was completely crushed. The impact of such a considerable mass had caused partial collapse of the bogie system and forced the complete unit some 2½-3m off its rail tracks. The reclaimer weighing 680 tonne had suffered catastrophic damage such that a major rebuild of the reclaimer was required.

The helicopter allowed comparatively close-up photographs to be taken of the pylon and structural components which were otherwise inaccessible.

Inspection of the main member of the counterweight boom structure revealed rust in some fractures which indicated a prior failure was likely to have existed where these were apparent, although there was some difficulty in establishing the age of the rust deposition. Clearly, the bin had not fallen in a direct manner by gravity or radius from the counterweight arm pivot. From a study of the structure, it appeared that the boom failed upwards in the first instance so that the load commenced its descent without the column affect of the boom structure. Clearly the tie connection to the top of the pylon was not involved in the initial failure; it did not fail until the collapse sequence was well established, since had the ties been involved in the initial failure the counterweight bin would have free fallen about the counterweight boom structure pivot point onto the coal stack at the rear of the reclaimer. This observation, plus the corrosion deposits in the cracks on the counterweight boom structure failures, allowed our forensic engineers to draw an initial conclusion: that an unsymmetrical condition almost certainly existed in the counterweight boom structure immediately prior to its collapse and this encouraged them to return to the eastern buffers for a more detailed inspection.

At the same time, enquiries of the operator of the bucketwheel reclaimer, on duty at the time of the collapse, revealed that when the reclaimer was slewing just prior to its collapse, it seemed to operate fast-slow-fast-slow and the operator advised this was unusual and likened it to "a dog wagging its tail". This statement also supported our forensic engineers initial conclusion that an unsymmetrical structural condition and, possibly, a partial structural failure state existed in the counterweight structure bracing immediately prior to the its collapse.

On returning to further inspect the buffers, the forensic engineer noted the two pieces of 150mm x150mm hardwood timber had been removed, but it was clear these were part of a cleaning timber installed at the end of the reclaimer's eastern bogies to sweep the rail clear of any coal which might fall onto same during travel operations. From this further inspection it was concluded that the reclaimer had, in fact, struck the buffers and that the cleaning timbers sliding along the rail at the front of the bogies had dropped down at the end of the rail track with the full compression of the cellular buffer rubbers. It became obvious the cleaning timbers had locked the reclaimer up against the compressed buffers and that someone had cut the cleaning timbers away with a chain saw to release the reclaimer after it struck the buffers and came to rest locked against them.

Our forensic engineers recalled seeing sawdust at the buffers as they reconstructed what had happened and photographs taken during the initial inspection confirmed both the presence of the timber and the saw dust. A very careful examination of one of the reinforced concrete buffer pedestals revealed an impact mark on the face of same where the steel bracket on the end of the bogie unit had struck the pedestal as the buffer rubbers were fully compressed and could no longer resist the impact movement of the bogie. A check of the bracket supporting the rail cleaning timber on the end of the complementary bogie revealed fine concrete particles adhering to its leading edge. There was also some distortion of the bracket where it had struck the pedestal and it was concluded from the fine concrete particles that the impact was quite recent.

A brief study of the eastern buffer revealed that for the rail cleaning timbers to have passed over the end of the rail, the buffer rubbers had to be compressed not less than 290mm and not more than 360mm during the collision and deceleration of the reclaimer.

Our forensic engineers immediately they established the deceleration of the reclaimer carried out a very brief analysis of the structure, including the counterweight boom in terms of its adequacy to withstand the forces generated by this deceleration. This analysis revealed that the bracing in the counterweight boom would more than likely have been stressed beyond a safe limit at several locations.

Having concluded there was an impact with the buffers at the eastern end of the rail tracks, our forensic engineers immediately enquired of key operational personnel as to the performance of the reclaimer in the weeks leading up to the collapse incident. They learnt, after several enquiries, that the reclaimer had experienced an impact incident with the eastern buffers only 3 days prior to the collapse of the unit. When asked subsequently why details of this impact incident were not conveyed at the outset to our forensic engineers, the response was, "We didn't think this was important".

The question was also asked why engineers did not inspect the bucketwheel reclaimer structurally immediately after the impact incident since it should have been obvious that such an impact would have placed substantial loadings on the boom, tower and counterweight structures as 680 tonne of reclaimer moving at a velocity of up to 0.57m/sec came to rest in a distance of 290 to 360mm. The forces at play for such a deceleration were massive.

The reason given at the time for a structural engineering inspection not being carried out was that it was believed that the reclaimer had been designed to withstand impact with the buffers at full speed.

Our engineers were disappointed that details of the collision of the reclaimer with the immovable object (the buffers) 3 days prior to its catastrophic collapse had not been made clear at the outset of their investigations. That collision event had to be considered and should not have been a matter of discovery as a consequence of the investigations.

Forensic engineers are aware, however, that often factors clearly affecting the performance of a machine or structure during a failure incident will be deliberately withheld and sometimes overlooked. On other occasions the information will not be made readily available as a result of operators and others fearing to bring forward details that might reflect on their performance, safe practice, etc. There is also in many cases the shock or distress state that follows a major loss event when those involved are unable to communicate adequately and convey to forensic engineers all of the necessary details, background etc.

The buffer structures are of substantial reinforced concrete design upon which is incorporated compressible cellular plastic buffers. They also incorporate a latch to lock down the reclaimer once it is brought up to the buffers as part of the restraint of the reclaimer when it is at rest in the storm parking position.

For the reclaimer to be brought into the storm park area which is some 10 metres long, the unit must pass a limit switch which activates a striker on the reclaimer bogie. When tripped, this prevents the reclaimer from being operated from the control cabin at the end of the bucketwheel boom. The full speed velocity of the reclaimer is 0.57m/sec and once the limit switch has been engaged, the operator must leave his control cabin and go down to a position on the rail track and operate an inching button to bring the reclaimer at creep speed of 0.05m/sec until it comes to rest against the buffers.

After the reclaimer had travelled at creep speed and been inched into the storm park area, a second limit switch is engaged and this brings the reclaimer to a halt and the main circuit breaker opens. It is then necessary for the operator to bring in an electrician to the unit to restore power and in order to override this second limit control, the operator has to depress a bypass button before the second striker is tripped by the back-up limit switch.

When the control selector switch was in auto and after the limit switches were reset, the reclaimer could travel at full speed until the reclaimer hit the buffers.

Further investigations indicated that on the occasion when the reclaimer hit the buffers the operator had been instructed to wash down the reclaimer. The operator travelled the reclaimer in auto control until it reached the operational striker at which point he then moved the selector switch to local control. A second operator took over the control of the unit at this point and there is confusion as to just what the control mechanisms were and what operations were undertaken when the unit was brought into collision with the buffers.

It is not intended in this paper to set down the ongoing and very detailed work that followed on the failure mechanism, sequence etc, but the forensic engineering investigations concluded that it was the impact with the buffers 3 days prior that gave rise to the catastrophic collapse of the bucketwheel reclaimer. The investigations into causation, collapse sequence, etc that followed analysed in detail the counterweight structure and the operation of the reclaimer and the remedial works required to protect the reclaimer from a second event involved simple changes.

The owners of the reclaimer were very reluctant to see the reclaimer built “as-was” for obvious reasons, but it was finally returned to service very much “as was”, save the controls were modified to ensure that under no circumstances was it possible for the reclaimer to collide with the buffers at full speed.

CONCLUSION

The investigation proved once again the value of accurate and detailed forensic engineering inspection work immediately after a loss event, including the value of immediate photographic records. The engineer must accept that those concerned with a major loss may be in a shock state immediately after the incident and in this distressed or shock state which may last a day or two or a matter of weeks after the event, the forensic engineer may not have conveyed to him all of the information relevant to the incident. The intensity and length of this period of shock state depends on many variables, including the extent of the loss, financial and physical, health of the persons concerned, their character, strength of their organisation, management support, depth and capacity of their consultants and so on.

At the same time the engineer has to be concerned with those "leaning on a crutch". This is an expression used to describe the practise where those concerned find it easier to lean on others and say and do nothing. This results in inertia in communicating matters affecting the investigation and good forensic engineers acknowledge this condition and use that fact to drive their investigations forcibly and in detail.

A good forensic engineer should never excuse his failure to establish quickly causation by placing blame on those who experienced or witnessed or were part of the loss incident who in the circumstances were in a shock state and were unable to properly communicate.

