Restoring timber structures - Repair and strengthening

STEP lecture D4
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Objective

To provide an outline of the follow-up procedures to inspection work, including a critical analysis of some commonly used techniques for *in situ* repairs and/or strengthening of timber structures, members and joints.

Summary

This lecture describes the wood technologist's approach to the identification of the aims of the work to be undertaken, and of external constraints, in the repair and strengthening of existing timber structures, after an *in situ* inspection has been performed. It also discusses, briefly, some techniques that are often recommended. This lecture does not include structural design, which is covered by other lectures.

Introduction

Following the inspection of the existing timber structure (see STEP lecture D3), decisions have to be made concerning any follow-up work that is necessary. Several aspects have to be considered, in close cooperation with experts, such as structural engineers, architects, wood technologists, restorers, historians, owner or administrators in charge of the building, and other concerned parties such as building authorities or officers in charge of conservation of the cultural heritage. Consideration of the following three aspects is recommended:

- identification of objectives, requirements and constraints;
- structural interventions;
- maintenance and conservation measures.

Identification of objectives, requirements and constraints

Restoration works on existing timber structures, which are often old or ancient and of some cultural importance, will relate to many different needs, which may often be conflicting. A clear identification of objectives and needs to be satisfied by the restoration work must be made before the technical aspects are considered, so that the experts may work on the basis of clearly stated priorities and constraints.

Amongst others, the following alternative or complementary *objectives* of a repair/strengthening intervention may be listed:

- conservation of the appearance of the structure;
- conservation of the original materials, for artistic, historical or cultural reasons;
- restoration of the original loadbearing capacity;
- increase or modification of the loadbearing capacity, stiffness, or serviceability;
- compliance with safety, fire, seismic or other regulations.

On the other hand the *constraints* need to be considered, such as the following:

- desires of the involved parties;
- economics;
- environmental situation;
- prevention of future decay and/or other damage;
- available time, expertise, materials, workmanship and technologies;
- compatibility between existing timber and materials available for repair and/or reinforcement

For clarity and simplicity only a few of the preceding considerations are detailed. However, it should be appreciated that all the issues are likely to be interactive, and any action taken to solve one of them may significantly affect several others.

Conservation of the original materials and structural concept
Because of artistic, historical or cultural reasons, the conservation of old timber structures is becoming more and more important and desirable, and often emphasis is placed more on conservation than on economic aspects. On the other hand (e.g. in many residential buildings) the lowest possible cost in order to obtain durability, serviceability and compliance with building regulations is frequently the main requirement: the cost of strengthening or repair becomes then the guiding parameter in choosing between various criteria for performing work on existing timber structures.

Philosophy of restoration and rehabilitation is not an objective of this lecture, but should be considered when establishing the rationale of decisions to be taken (Tampone, 1992; Bertolini, 1992).

Specific roles of the wood technologist
Some aspects of restoration work are peculiar to timber structures, and usually require the specific expertise of a wood technologist. His specific contribution may include the following subjects:

- identification of wood species;
- evaluation of durability of the timber members in their present conditions (according to wood species, heartwood distribution, environmental conditions, etc.), and any need for preservative treatment in order to ensure the desired durability;
- assessment of the actual structural performance of the timber members.

The better knowledge provided by the wood scientist makes it possible nowadays to conserve structural members that until a few years ago would have simply been removed and substituted. Also, when the original structure does no longer meet the minimum safety requirements, a good knowledge of structural timber often makes it possible to take action so that old members may still contribute to the global loadbearing capacity.

Further aspects that the wood expert should especially take care of are:

- the compatibility between the wood of the member and the new materials used;

- the influences of the repair on the serviceability, reliability and durability of both the repaired members and the whole structure.

Conservation of the appearance of the structure
The preservation of the appearance of the structure is related to the amount of degradation of timber members. Insects, fungi and fire normally affect the external wood layers, and repair works would often require their removal. When this is not possible or desirable, hardness and conservation of deteriorated wood may be improved through impregnation with appropriate resins.