His investigations must be intent and the photographic records at the outset can be invaluable.

The dramatic state of the collapsed 680 tonne bucketwheel reclaimer left most of those present at the site in a state where "they couldn't take their eyes off the debris". The two pieces of insignificant150mm x 150mm (6") cut timber were the key to establishing at the outset that there had been a significant impact event prior to the collapse of the reclaimer. By following up that evidence the chain of events leading to the final collapse was progressively revealed, the incident details established and the sequence of ongoing causation investigations was then clear cut.

THOROUGH INITIAL FORENSIC WORK OVERCOMES COMMUNICATION DIFFICULTIES AT MAJOR LOSS INVESTIGATIONS

Applying lessons from failures to management and design

JONATHAN G M WOOD Structural Studies & Design Ltd, Chiddingfold, Surrey, UK.
RAEng Visiting Professor Aston University.

INTRODUCTION

Over the last 35 years I have worked on the investigation of 'failures' of silos, box girders, bridges, tunnels and buildings and a miscellaneous assortment of other structures and objects. For the last 15 years much of this work has been on structures where the deterioration has been a major contributory factor. The details of these investigations were in reports to clients, some of which were used in litigation. Some clients and sometimes the courts require total confidentiality. Other clients have given permission for and on occasions encouraged, the use of results directly or indirectly in publications or to assist in the development of standards and industry guidance, some of which are referenced below.

'Failures' range in severity, being difficulties, problems, failures or collapses. It is worth distinguishing between the general run of difficulties and problems which are investigated and resolved in the normal course of engineering practice and the more limited range of failures and collapses which attract the attention of the media and lawyers and have been the main focus of this conference. If we can identify and analyse the difficulties and problems, particularly where they were 'near misses', and rapidly communicate the lessons to those dealing with similar situations, we can substantially reduce the risks of major failures and collapses, as well as the hazards of litigation. This will also help the process of successful innovation.

LINES OF COMMUNICATION

The routes and timescale for transferring information from failures to working engineers are uncertain. When the rare major 'political' structural collapses occur they have often triggered substantial programmes of investigation, research and accelerated rewriting of Standards and codes (eg Ronan Point and Milford Haven box girder collapse). Lesser failures are soon forgotten and the lessons are often not learned. Improved communication of data from failures to practising engineers, those who write codes and guidance and the research and teaching community is needed.

Lessons from failures must be communicated both within professions and between specialisations. This becomes more difficult as new sub-specialisations are regularly spawned and develop their own distinct languages. The unclear contractual interfaces and communication difficulties between specialisations are in themselves a frequent a contributory factor to failures. Similarly there is a need to communicate across the generations highlighted by a recent graduate's remark 'What was Ronan Point?'.

Structural Failures

Most structural failures occur deliberately in laboratory testing. The enormous body of published

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999, 148–156

research data provides an essential yardstick of the 'state of the art' for forensic investigation. There is a well established, but slow, route from structural research via publication in research or professional institution journals into the drafting of British Standards and Codes of Practice and industry guidance from the Institutions, CIRIA, BRE, TRL, Steel Construction Institute, Concrete Society and the wide range of other specialist organisations, as well as commercial documentation on specific products. Eurocodes have extended this chain of communication. This body of received good practice is the reference source for designers and contractors and their suppliers in their endeavour to act reasonably and minimise liabilities.

In the best engineering teams this codified and documented good practice is supplemented by the caution and experience of older members of the team in design or review and from the RE or contractor's staff considering the practicalities and safety of construction. However too frequently the letter of the codes, now often summarised in a computer package, is followed without considering if the structure and application are within the range considered by those who drafted the documents. This computerised code compliance works reasonably well for conventional structures, in part because of the generosity of the factors of safety used. However when unusual conditions or structures are involved problems can occur. When they do we must create a fast track to upgrade the codes and guidance.

Durability Failures

The poor durability of many 20th Century innovations in materials have become a matter of increasing concern and expense to owners [1] [2]. Durability research is inherently more difficult because the processes are long term, with complex interactions between materials and the microclimate, so they cannot be accelerated without distortion. Much short term durability research has misled. One can make and break a steel structure in a few days and a concrete one in a month, but durability tests take decades so we have to look for structures that have matured for decades and analyse their problems, preferably before they collapse [3]. The information necessary for improving design must largely come from the rigorous analysis of problems and failures in the field with complementary laboratory work [4] [5]. Much more work is needed in analysing durability failures and applying the lessons to design and specification if we are to avoid the waste of resources and environmental cost of premature reconstruction of our 20thC infrastructure.

Organisational Failures

In all investigations there is the narrow technical question of identifying the physical, chemical and occasionally biological reasons for the failure. There are also wider questions of why the circumstances which lead to the technical fault arose [6] [7]. These often relate to the gaps or ambiguities in the allocation of responsibilities for specification, design, construction, operation and maintenance or the inadequacies of time and resources for the work. Limitations in the technical competence of those involved and the availability of information to them are another recurrent feature of failures.

Impediments to Proper Communication

There is a natural human instinct to avoid association with failures and to seek to minimise their importance and impact. Even within major construction organisations, instances of failure are often hushed up, rather than being used to highlight the organisational and technical causes, so that all learn from the unpleasant experience and are less likely to repeat it.

Commercial organisations have similar approach and a tendency to divert attention from problems with products they are associated with, but they emphasise those of their competitors. These instincts to preserve market share and to communicate only the positive, spill over into and distort, the deliberations of the industry committees on Standards and guidance documents. Most people now apply a degree of scepticism when hearing of tobacco industry research on cancer and similar scepticism is prudent in evaluating construction research. I have drawn attention to these realities not because I think one can alter human nature or commercial instinct, but to highlight the need for the data from rigorous analysis to balance the commercial views. This is essential if we are to meet the long term interests of the customers of the construction industry. These customers, including Government, must provide more funding to facilitate this.

The customers of the construction industry, and many organisations in the construction industry, tend to react hastily to particular problems with structures and materials. Frequently there is a general ban or an aversion to the use of designs or materials with any indirect link to the early anecdotal reports of a failure. There is a heavy cost to the society from these disproportionate and unselective reactions which lead to the abandonment of established technologies in favour of the new and untried, which after a few years reveal their own problems. Promptly reported accurate diagnosis of the faulty details of design, materials and or construction and methods of avoiding the recurrence of problems by proper development will save resources and reduce risk.

Forensic Aspects

It is perhaps unfortunate that the narrow term 'forensic' (ie used in courts of law, OED) engineering has crept across the Atlantic, as most investigative work is carried out to diagnose and to identify solutions. Once investigation becomes overlaid by the legal process, which is adversarial and focusses on blame attribution, it becomes more difficult to draw balanced conclusions on the technical and organisational problems that lead to failure. Litigation can also delay or limit the dissemination of information. In some instances technical conclusions drawn by legal tribunals are wrong and this becomes apparent in reviews of failures using data from later research [8]. There could be considerable benefit from reviews of past failures with technical hindsight. This might be more beneficial than some of the 'Foresight' exercises that have recently been diverting Government.

Specific testing related to the features of a structure with problems can make a substantial contribution to available knowledge. Sometimes it needs the authority of a QC in litigation to justify the expenditure on rigorous testing (eg [9]). In litigation good test data is always stronger than theory and opinion, but if it is only available to the litigants the opportunity to reduce risk in the wider construction community is lost.

There is a risk that forensic engineering will become yet another distinct specialisation [10], with its own publications and conferences, apart from the wider established forums of the construction industry. Basic investigative skills should be one of the normal capabilities of all Chartered Engineers and training in them and in the lessons from failures should form part of all undergraduate courses and CPD. Each branch of engineering needs to have practising members who have further developed their investigative skills, often by working with the research community, in their specialities. Those who have investigated problems and failures can best assess and communicate the lessons in evolving improved designs. They need to ensure that this information is also packaged and routed into the development of standards and into the teaching process.

INNOVATION, FAILURE, OSTRACISM AND REDISCOVERY IN CONSTRUCTION

The changing fashions in the construction industry show cycles of enthusiastic innovation, then problems and failures, leading to abandonment and then with a new generation rediscovery. Many clients are risk averse and misguidedly avoid innovation. This aversion to innovation is not good for the industry or for clients, as proper innovation will reduce risks and improve value.

The development and popularisation of a new structural form or material, is often based more on enthusiasm than research. Then inadequate analysis and reporting of the difficulties and problems inevitably associated with innovation, lead to misunderstandings and a general ban, prejudice or a reluctance to use the form. The problems attract the attention of the Universities leading to programmes of research into the material and its use. This knowledge explosion often coincides with the commercial death of the structural form. Examples of this including box girder bridges [11] [12], post tensioned concrete bridges, high aluminum cement, epoxy coated reinforcement, GRC etc. Then 20 or 30 years later the pendulum swings back. The true potential of the material, when properly used, then becomes apparent and it enjoys a rejuvenation in the market place. If we are to avoid the economic damage that these wide swings in construction fashion produce, we need more rigorous step by step development of innovative structures and materials so that they are not used inappropriately and the early warning signs of their limitations are identified, investigated and communicated.

One result of innovation problems has been the growth of a large list of 'Excluded materials' in construction contracts. BRE and some property owners are now seeking to review and correct these lists [13] [14]. Many of the problems related to the misuse of materials in specific adverse conditions, but the materials can be used satisfactorily in many applications. With our improving methods of analysing failures, particularly those associated with materials, we need to review old reports and revise and refine earlier conclusions. Even where original investigations correctly identified causes, the public perception often retains the misunderstandings from early reports (eg misattribution of early cases of AAR to marine source of aggregate, ‘HAC’ failures which were largely due to poor details and tolerances). To obtaining a balanced picture one must combine ‘failure’ investigations with ‘success’ investigations of proven use.

BROADENING THE OBJECTIVES AND BUDGETS OF FAILURE INVESTIGATION

The primary questions in investigation are ‘What has gone wrong?’ ‘How do we put it right?’ and then ‘Who pays for it?’, at which stage it tends to become forensic with lawyers involved! These are generally regarded as closed questions within the framework of a specific contract and often there is no budget, time or inclination from the parties that the wider lessons should be learnt.

For the more senior members in contracting and consulting engineering organisations there should be a commercial concern to ensure that the lessons from any problem are properly communicated within their organisations and the industry, as the financial penalties and, where safety is concerned, the legal penalties, of a further problem may be more major. They should ensure that this is resourced and funded. For engineers who are members of the professional institutions there is also a need to communicate information on particular hazards to their fellow professionals through SCOSS or by the publication of notes or reports in journals.

Where public safety or the safety of employees is concerned the heavier duties imposed by Health & Safety legislation arise. There is a conflict between the obligations of companies and individuals to act reasonably to properly communicate risks to their employees and the public and their wish to keep commercially confidential the risks associated with their products. When parties to litigation settle and agree to keep all documents and test data confidential they may be failing in their duty to act reasonably to minimise risks to their employees and the public.

DEFICIENCIES IN STANDARDS AND GUIDANCE

The law has 2 yardsticks for engineering performance, reasonable good practice and fitness for purpose.

Many failures I have investigated have been due to ignorance of reasonable good practice by those involved in design and/or construction. Sometimes this is because the contractual arrangements have given responsibilities to those with inadequate training, experience or qualifications. This is often a consequence of design and build contracts taken on by those with experience of building, but not design.

A more difficult situation arises for the working engineer and in litigation, when structures fail to be 'fit for purpose' despite complying with 'reasonable good practice' as set out in British Standards, BRE Digests, CIRIA Reports and documents produced by commercial bodies. This can occur when revisions to standards lag behind developing knowledge and innovations in design. It also occurs when standards make simplifications appropriate to a limited range of conditions without making this clear. Accelerating the feedback from construction problems to the Codes and guidance documents to eliminate these flaws in codes should have high priority.

Loading

Developments in high rise racking and rolling library storage have increased loadings on structures and their sensitivity to deflections. Because information in BRE Information Paper 19/87, which recommended a revision of BS 6399:1984, was not consulted by a specifier who relied just on the BS, a warehouse floor had to be rebuilt at the cost of over £1,000,000.

Limitations of in BS153 HA loading for long span bridges, which became apparent during the Merrison checks in the 1970s on the Severn Bridge, showed that it underestimated traffic loading by a factor of three even before the effects of increased permitted vehicle weights. When the load intensity was estimated in the 1940s it was assumed that vehicles would be spaced further apart on long spans. Should the designers in the 1960s have checked this when embarking on a project of such magnitude? In that instance the Department of Transport as client was able to rapidly bring in the revised loadings for appraisal and for design to BS5400. This rapid reaction will become more difficult as the Highways Agency seeks to shed responsibility for design standards by limiting contract requirements to broad performance objectives [15] .

Old Structures

Appraisals of older structures frequently reveal details, original design assumptions or structural problems requiring investigation. Sometimes changes in use or our better knowledge of structural behaviour show old structures to have a lesser factor of safety than originally intended and that now required. The IStructE 'Appraisal of Existing Structures' [16] provides an excellent summary of information gained from such investigations.

Durability

Standards relating to the durability of 20thC materials, like reinforced concrete, have a particularly poor record of delivering fitness for purpose. There have been improvements as CP114 developed via CP110 to BS8110 and now Eurocodes. However the lack of a factor of safety in durability design, the industry pressure to simplify specification and minimise cost and the poor detailing of designs which create aggressive conditions and make the achievement of correct covers and compaction difficult, will ensure that durability problems will continue to plague building owners.

The detailed analysis of the slow realisation of the industry of the problems from chlorides in concrete and progressive changes in standards in UK and US has been published by CIRIA [17]. This well illustrates the slow timescale from the realisation of problems to the application of data from failure investigation in standards. For concrete in the most severe conditions of chloride exposure these developments continue [18].

Alkali Aggregate was first identified as causing serious structural problems in the UK at Charles Cross Car Park in Plymouth in 1975. Data from detailed investigations of the many structures which have been damaged by AAR, some of which lead to litigation, have substantially contributed to the development of recommendations for dealing with structures with AAR [19] [20] and in the developing the recommendations for minimising the risk in new construction [21]. However the current specification recommendations for general construction need specific development for major projects [22] and long life structures particularly for the severe conditions in tunnels and dams revealed by investigations.

Silos

Silos are produced from kits of standard parts by design and build contractors for a competitive market which demands ever larger sizes and where price is more important than safety. They are particularly prone to failures [23] and litigation. Failure investigations (eg appended Data Sheet) have provided much of the information for improved standards [24] and guidance [25].

FORMAT FOR COMMUNICATION OF FAILURES

SCOSS has done excellent service in reviewing and publicising a wide range of structural risks and its periodic summary reports [26] are widely circulated and read. NCE provides early information on major failures world wide, but the detail that emerges from full investigation is seldom available until much later, if at all. NCE [27] are advocating better reporting of failures.

To better communicate the information from failures throughout the construction industry we must bridge the gap between those with the knowledge of failures to the specific individuals who need to know now or in the future. This may be done directly, as a summary, or indirectly by the updating of the standards and guidance on which most engineers rely.

We are all already swamped with information and are only interested in the failures which relate to the work we are currently involved with. Unless we use information technology to sort out the subsets of failure details which relate to the work of particular groups of engineers we will not successfully deliver the information. Similarly information technology will enable us to deliver these selected sets more quickly.

The essential requirement is the distillation of the key facts from the mass of information which start to accumulate when things go wrong. For most of the investigations I have been concerned with this could be achieved as follows:

- ***Summary,*** key word style 3 lines max. referring to
  - ***Data sheet,*** one A4 sheet, text with up to 3 photos or diagrams referring to:
    - ***Published reports,*** (eg [28]) based on and possibly referring to the existence of:
      - ***Detailed reports***, possibly confidential, prepared on the failure.

Selected sets of A4 data sheets could be bound into design and site office sets related to particular activities, especially where hazards are known to be high (eg crane failures during site operations, erection stages of major bridges, bored tunnelling operations, NATM tunnelling, punching failures of flat slab structures, corrosion in prestressing, weld failures, trench wall collapses, barrier failures on car parks and bridges, etc., etc.). The most important historical cases and international experience should be included.

SCOSS would be a suitable organisation to set the format and ground rules for the summary and A4 data sheets and their dissemination in traditional and/or electronic format. A possible format, with data on the first collapse I investigated, is appended to this paper. Using the format many organisations could prepare data sheets, and subject to review for accuracy, make them available.

Difficulties would arise where there was inadequate data to clarify the causes of failure and/or a dispute. This could be overcome if the ground rules for the A4 data sheet required agreed facts to be separated from a list of all possible causes of the failure, with reference to any documents supporting particular views.