Restoration of the original loadbearing capacity
Timber members affected by heavy decay or damage can be strengthened through repair works. It should, however, be noted that many old timber structures are oversized, considering the structural requirements. After a detailed inspection and careful assessment it is therefore possible that (in spite of past damage suffered by the members) residual cross sections are still sufficient to provide a loadbearing capacity complying with present and anticipated service conditions. In such cases there should be no obstacle to report: "no repair work needed", allowing work to concentrate on the prevention of further decay.

Strengthening
The loadbearing capacity of a timber structure needs in certain cases to be improved through appropriate structural consolidation, in order to comply with increased performance requirements (e.g. modifications in the use of the structure).

Compliance with safety, fire, seismic or other regulations
It is a matter of fact that in some European countries building regulations have been written by experts with insufficient knowledge and experience of timber structures. The lack of specific regulations may need to be countered by reference to research papers pointing out the good seismic and fire behaviour of timber structures. A substantial improvement is likely to occur after the implementation in these countries of EC5 Part 1-2: "General rules Structural fire design", and EC 8: "Design provisions for earthquake resistance of structures".

Working conditions
The available time, expertise, materials, workmanship and technologies should be clearly identified before the working plans are completed, in order to assure that the desired quality of the whole work may be obtained. Even more than for other kinds of repair works, timber structures require that no shortcuts be seeked, specially at the initial stages; also, the time required for collecting and analysing information should be allowed for, in order to avoid mistakes that would make successive remedies much more expensive or even impossible.

Compatibility
Compatibility between different materials should always be a major concern; this is specially true for materials used for repairing and/or strengthening timber structures. Whenever glued or rigid connections are made, special care is needed in order to avoid stresses (and possible failures) caused by differential deformations related to the following:

- differential shrinkage between wood and non-hygroscopic materials;
- differential shrinkage between different anatomical directions of wood;

- different thermal expansion coefficients between wood and metals;
- different displacements between structural parts or members with different stiffnessess.

Other compatibility problems may arise from chemical factors, such as corrosion of steel fasteners caused by wood extractives under high moisture conditions. Finally, condensation of moisture (and consequent decay problems) is often a result of poor compatibility situations, such as:

- wood placed in close contact with metals or stone featuring a different heating or cooling rate, under insufficient conditions of ventilation;
- possible condensation of moisture within timber pieces, at the interface between wood and resin.

Structural repairs

Broad classification criteria
In general, no two identical situations exist in old timber structures: therefore restoration works and repairs need to be chosen, designed and implemented case by case. Also, as already noted, problems and solutions are deeply interconnected and may be not faced separately. Nevertheless it is useful to lay down the following broad classification criteria, in order to help clarify meanings, scopes and limits of the numerous technical solutions which up to now have been, or may in the future be proposed for structural repair work.

Repairs may basically deal with one or more of the following levels of the structure:

- individual structural timber members;
- structural units;
- whole structures;
- connecting joints;
- external constraints or connections.

After the repair works the original timbers:

- may fulfil the same structural functions they were originally assigned (untouched, if recognised as needing no structural repair; after repair or strengthening, if needed);
- may still fulfil a structural function, although in conjunction with newly added members;
- may be left in place just for aesthetic reasons, or for conservation of the material's historical authenticity, the structural functions being totally fulfilled by other loadbearing members, such as substitution timbers, steel or concrete.

A note about strengthening
Once the strength properties of timber have been lost because of decay or fracture, the original strength of the wood *material* can not be recovered (even to a partial extent) by means of impregnation with any kind of resin or other process. On the contrary, a timber member, sub-assembly or structure may be

repaired, reinforced and/or stiffened, as needed.

Repair by gluing new parts

Decayed or badly damaged segments (often beam ends) may be replaced by newly added parts (wood, glulam, epoxy, etc.), usually connected by glued rods made of steel or fibreglass. Structural design should mainly rely on adhesion of rods parallel to the grain of wood, since moisture variations and differential shrinkages may impair strength of gluelines perpendicular to the grain (Ceccotti, Mannucci and Uzielli, 1990). Appearance and authenticity of original materials are lost.