Early after a significant incident a provisional data sheet could be produced which could be revised as each stage of the investigations were concluded. This would accelerate the dissemination on items now covered by SCOSS's periodic summaries.

CONCLUSIONS

There are substantial benefits to the construction industry and to its customers from improving the quality and speed of communication of information from failures, whether they are difficulties, problems, failures or collapses.

The analysis of the causes of failures must include the organisational and contractual circumstances and staff training and qualification which lead to technical failures, as well as the technical analysis.

Successful innovation and the orderly development of contracts and site organisations, designs and construction has been disrupted and distorted by

1. Lack of properly funded development stages of innovation, with proper diagnosis of early difficulties and problems before major failures occur.
2. Failures to identify and find remedies for the detailed localised causes of failures leading to a generalised prejudice and contractual exclusion against sound engineering designs and materials .
3. The slow process of developing quality guidance and standards and rapidly and correctly incorporating the lessons of failures in them,

The development of a standard format for a failure data sheet and procedures for electronic sorting and dissemination, could provide a means of reduce risks and speeding the development of improved contracts, designs, materials and construction procedures

The development of an accurate data base of important failures worldwide would be an invaluable resource in University teaching, CPD, training in design offices and on site, and for the organisations which develop design guidance and standards.

Failure Data Sheet: Farm Forage Silo Collapse. 1965

Summary: A bolted vitreous enamel steel sheet forage tower silo 15m high 5.6m diameter collapsed following the progressive shearing of bolts up the vertical lap bolted joint. Silage pressures in excess of design values and stress concentrations on bolts lead to failure initiation.

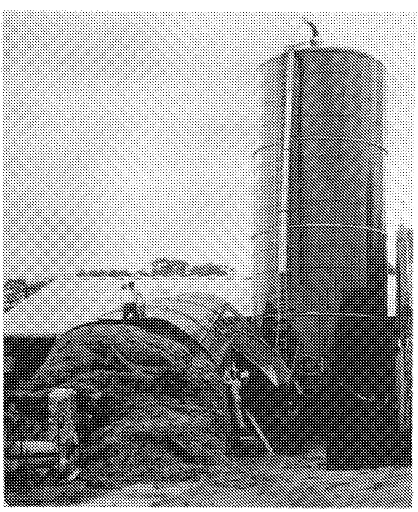
Structure: The silo was one of a pair constructed on a dairy farm in the Scottish borders in 1963. The cylindrical silos 5.6m diameter and 15m high were constructed of vitreous enamelled 1.8m x 0.9m steel sheets with vertical and horizontal bolted lap joints. Sheet thickness was 4.7mm for lower rings to 2.4mm for upper section. One sheet per ring had a large manhole and door which was immediately adjacent to the bolted joint at lower levels.

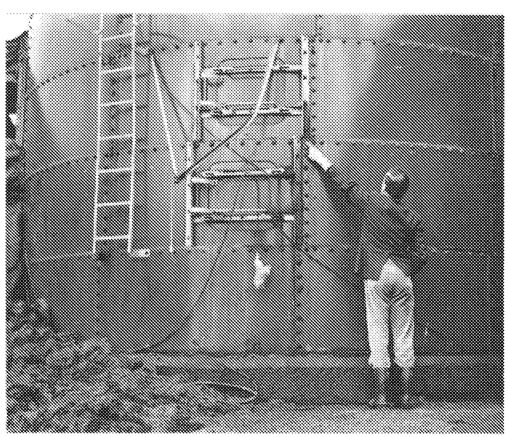
Use: The two silos had been successfully used in 1963 and '64 for young slightly wilted grass, but with some effluent. Both silos had been filled in 1965 and after settlement further filling was planned. The silo which failed had been filled in May and June with three layers of young grass the lowest of which was 75 to 80% mc, at higher levels it was drier at 60 to 70%. There was a large amount of effluent seepage exuded from joints at the lower levels.

Failure sequence: At 0730 and again at 1130 on 2nd August two bolts at the double lap between vertical and horizontal joints between rings two and three up had failed in shear. The progressive spread of bolt shear failures down and up to 6m was observed between 1350 and 1420 when the silo collapsed, Photo 1. Photo 2 shows, on the other silo, the bolts which initially failed.

Assessment: The silo was designed for fibrous maize and alfalfa crops which can be wilted to part dry in US conditions. The young compressible grass and more difficult weather conditions in UK gave much higher pressures. The bolted joint strength, designed assuming uniform load per bolt, was reduced by the drilling of holes for a cylindrical geometry but assembly as conical, the manhole adjacent to joint, the use of fully threaded bolts which sheared on the weaker threaded section, some corrosion from acid effluent. Report by W F Cassie and J G M Wood 12.1.66, details from SS&D, Northbridge Ho. Chiddingfold GU8 4UU.

Actions: Report on failure to manufacture used to improve designs and instructions for use. Data from collapse was used in research (PhD Thesis, J G M Wood, Univ. of Newcastle on Tyne 1970) and in developing BS5061:1974 for forage tower silos. See 'Greater Safety on the Farm- a standard for tower silos', BSI News May 1974.





REFERENCES

1 Wood J G M, "Durability design: applying data from materials research and deteriorated structures", 'Bridge Management 3', Ed. J Harding et al, Spon, 1996.

2 Gerwick B C, "The Economic Aspects of Durability - How much added expense can be justified?" pp. 1-19 Proc. Symp. 'Durability of Concrete', Ed. Khayat K H, ACI/ CANMET, Nice, 1994.

3 Woodward R J and Williams F W, "Collapse of Ynys-Y-Gwas Bridge, West Glamorgan". pp 635 - 669, Proc. Instn. Civ. Engrs, Pt 1, 4. August 1988.

4 Wood J G M and Crerar J, "Analysis of chloride ingress variability for the Tay road bridge", 'Structural Faults & Repair - 95'. Ed. M.C. Forde, Edinburgh, 1995.

5 Wood J G M, Nixon P and Livesey P, "Relating ASR damage to concrete composition and environment", pp450-457 'Alkali-Aggregate Reaction in Concrete', Ed. Shayan A, 10th Int. Conf. Melbourne 1996.

6 Walker A C, "Study and Analysis of 120 Cases of Structural Failures" Proc. of Symposium on Structural Failures in Buildings, IStructE, London April 1980.

7 Report of the Royal Commission, 'Failure of West Gate Bridge', Melbourne 1971.

8 Burland J, "Ground structure interaction: Does the answer lie in the soil?" in preparation, The Structural Engineer, 1998

9 Wood J G M, Chrisp T M, & Blackler M J, "Comparison of Model and Full-Scale Test Results with Simplified and Finite Element Analysis of Eccentrically Discharged Silos". ISO/FIP. Int. Conf. on Silos, Karlsruhe, W.Germany, October 1988.

10 Carper K L, "Current structural safety topics in North America", The Structural Engineer, June 1998

11 Inst. of Civil Engineers "Steel Box Girder Bridges" Proc. Int. Conf, ICE, London, 1972.

12 Rockey K C & Evans H R, "The Design of Steel Bridges", Granada, London, 1981.

13 BRE Digest 425 "List of excluded materials : a change in practice", 1997.

14 BCO/BPF "Good practice in the selection of construction materials" BCO/BPF 1997.

15 Pickett A, "Global Overview", IABSE Henderson Colloquium on Design, 1998.

16 IStuctE "Appraisal of Existing Structures" 2nd Edition SETO, London, 1996.

17 Pullar-Strecker P, Appendix to "Corrosion Damaged Concrete, assessment and repair" CIRIA Butterworths 1987

18 Wood J G M, "Achieving Durable Concrete", 'Prediction of Concrete Durability', Proc. STATS 21st Conf. London 16.11.95. Glanville J & Neville A (Ed), Spon.1997

19 The Institution of Structural Engineers, "Structural Effects of Alkali-Silica Reaction", Technical Guidance on Appraisal of Existing Structures", London, 1992.

20 Wood J G M & Johnson R A, "The Appraisal and Maintenance of Structures with Alkali Silica Reaction." The Structural Engineer, 71, 2 pp 19-23, 19th January 1993

21 Hawkins M R (Chairman), "ASR - Minimising the Risk of Damage to Concrete - Guidance Notes and Model Specification Clauses", Concrete Society TR30, 1995.

22 Wood J G M, "Some Overseas Experience of Alkali Aggregate Reaction and its Prevention:- Specification for Major Projects: Bridges, Tunnels and Dams." ITBTP Annales. Paris, No 518, Nov 1993.

23 Wood J G M, "Silos: Evolution by Failure", Structural Engineering Int., May 1997.

24 BS5061:1974 "Specification for Cylindrical Forage Tower Silos and Recommendations for their Use". BSI London, 1974.

25 BSI/BMHB 'Silos: Draft Design Code'. BSI and BMHB, London 1987.

26 SCOSS Report Summary "Structural Safety 1994-96" January 1997.

27 Parker D "Speaking out for Safety", pp 20-21, New Civil Engineer, 9/16 April 1998.

28 Chapman J C, "Collapse of the Ramsgate Walkway", The Structural Engineer, Jan 1998.

Application of computer technology

PETER GARDNER
Head of construction and Research, Southampton Institute, Southampton, UK and Convenor of the Institution of Structural Engineers' Study Group on Computers in Structural Engineering

INTRODUCTION

The use of computers in engineering and particularly engineering design, is becoming widespread. Design is a process that relies heavily on mathematical analysis and the computer is capable of performing large amounts of calculation very rapidly. Over the last decade there has been a dramatic increase in the development of applications packages used to assist design engineers. The computer has also influenced almost every other aspect of construction. Drawings are produced on CAD packages, work is programmed on computer, cost and quantities are analysed electronically, and designers and contractors have the capacity to communicate via their computers. Given this widespread adoption of computer technology by the construction industry and every other branch of engineering, it seems probable that the computer will have some role to play in any forensic investigation. This paper investigates issues relating to the computer's contribution to error, ways in which risk can be minimised and the use of computers to aid forensic investigation.

THE ROLE OF COMPUTERS IN ENGINEERING PROJECTS

The computer is such a powerful tool and its influence so profound that it cannot have a neutral effect on the execution of engineering projects. The first use of computers was restricted to large mainframes running complex analytical programs in batch mode. They usually addressed specific problems which sat in isolation. Gradually the increasing power, and reducing cost and size of hardware, coupled with the increasing scope of software, saw an infiltration into almost all aspects of an engineering project.

There are two principal driving forces for this increasing use of computers:

- Increased efficiency
- Enhanced engineering understanding

Both are critically important to forensic investigation.

Until recently development has concentrated on ever more sophisticated and wide ranging applications, each addressing specific themes. However, we are now entering a new phase of development - that of integrated systems. The previously separate packages are now being linked together in whole systems which effectively automate parts of the engineering process. Packages pass data automatically between applications, effectively producing a unified design, construction and management tool. This development is predicted to have a profound effect on the operation of design and construction and carries with it opportunities and costs.

Forensic engineering: a professional approach to investigation. Thomas Telford, 1999

THE COMPUTER'S CONTRIBUTION TO ERROR

Unless a full scale destructive test is carried out on each and every structure, some form of modelling must be conducted to enable engineers to predict behaviour. Modelling involves producing a simplified and idealised representation of a real structure that enables analysis to be performed, and which in turn allows the design of the structure in question. The mathematical analysis can be carried out manually but increasingly utilised a computer.

The modelling process as applied to computer assisted design is shown diagrammatically in figure one. The real world structure is converted into a conceptual model. Software is selected that is used to analyse the model. The result of this analysis is taken to predict the behaviour of the real world structure.

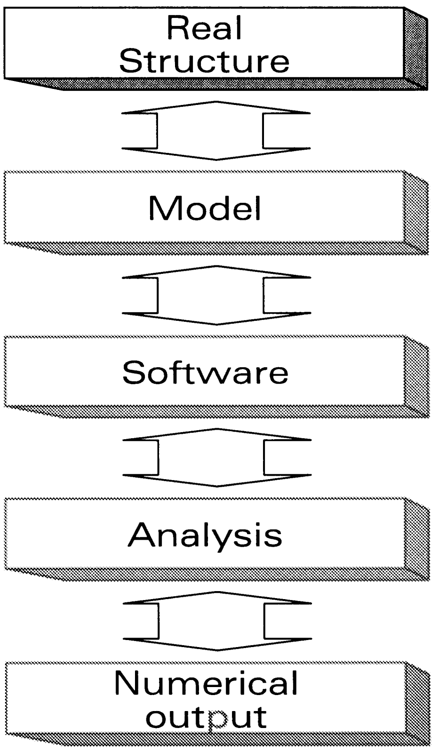


Figure 1. Diagrammatic representation of design process

(Reproduced from Gardner and Dobson, 1997)

Any form of error throughout the stages of this process may lead to inappropriate design. Error can take many forms: arithmetic, error, error in software coding, or error in assumptions used to create the model. Although there are probably coding errors in some software, the evidence available to date suggests that the greatest danger lies in error in the modelling process rather than the computational process. Numerous assumptions are made during the design process and a false assumption can still produce what appears to be a valid solution. The difficulty lies in the fact that the solution applies to a theoretical structure which may not behave in the same way as the real structure. This type or error can be particularly difficult to identify.

It must be recognised that there has always been the potential for error in engineering design. However computers do bring new factors to bear. Software effectively codifies engineering knowledge, which can lead to the false assumption that the expertise is held by the computer. Even though the computer can perform analysis at breathtaking speed with very high levels of accuracy, it is essential that the judgemental decisions that are so important to engineering design are taken by experienced engineers. However there is evidence to suggest that in some cases the power of the software is encouraging those with inadequate structural training or knowledge to engage in analysis and design (SCOSS, 1994) and in others that over-reliance is being placed in computer generated output.

There are thankfully few examples where the computer has had a significant hand in catastrophic error but there are many examples of less significant error. As the use of computers becomes widespread, they will inevitably attract more attention in forensic investigation, as they are more likely to have featured in the design, construction and operation of the facility in question.

There are two well-known collapses that are attributed, at least in part, to computers.

Hartford Stadium, Connecticut, USA

The Civic Centre in Hartford Connecticut, USA consisted of 2½ acres of roof supported on only four columns. In 1978 when loaded with snow (but fortunately empty of spectators), it collapsed. The complex roof was designed with considerable computer assistance and would have been virtually impossible to design manually.

The collapse was attributed to two factors: a joint with eccentricity was assumed in the computer model to have no eccentricity, and a strut was assumed to be braced when in fact it was not. The strut that initiated the failure had a capacity of 9% of that assumed in the design. The actual deflection was twice that estimated by the computer analysis.

Despite the heavy snow load, the imposed loads were well within the design loads. It is reported that the structure exhibited signs of distress during construction and in its subsequent operation but that these warnings were ignored.

Sleipner Offshore Platform

Sleipner was an offshore oil structure constructed in Norway. In 1991 it suffered a catastrophic collapse. The computer analysis was complex, using finite element analysis. It is reported that an error in the generation of the finite element mesh gave a poor representation of the shear forces at a critical joint, which resulted in a 45% under-estimate of the shear force. The joint was also poorly detailed. The combination of these two factors led to its failure and the subsequent loss of the whole structure.

Lessons from Hartford and Sleipner

Both structures were highly complex and relied on the computer for analysis. In the case of the Hartford Stadium, it could be argued that the availability of the computer had encouraged a more complex design, which exacerbated the problem. A simpler structure would have been easier to check with manual calculations. The construction of the Sleipner platform probably could not have been made significantly simpler but the error here seems to be that the full implications of the design's complexity had not been appreciated.

Both structures were represented by models which were not sufficiently representative of the actual structure to give reliable results. Despite the magnitude of these errors, in both cases the collapse was attributed to a combination of factors, rather than a single error.

Other Errors

There must be many other errors of a lesser magnitude that have gone undetected. The American Society of Civil Engineers (ASCE) has catalogued error it has identified in an attempt to learn and improve. ASCE collected data on 52 cases of error relating to the use of computers. Of those, 17% were caused by hardware, 25% by software and the remaining 58% by some form of user error. These figures must be viewed as indicative at best, as they are based on small samples and there must be a vested interest in not disclosing information of this type. Also the consequences of the errors vary enormously. Thankfully, only two of the 52 cases resulted in catastrophic failure (one of which was the Sleipner Platform referred to above).