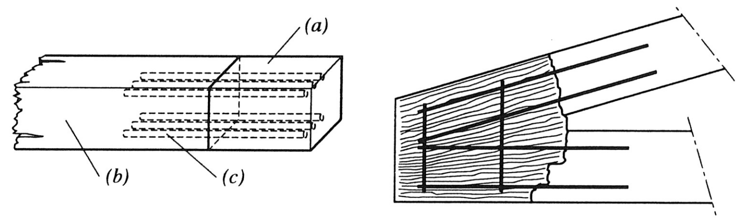

Figure 1 *Replacement of inefficient segments of original members with epoxy. (a) Beam end replacement, (b) original timber, (c) steel or fibreglass rods.*

Repair by means of traditional joints

Decayed or badly damaged segments may be replaced by new parts made of solid wood, connected by means of traditional joining or repairing techniques. However, original strength may seldom be fully recovered. Only traditional methods and materials are used. Appearance and authenticity of original materials are lost.

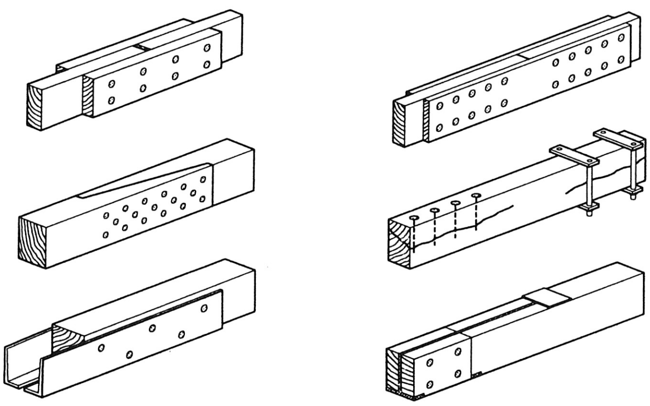

Figure 2 *Replacement of inefficient segments of original members by means of traditional joints; left, top to bottom : splice joint covered by bolted wooden plates, nailed spliced bevelled joint, bolted end joint, with steel channel; right, top to bottom: splice joint covered by bolted steel plates, shear reinforcement with nails or steel clamps, splice joint with internal steel plate.*

Enhancement of cross-section

The cross-section of a member may be enhanced by adding (gluing, nailing, bolting, etc.) reinforcing parts (wood boards, steel beams, etc.). Original appearance and aesthetics are usually lost.

Note that if the same reinforcement parts are simultaneously connected by more than one technique (e.g. nails and glue, or bolts and glue), the strength of the two connections will not add up, because the stiffer connection such as the glue will take most of the load, and only after its failure the more ductile one will gain significance; it is therefore inappropriate to add nails or bolts "just in case" the glue failed, if they are not properly designed to take the whole anticipated load. However nails or bolts may be of great use in providing pressure and keeping members in position while the glue cures.

Glued-in plates

One or more steel plates (almost as deep as the beam) may be glued into grooves vertically cut *in situ* along the whole length of beam (see Figure 3). Plates, which are hidden and are protected from fire and corrosion, take up almost all the load. Special equipment is needed for cutting the grooves (Tampone, 1989). Geometrical feasibility, buckling, support conditions, etc. need consideration.

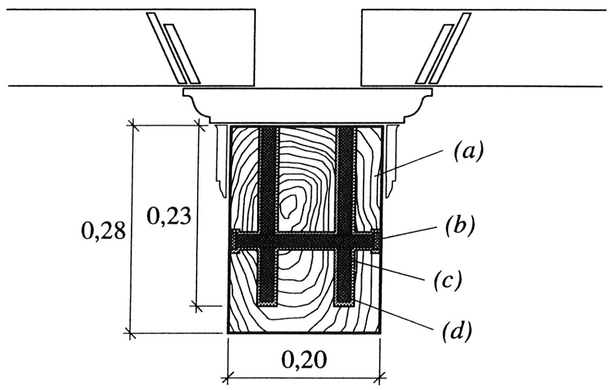

Figure 3 *Glued-in plates, along the whole length of a white fir beam (a) (from Tampone, 1989, modified), (b) threaded steel rods, (c) steel plate, 10 mm thick, (d) epoxy resin.*

Glued-in rods

Steel or fibreglass rods may be glued into grooves cut along the tension edge of the beam. Failure is thus no more caused by strength-reducing defects located at tension edge, and occurs at compression edge, whose strength is not increased; failure behaviour also becomes more ductile (see Figure 4). Limit-state reliability is therefore increased, rather than strength or stiffness. (Ceccotti and Marradi, 1993).