Some of the errors identified by ASCE were:

- Chip problems affecting floating point calculations.
- Bug in software caused contractors to under-bid for a project by $250,000.
- Incorrect modelling and input data caused over estimation of factor of safety.
- Five nuclear power plants were shut down when a seismic analysis showed to be flawed (the plants were re-opened when re-analysis proved inadequate design).
- Software underestimated steel required in reinforced columns.
- An incorrect modelling assumption led to columns in a high-rise reinforced concrete block getting bigger towards the top of the building.
- A large concrete airport hangar was designed without the inclusion of it self-weight.

(Source. Rens, 1998)

THE COMPUTER'S CONTRIBUTION TO ERROR REDUCTION

Errors will always occur and there are no errors that can be completely blamed on the computer. All error eventually links back to people.

It is reasonable to assume that in a computer-assisted environment, some errors would have occurred had the design been produced manually and will be averted in a computer-assisted environment. 3D models will considerably reduce construction 'lack of fit' problems and will allow analysis of some factors that previously relied on empirical design. Manual calculation must occasionally involve simple arithmetic error and computers will virtually eliminate this form or error.

It therefore follows that there may be structures that would have collapsed had they been manually designed but as a result of computer design are happily performing their intended function. These are computer averted disasters.

THE COMPUTER'S CONTRIBUTION TO INVESTIGATION

Although the computer can be a contributory factor in error or collapse, and this paper has concentrated on this aspect, the computer also has a significant role to play in technical investigation of failed projects.

The analytical power of the computer and the advanced nature of modern software, enables sophisticated analysis to be performed in virtually any situation, given the resources and expertise to mount a detailed investigation. Software in general, and finite element software in particular, can be used to model many static and dynamic problems. It is also possible to investigate large numbers of 'what if' scenarios. This places a very powerful tool at the disposal of the forensic investigator.

Consulting engineers have gained experience of complex analysis and can use this experience to assist with investigation. It is now possible to model very complex stress distributions, the dynamic behaviour of structures, the progress of fire in structures and just about any other characteristic that warrants investigation. To illustrate this point some of the more unusual investigations that have been reported are:

- Stress distribution in under-garments, with the aim of designing more comfortable underwear.
- The flight characteristics of a football, with the aim of enhancing its performance.
- Pressure distribution in bedridden patients, with the aim of reducing the occurrence of bedsores.

These examples suggest that it is possible to model and analyse just about any problem, given adequate resources.

In addition to the technical assessment of a failure, an investigation should ascertain whether computer tools were used in an appropriate manner. A number of organisations have published guidance on good practice. Failure to follow good management practice could be a contributory factor in failure.

GETTING THE BENEFITS WHILST AVOIDING THE PITFALLS

Although some still argue against the widespread use of computers, it is generally accepted that they are here to stay and they do produce benefits (particularly in terms of productivity). It then becomes critically important to achieve the potential advantage without increasing risk. This can only be achieved with adequate management controls.

Various bodies have provided guidance on good practice. NAFEMS, the association for finite element methods and standards, has produced guidance on management and technical issues relating to finite element analysis. Their work amounts to a philosophy for safe finite element analysis and revolves around a combination of an appropriately experienced analyst, computer tools and a professional support environment (NAFEMS, 1995). Although their guidance is provided in the context of finite element analysis, the principles apply to all forms of analysis and design.

The Steel Construction Institute (SCI) have also produced guidance on modelling steel structures for computer analysis (SCI, 1995). They reiterate the importance of engineers developing a qualitative understanding of structural behaviour, which they argue is critical to create appropriate models and particularly to appraise the results. The Institution of Structural Engineers has set up a task group to produce guidelines which would have more general application and apply to most forms of engineering design (ISE, 1998).

The key issues connected with safer computing revolve around using adequately qualified staff and having management systems in place that provide checks on the models used, the software (and hardware) selected and the output produced.

The experience of qualified staff should enable appropriate models to be developed and for a 'feel' for correct solutions to be developed. The complexity of the scheme is an important factor. Unnecessary complexity should be avoided as it makes it more difficult to develop an intuitive understanding of behaviour. However some structures by their very nature are highly complex and should only be designed by appropriately experienced staff.

A philosophy of validation and verification should be adopted. Checks and controls can be built into the process, which enable the following questions to be answered: Is the model appropriate, is the software suitable to analyse the model, has the software been adequately tested, is the hardware capable of running the software, are the results consistent with the expected solution? Above all, don't have blind faith in computer based output.

One technique that can be particularly useful in validating outputs is to perform an independent analysis on a simplified version of the structure. This could take the form of manual calculations or an alternative computer analysis. The simplicity allows for rapid calculation but more importantly provides a solution that can be readily understood. The scope obviously depends on the complexity of the original structure but often provides a good approximation to the final solution.

Training is also essential. Software can be complex and has its limitations. As programs become more user friendly the assumption that one does not need specialist knowledge or training to operate software should be avoided.

It is the adoption of constant checking and challenging of basic assumptions that is the key to avoiding error. With the benefit of hindsight, many of the problems that have occurred have exhibited signals that should have flagged up as a problem but were missed by the individuals at the time.

CONCLUSIONS

The computer should not be seen as the villain. There were errors prior to the computer era and there will continue to be errors. The scale of the uptake of computers has resulted in radical changes in engineering design and construction, which in turn has resulted in a different type of risk. However it should never be forgotten that the computer is only a tool, albeit a very powerful one. Computers are operated and managed by people and they must assume responsibility for the eventual output.

Engineers have always modelled structures and rely increasingly on mathematical analysis to predict behaviour. The computer enhances the ability to conduct detailed analyses. This is an advantage rather than a disadvantage as it usually provides far grater understanding of behaviour than was possible in the past, along with efficiency in design time and the potential for more efficient structures. The danger lies in the increased difficulty in spotting inconsistencies or errors, especially in complex analyses.

The evidence suggests that the modelling process poses the greatest risk, where inappropriate or false assumptions are made. The complexity of some structures, and the resulting analysis can mask error. Over confidence in computer generated output exacerbates the problem.

It is the industry's responsibility to ensure that the available technology is used in a way that maximises the opportunities as well as minimising the risks. This can be achieved by ensuring engineers are adequately trained in the use of advanced software and work within their capabilities and experience.

REFERENCES

FELD, J. and CARPER, K. (1996) *Construction Failure*, John Wiley and Sons
GARDNER, P. J. (1995) *IT in Structural Engineering* (Results of the Members' Survey on IT Computers) The Structural Engineer, vol 73, No. 21.
GARDNER, P. J. and DOBSON, R. (Eds) (1997), *The very model of analysis - Modelling Structures for Computer Analysis*, The Institution of Structural Engineers, London
GARDNER, P. J. (1998) *An Investigation into Information Technology and Related Factors, and their Effect on the UK Structural Engineering Profession*, Unpublished PhD Thesis
ISE (1998) *Effective Computing: guidelines for the safer use of computers in engineering calculations,* Draft Report Unpublished
LEVY and SALVADORI (1994) *Why Buildings Fall Down*, Norton, New York
NAFEMS, (1995) *SAFESA Management Guidelines to Structural Qualification Supported by Finite Element Analysis*, Glasgow.
RENS, K. L. (1997) *Forensic Engineering*, Proceedings of the First Congress, ASCE
SCI (1995) *Modelling of Steel Structures for Computer Analysis*, The Steel Construction Institute
SCOSS (1994) *10^{th} Report of the Standing Commttee on Structural Safety*, ISE, London
ZEINKIEWICZ, O. C. (1992) *The Finite Element Method: its benefits and future*, The Structural Engineer, Vol 17, No. 20.

Conference overview

At the start of this conference the chairman, Brian Neale, defined forensic engineering as "the engineering investigation of failures that may lead to legal activity". It is not surprising that, with such an all-embracing definition, the conference has involved seventeen papers and some three hours of discussion. The intention was that the conference would provide an opportunity for engineering, legal and insurance professionals to develop a better understanding and an improved working relationship by exploring essential aspects of the subject. It was also hoped that lessons learned from recorded investigations would be made available to practising professionals. The conference concentrated its focus on the forensic investigation of incidents arising in buildings and structures.

1. **The expert witness**
   These are the papers of William Marshall (*Engineering*), John Ward (*What are lawyers looking for?*), Vivian Ramsey QC (*Supporting the legal process: legal aspects*) and John Barber (*Ramsgate walkway collapse: legal implications*). Not surprisingly, the presenters were unanimous in what they looked for from the expert witness. John Ward set this out as honesty, clarity of thought, clarity of expression, thoroughness, open mindedness and tough mindedness. Above all the expert witness has to be demonstrably independent and must never stray into the realms of advocacy. In his concluding remarks, William Marshall hoped that the conference would "draw engineers' attention to forensic procedures and point to standards of excellence and distinction which the law is right to expect from the engineering professions".

2. **The investigator**
   It was stressed throughout the conference that in forensic investigation there is no substitute for engineering skills, diagnostic skills, meticulous attention to detail, open mindedness, objectiveness, recording skills and visualization. The papers of Dr John Chapman (*Lessons from the collapse of the Ramsgate walkway*), Dr Peter Lindsell (*Investigation of non-catastrophic failures*), Professor Rob Shepherd (*Field investigation following natural catastrophe damage*), Avijit Maitra (*Technical evidence to support enforcement*), Dr John Maguire (*The technical investigation of failure – a view from the marine industry*), Rod Sylvester-Evans (*Piper Alpha case study*) and Dr Peter Ho (*Bucketwheel reclaimer collapse – New South Wales*) all demonstrated the ability of engineers to piece together, sometimes from scant information, a model of events that can be tested for acceptance by the courts. Each paper included the lessons learned from the failure and in that alone they more than met the objectives of the conference.

3. **The specialist**
   This is a category for those papers other than those specifically aimed at expert witnesses or investigators. Inevitably the papers were diverse in their subject matter and included the highly specialized papers of Professor Bushan Karihaloo that dealt with the

application of fracture mechanics as a means of averting catastrophic failures and of Dr Naysan Emami on microbiological attack on concrete.

The paper by Peter Gardner on the application of computer technology could well have been included in the investigator category as it identified the analogy between forensic engineering and computer programming. Both disciplines rely heavily on an initial model and no amount of correct analysis will give the right answer if the model is wrong.

There were two vital papers on the influence of insurance on forensic engineering. Bill Gloyne (*The unrecognized importance of insurance*) and Gerald Williams (*The premium has been paid but will the claim be?*)* dispelled much of the mystery and some of the anxiety that surrounds insuring projects. The references to risk management, claims management and loss adjustment made these contributions essential listening for all practicing engineers.

It is tempting to put the paper by Professor Jonathan Wood (*Applying lessons from failures to management and design*) in a category of its own. It was a happy circumstance that this was the final paper of the conference because it emphasized the need for lessons from failures to be given the widest possible publicity. Only by this means will repeat performances be avoided. Jonathan Wood also made a plea for the development of an accurate data base of important failures worldwide and a standard format for a "failure sheet" to promote dissemination of knowledge.

Discussion

SESSION 1: SETTING THE SCENE
Chairman: Gerlando Butera

The role of the court appointed expert, as envisaged in the proposals of Lord Woolf concerned some delegates. One delegate suggested that such an appointment is likely to be too late in some cases as the evidence may have gone cold or may no longer exist. Too often, the expert becomes involved when the parties are facing court proceedings. One expert held that, while this was this experience, he never felt disadvantaged by it. He valued the role of reviewing the work of others and then giving his own opinion. He felt that this was the essence of his role and it strengthened his independence in a case. A speaker who had direct experience of acting as a court appointed expert felt that this greatly strengthened his independence as he was reporting to the judge and not to any intermediary. The situation only became intolerable when the judge ruled that both sides should jointly pay his fee. The losing side had some difficulty with this!

Insurance matters concerned a number of delegates. Some held the view that lawyers should only be involved when insurers had already formed a view as to whether or not there was an

* Paper not included in proceedings at author's request

application of fracture mechanics as a means of averting catastrophic failures and of Dr Naysan Emami on microbiological attack on concrete.

The paper by Peter Gardner on the application of computer technology could well have been included in the investigator category as it identified the analogy between forensic engineering and computer programming. Both disciplines rely heavily on an initial model and no amount of correct analysis will give the right answer if the model is wrong.

There were two vital papers on the influence of insurance on forensic engineering. Bill Gloyne (*The unrecognized importance of insurance*) and Gerald Williams (*The premium has been paid but will the claim be?*)* dispelled much of the mystery and some of the anxiety that surrounds insuring projects. The references to risk management, claims management and loss adjustment made these contributions essential listening for all practicing engineers.

It is tempting to put the paper by Professor Jonathan Wood (*Applying lessons from failures to management and design*) in a category of its own. It was a happy circumstance that this was the final paper of the conference because it emphasized the need for lessons from failures to be given the widest possible publicity. Only by this means will repeat performances be avoided. Jonathan Wood also made a plea for the development of an accurate data base of important failures worldwide and a standard format for a "failure sheet" to promote dissemination of knowledge.

Discussion

SESSION 1: SETTING THE SCENE
Chairman: Gerlando Butera

The role of the court appointed expert, as envisaged in the proposals of Lord Woolf concerned some delegates. One delegate suggested that such an appointment is likely to be too late in some cases as the evidence may have gone cold or may no longer exist. Too often, the expert becomes involved when the parties are facing court proceedings. One expert held that, while this was this experience, he never felt disadvantaged by it. He valued the role of reviewing the work of others and then giving his own opinion. He felt that this was the essence of his role and it strengthened his independence in a case. A speaker who had direct experience of acting as a court appointed expert felt that this greatly strengthened his independence as he was reporting to the judge and not to any intermediary. The situation only became intolerable when the judge ruled that both sides should jointly pay his fee. The losing side had some difficulty with this!

Insurance matters concerned a number of delegates. Some held the view that lawyers should only be involved when insurers had already formed a view as to whether or not there was an

* Paper not included in proceedings at author's request

opportunity for recovery. One delegate, not a lawyer, made a strong plea for the involvement of lawyers as soon as possible in an investigation if only to provide privilege to discussions. A further aspect of insurance, raised in the Latham Report, was a proposal for a mandatory latent defects insurance. To be effective such insurance should have an obligatory waiver of subrogation rights in favour of the negligent contractor or professional. Not surprisingly contractors and professionals are widely receptive to the idea but not so, the client body. There seemed to be some benefits in a policy that just protects those who have suffered the loss and does not try to do anything beyond that.

An experienced expert witness wondered why so much time and effort is spent in arguing a case when so little is spent in attempting to get both sides to negotiate a settlement. He recently had experience of being brought in to help resolve a dispute that had been running for nine years. Within four days, he had effected a negotiation and the case was settled. A lawyer quoted some statistics from his own firm. About 97% of cases are settled out of court and most of these before the formal proceedings begin. A case that has been running for nine years may well be able to be settled just because of that. Parties need time to assess each others position and financiers need to sort out the financial implications of a dispute. He concluded, however, that nine years would be at the extremity of the patience of most parties. Mediation is a valuable tool in the right hands and many law firms have departments that specialize solely in that. The skill comes in being able to talk to both sides without risking the inference that the party that makes the first move may appear to be the weaker. This may lead to the involvement of an independent mediator who has not been involved in any of the previous proceedings.

A final point in the discussion of this session concerned the in-house expert. Some fears were expressed about his or her independence. The Court is not concerned whether the expert is in-house or not but it insists that the expert is totally independent. An in-house expert may expect a rigorous examination on this.

SESSION 2: EXAMINING A HIGH PROFILE CASE
Chairman: Eamon O'Leary OBE

The Ramsgate case raised the question not only of the duties of the designer but more importantly of the client. One delegate had the view that the duties of the designer are clearly understood. These are to exercise reasonable skill and care in the work undertaken. Following Ramsgate the duties of the client seem to go beyond that. The client must not only exercise similar skill and care but must ensure that those who are appointed do likewise. In effect the client is responsible for all. At Ramsgate the client not only appointed a designer considered to be both competent and experienced but in addition an approver also considered to be competent and experienced. The client still shared responsibility for the tragic event.

There was some sympathy with this viewpoint from the platform but the Court felt that the client should have sought increased safety by installing safety chains in the event of failure of any other supporting component. That such a failure did occur endorsed the Court's view. In addition, the client should have investigated the lack of bearing lubrication that had been specified.

Another delegate held the view that the lack of lubrication was irrelevant. He also reminded the session that the client had raised the issue of safety chains with the designer and because of that, the client was held to share responsibility. It did not seem fair. The session was reminded that the matter might not be finally settled, as there was the possibility of an appeal on the judgement.