Tie-rods

Steel cables or rods, equipped with spacers or other devices, may be used in order to contribute to strength and stiffness of individual members or trusses; by means of turnbuckles, the tension may be adjusted either to pre-stress beams or just to control excessive deflections (Marradi, Messina and Paolini, 1989). Periodic adjustments or insertion of elastic components may be needed to compensate for creep and for shrinkage/swelling caused by moisture variations (Ceccotti and Marradi, 1993). The structural conception of trusses may turn out significantly modified. Examples are shown in Figure 5 and 6.

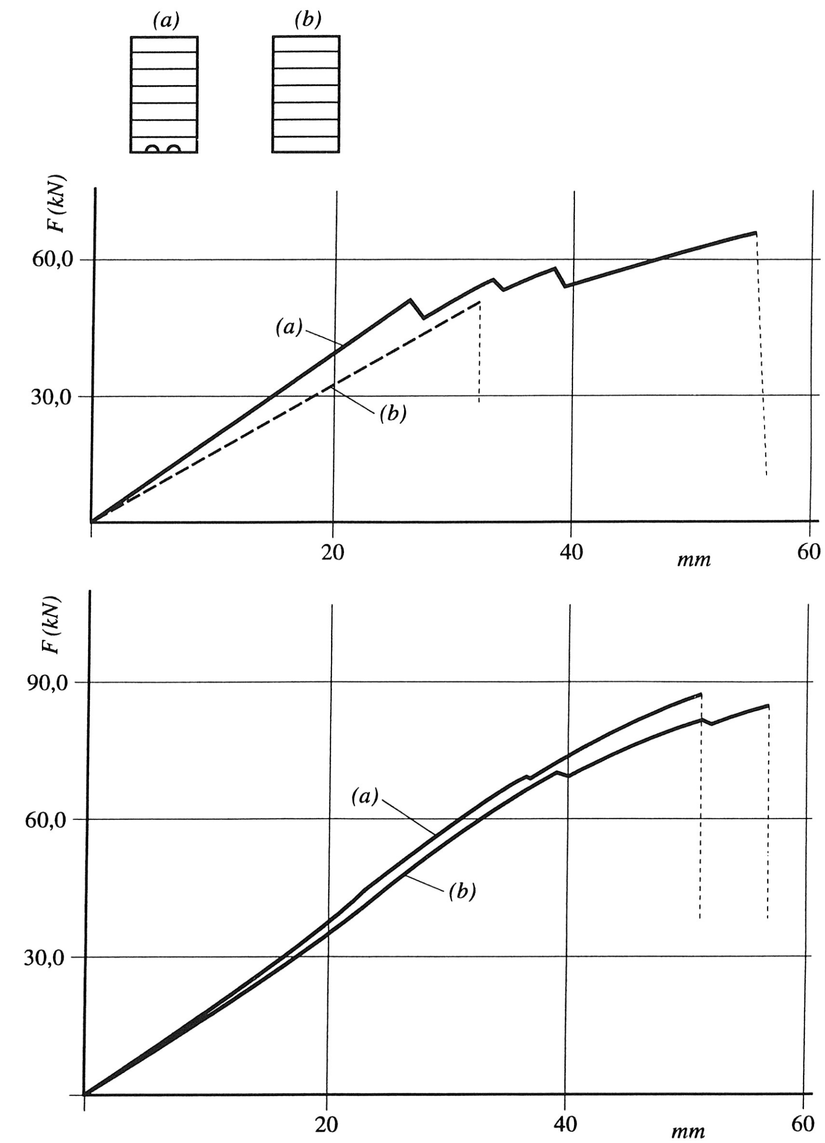

Figure 4 *Effects of steel or fibreglass rods glued with epoxy resin into grooves cut along the tension edge of the beam on its load-deformation behaviour. (a) reinforced cross-section, (b) timber cross section without reinforcement. Top diagram: beams with large defects, bottom diagram: beams with minor defects.*