The meeting was reminded that the Health and Safety Executive is not principally interested in "ambulance chasing". It is more concerned with ensuring that the lessons from an incident are learned and drawn to the attention of the industry so that repeats can be avoided where possible in the future. It has been said that the *Health and Safety at Work etc Act 1974* does not require HSE to state how work should have been carried out. The Act sets out the responsibilities of the various parties and it the job of HSE to see that these responsibilities are carried out.

SESSION 3: APPROACH TO TECHNICAL INVESTIGATION
Chairman: Eamon O'Leary OBE

A delegate referred to a number of instances of collapses of masonry buildings in storm conditions in Australia. Failure of wall ties was identified as the root cause and as a result legislation had been introduced banning the use of all but stainless steel ties in such conditions. He asked if there was similar legislation in the United States. In reply, he was told that in earthquake zones in the US, most buildings are built in reinforced concrete or structural steel where continuity of structural elements is a prerequisite. Unreinforced masonry has been banned in California so the problem of wall ties does not arise with new buildings. Old masonry buildings, not already affected by earthquakes are now monitored much more closely and owners have been persuaded to carry out programmes of retro-fit.

Structural steel is still the most popular material for multi-storey buildings in California but some concern is being expressed about design aspects following the Northridge earthquake. Some concepts from fracture mechanics may help in overcoming these. Research is continuing and is showing that some earlier design requirements need to be amended.

SESSION 4: SUPPORTING THE LEGAL PROCESS
Chairman: Michael Neale OBE

At the start of the discussion the speaker was asked to expand a little on the differences in the legal process between criminal and non-criminal cases. In most criminal prosecutions it is a jury rather than a judge that has to be persuaded. The difference is one of focus. When presenting a case before a jury one has to be extremely careful to simplify what the issue is and not to cloud it with any irrelevancies. The burden of proof is more rigorous in criminal cases because the jury has to be convinced beyond reasonable doubt of the strength of your case. A civil case before a judge may rest on the balance of probabilities. An expert, expressing an opinion in a criminal case, has to reflect very carefully on the level at which his or her opinion is held although the expertise and experience required is similar in both situations.

Some useful advice on meetings of experts was offered by a delegate as a prelude to a question on fast-track justice. He contended that expert meetings should always be held on a "without prejudice" basis. Any restrictions placed on the various parties should be established. A record of documents seen by the parties should be drawn up as this may help to remove genuine differences of opinion that might arise where one party may not have seen all the documents. Each party should keep notes but no joint record of the meeting should be produced. Parties should be reminded that there will be no agreement until there is a signed document agreed by all the parties. This agreement should be a schedule, which simply lists areas of agreement and disagreement.

Addressing the question on fast-track justice the speaker was very much in favour of this. It puts an enormous burden on the tribunal and on the parties to make sure that the case is properly prepared. This becomes obvious when one considers that a four-day arbitration may well replace a six-month hearing before a court. It is sometimes said that in English legislation the preparatory work for court proceedings and the initial submissions in court enables parties to come to a settlement. The trouble with many alternatives to court procedure arises when parties find that they cannot accept non-binding findings. The dispute starts up again and parties realise that they may have been better advised to seek court resolution in the first place.

SESSION 5: PICKING UP THE PIECES
Chairman: Michael Neale OBE

One delegate expressed concern about the lack of communication back into the industry of lessons learned from many cases and he felt that the insurance industry held much of the responsibility for this. An insurance expert agreed that any improvement in communication should be welcomed but parties must be allowed to settle differences in private. There are often strong and compelling reasons for parties not to divulge details of their failings or their settlements. One possible way round this difficulty might be to produce anonymous reports at the end of such settlements but all sides would have to agree to this, something not easily achieved.

The subject of microbiological attack provoked an interesting discussion on the properties of concrete. One delegate wondered why, with an admixture to improve the strength and permeability of concrete, the resultant was only a 35N concrete. He suggested that the cement content must have been significantly reduced. He also speculated that if the aggregates were highly porous the disintegration of the concrete would proceed more quickly. On the first point the speaker referred to a continuing dispute between the parties about the quality of the concrete and in those circumstances it would be inappropriate to discuss this matter further. The porosity of the aggregates had been investigated but the speaker was firmly of the view that the root cause of the problem was the microbiological attack.

Microbiological attack was also raised as a potential problem for buried steel structures. The speaker indicated that research into this problem was at present under way but it was not relevant to the problem that confronted the team investigating the affected structure that was the subject of the paper.

Doubts about the level of understanding of complex technical matters by the judiciary prompted one delegate to suggest that such cases should be heard by specialist judges or tribunals. One of the speakers refuted this proposal. He felt that it was up to those presenting cases to ensure that the Court heard and understood the arguments and reasoning behind them. The present system works surprisingly well and is understood by most involved.

The usefulness of photographs for the forensic engineer was raised and was endorsed by a speaker who suggested that it is worth ensuring that each photograph includes a dimensional reference, such as a tape measure or ranging rod, to clarify scale. Where possible the date and time of each photograph should be recorded and witnessed.

The HSE's perception of an acceptable probability of success before initiating a prosecution interested some delegates. A figure of 98% was suggested. It was felt that anything less than that could suggest reasonable doubt. Where the probability falls to 70%, those investigating the case would alert their managers to areas where there is doubt. In such circumstances the matter would be unlikely to proceed.

SESSION 6: INCIDENT RECONSTRUCTION
Chairman: Brian Neale

The collapse of the bucketwheel reclaimer in New South Wales raised questions on the design speed for the design of buffers. A speed limit of 7 m/s had been imposed on the failed machine. The forensic engineer identified that the damage occurred at a speed less than that. This helped to confirm that the design of the buffer was inadequate.

The reconstruction of events leading to the collapse of the Piper Alpha platform was one of the most complex forensic investigations ever undertaken. In response to a question of the degree of certainty that had to be achieved in coming to a conclusion, the speaker enlarged on the brief for the investigations. The case was heard before a public inquiry under Lord Cullen. He had insisted that a range of credible options should be presented with detailed reasons for rejecting all but the selected option. In the circumstances he could not refer to a specific degree of certainty other than to add that it was a very high figure.

One delegate suggested that a "black box" installed in the platform could have saved much speculation. This was accepted but, with modern communication technology, activities on such platforms are recorded on shore and can be reconstructed at anytime in the event of an incident.

The Chairman reminded delegates that the *Health and Safety at Work etc Act 1974* was introduced after the Flixborough disaster and that has significantly affected the approach to occupational health and safety matters.

SESSION 7: LESSONS TO BE LEARNED
Chairman: Brian Neale

The need to disseminate information from failures throughout the industry was heartily endorsed by those attending the conference. One delegate warned those present of the problem of collective amnesia. Lessons from bridge failures last for about 30 years. In the process industry this period can be as short as 10 years. He feared that not many young engineers today had heard of the Ronan Point collapse. This emphasized the need for repeated dissemination of lessons learned. It also raised again the problem of lessons that could be learned but never would because cases were settled in private.

It was felt that only a confidential reporting system would have any chance of success. Such a system works in the aircraft and shipping industries but there does not seem to be the same commitment in the construction industry. In the nuclear industry reporting is highly developed and available to those involved in the industry. It is not available to those outside the industry and has been accused of being secretive because of that, but it does work. The Standing Committee on Structural Safety the Institutions of Civil and Structural Engineers and the Health and Safety Executive are involved in seeking a solution to the problem of confidential reporting of incidents in the construction industry.

CONCLUSION
Brian Neale, Chairman, Organizing Committee

In the first paper of this conference, William Marshall wrote the following:

> "It is my hope that this conference will draw engineers' attention to forensic procedures and point to standards of excellence and distinction which the law is right to expect from the engineering professions."

The conference opened with the engineer acting as expert witness and concluded with the need to learn lessons. The ultimate aim of forensic engineering must be to ensure that lessons of past failures will prevent future failures. The spin-offs from forensic engineering are the lessons learned. I hope you will agree that, in this our first international conference, we have covered procedures, failures and lessons and that in any future conference these themes can be developed.

In formally closing this conference I wish to record my thanks, and that of the Organizing Committee to our speakers, to our chairmen, to those who took part in the discussions and to you all for attending and making the conference possible. I would finally wish to thank Thomas Telford Conferences for the planning, organizing and recording of the conference and also to the support we have received from the Forensic Engineering Group Cardiff University, the Health and Safety Executive, the Institution of Mechanical Engineers, the Institution of Structural Engineers and the Standing Committee on Structural Safety.