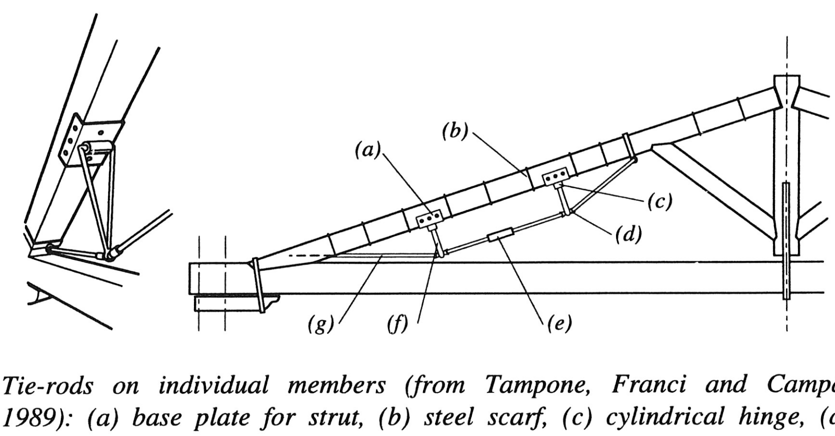

Figure 5 *Tie-rods on individual members (from Tampone, Franci and Campa, 1989): (a) base plate for strut, (b) steel scarf, (c) cylindrical hinge, (d) clamp, (e) turnbuckle, (f) strut, (g) steel cable, left: detail in perspective view.*

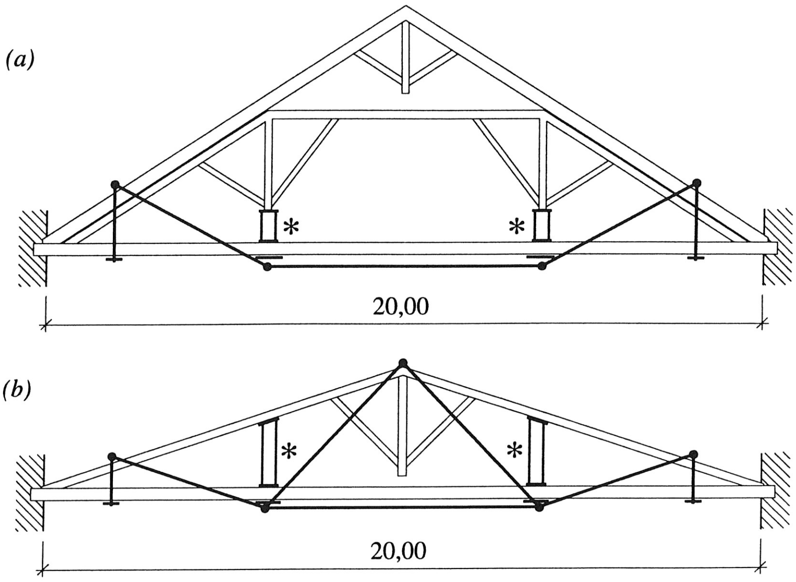

Figure 6 *Tie-rods on two types of trusses (from Marradi, Messina, and Paolini, 1989): the internal elements marked * have been added together with the tie-rods, significantly modifying the structural conception.*

Modification of support conditions

Supports of decayed parts (e.g. of beam ends) are moved to locations where timber is sound; this may also result in reducing the span of the beams. Often used for non-visible beams supported by thick walls, where brackets may be effectively fixed (see Figure 7).

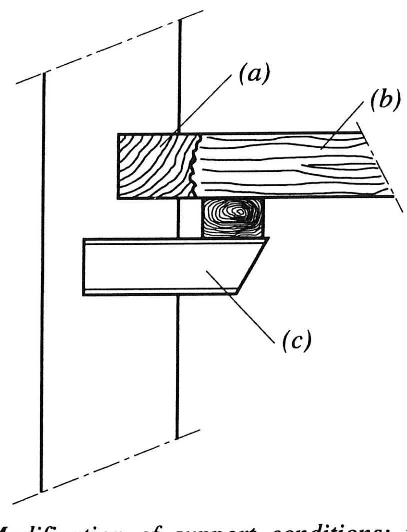

Figure 7 *Modification of support conditions: the decayed beam end (a) has been unloaded by moving the support towards the sound beam part (b) which rests on a wooden sleeper, which in its turn rests on an I-beam bracket (c) through a neoprene saddle, intended to prevent moisture condensation caused by temperature differences.*

Additional loadbearing members

Loads are partially or totally carried by additional members (steel or concrete beams, columns, etc.; see e.g. Bertolini, 1992). Structural conception is altered. Appearance and authenticity are partly lost.

Replacing timber members
Some or all of the structural members may be replaced by new timber members, adopting the original techniques as far as possible. Great care is needed in considering technical compatibility; e.g. using insufficiently seasoned timber may lead to non anticipated unbalances or stresses.

The correctness of replacing original parts in historically significant structures is questionable, since authenticity of materials is lost, whereas aesthetics and authenticity of conception might be conserved.

The exceptional case of a six-stories timber-framed house (Knochenhaueramtshaus, Hildesheim, Germany), originally constructed in 1529, entirely destroyed in wartime and reconstructed according to historical techniques, reconciling historical claims with the design codes of the present day and vice versa, is reported by Kessel, Speich and Hinkes (1989).

Re-establishing or improving geometry and/or stability
Excessive structural deformability or instability may be prevented or reduced by adding, repairing or re-establishing bracings (generally tension members are made of steel, compression members of timber). Authenticity is conserved, with possibly minor aesthetical alterations. Significant improvements are obtained in static and seismic behaviour, even though the original structural conception might result altered. Great care is needed in designing connections between parts with different anticipated displacements.

Similar means as above may be used to re-establish correct geometry (e.g. to reduce or eliminate deformations, members "out of plumb", etc.). Great care and accuracy needed in designing and implementing the work, choosing and manufacturing anchorages, etc. Structural conception might result altered.

Timber-concrete and timber-panel composite structures
An effective kind of work, already implemented in a number of cases in different countries, is the timber-concrete composite technique (see STEP lecture E13): a reinforced concrete slab is connected to the beams by means of shear connectors (various types exist, such as glued, screwed-in, fitting in grooves, etc.), so that it is not just supported by beams, but cooperates as well in resisting bending moments (slab is in compression and beams are in tension). Bending strength and stiffness greatly increase, and seismic behaviour improves. Beams need to be in good conditions, in order to contribute in the mixed structure.

Timber-panel composite technique is similar as above, except that structural wood-based panels, connected by means of nails or similar fasteners, are used in place of the concrete slab. This system, not yet widely used in rehabilitation of old structures, is much lighter than concrete; on the other hand, it provides a smaller structural improvement.

Maintenance and conservation measures
Maintenance work should always carried out with a view to the continued conservation of the structure: no work may be considered as "the final one", needing no further care or maintenance. The action of potential deterioration agents (both biotic and abiotic) should be anticipated and prevented.

Moisture, in its various forms and origins, including the effect of alterations that may have been made on the environment (vapour barriers, waterproofing, sources of condensation, increased or decreased ventilation, closed windows or other openings, sealing of beam end supports, etc.) should always be considered a major threat to the conservation of timber structures, including those which have undergone recent or earlier repair works.

Special care should be taken to ensure the proper execution of recommended repair or prevention works. For instance an inaccurately performed preservative treatment (e.g. one leaving unprotected surfaces), or the inappropriate succession of works (e.g. drilling or notching timber after it has been treated, resulting in untreated wood surfaces to be exposed to the attack of insects) will hardly improve the durability of the structure.

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