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Cow Comfort on Cubicle Beds

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The Milk Development Council

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Executive Summary

This project was set up to improve the understanding of dairy cow comfort in cubicles by investigating the impact absorption of Pasture Mat rubber-crumb mattresses and Maxibed ethylene vinyl acetate (EVA) mats. The comfort performance findings of these bed types were identified and are reported to help dairy farmers with product choice.

Performance criteria were measured by two separate compression measurement procedures, quasi-static and dynamic impact testing. The criteria considered were short-term and long-term injury reduction based on mat or mattress surface deflection and the forces exerted on a carpal joint (knee) during upward and downward movement by a cow in cubicles.

Quasi-static test results suggested that the new condition rubber-crumb mattress was a softer bed than the new EVA mat. However, both beds showed a satisfactory level of softness for the getting up action of a cow. Dynamic impact test results suggested also suggested that the new rubber-crumb mattress was the softer bed of the two types but the 4 year old beds tested suggested an opposite finding. The EVA mat had stayed at the same level of softness whereas the rubber-crumb mattress had become a harder product.

The project team also designed a computer model of both types of cubicle bed. This work was done to enable beds of varying densities and thicknesses to be analysed quickly and cost-effectively in terms of softness. That is, long-term performance was evaluated in this way to back up the findings of the farm-based dynamic impact tests.

The benefits to dairy farmers resulting from this project are as follows:

- future impact absorption of cubicle beds of any type and age can be tested by quick and cost-effective analysis using the computer model;

- future impact absorption of cubicle beds of any type and age can be tested by quick and cost-effective analysis using an international standard test as set out in this report;
- the injury reduction performance of a four year old EVA mat was found to be similar to that of an un-used version which suggested that these beds are a reliable long-term investment;
- new rubber-crumb mattresses showed the best short-term injury reduction performance but a significantly reduced long-term performance.

1.0 Introduction

1.1 Scope of project

This project has been undertaken to find out more information about the processes of impact injury when a dairy cow gets down to and up from a cubicle bed. The impact absorption of Pasture Mat rubber-crumb mattresses and Maxibed ethylene vinyl acetate (EVA) mats were investigated and the findings are reported to help dairy farmers with cubicle synthetic bed investment decisions. It follows on from a report to the Milk Development Council in 1999, MDC Project 96/R6/01, which concluded that rubber crumb mattresses caused less knee and hock damage than ethylene vinyl acetate mats in a one-winter study, (Kelly and others, 1999). Previous studies by Underwood and others 1995 and House and others 1994 indicated that rubber crumb mattresses and various types of mat cause less harm to the leg joints than concrete and sawdust alone. This is due to improved mechanical impact attenuation.

An important part of the current work was to determine the impact attenuation of a cubicle mat or mattress at the beginning of its use and also when it had been in place and compacted over a few years. Static and dynamic compression tests were carried out and computer models were made to evaluate impact attenuation and, therefore, injury reduction potential. Investment choice by a farmer will be helped by knowing the immediate and long-term injury-reduction effect of a synthetic bed.

1.2 The action of a dairy cow getting down onto a cubicle bed

The descending process is a dynamic one. The actions are described in detail in Section 2.0. A series of dynamic impact tests was carried out by dropping a mass onto a surface and recording the pattern of acceleration due to gravity for a given drop height. These took place on a farm in order to determine the impact attenuation property of cubicle beds that have been in place for 3-6 years. The information gained was as follows:

- Maximum acceleration for a given drop height and mass;
- Maximum force for a given drop height and mass;
- Force versus deflection relationship.

1.3 The action of a dairy cow getting up from a cubicle bed

A cow rising from a mattress or mat involves or more sustained push onto the bed. This is a less dynamic process and was simulated in this project in laboratory conditions. Samples of new mats and mattresses were subjected to a quasi-static compression test using a Lloyds Instruments Ltd LR 30K machine at the mechanical engineering laboratory of the University of Glasgow. The information gained was as follows:

- Force versus deflection relationship for a given cubicle bed material sample.

This was used for detailed analysis in a computer software called Abaqus which is a finite element analysis package and is essential for understanding the nature of deformation under load in a hyperelastic material, such as a dairy cow cubicle mat or mattress.

2.0 The knee-joint/synthetic bed interface

Lying surfaces for dairy cows must provide softness, durability and sufficient friction to allow rising and lying down without slipping. Cubicle behaviours such as 'lying down' or 'standing doing nothing' are indicators of animal comfort (Chaplin and others, 2000).

The movements shown by an adult dairy cow to take her up and down from a cubicle bed have been shown to be laboured.

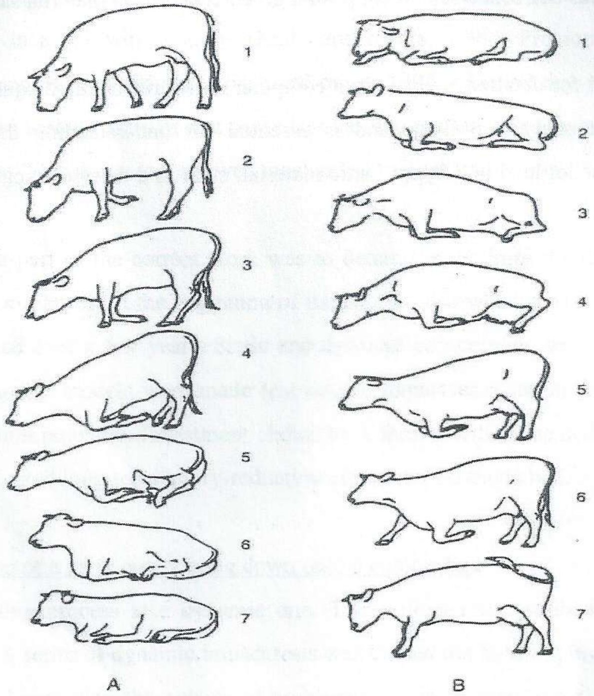


Figure 2.1 The sequence of a dairy cow lying (A) and standing (B) as illustrated by Phillips (1993) from Fraser and Broom (1990)

In mechanical impact terms the time to fall includes a quick drop of the knee joints onto a surface and was simulated in this project by a dynamic compression test. The action to rise involves a sustained pressing of the knee joints into a surface and was simulated by a quasi-static compression test.

Lying behaviour of cows in cubicles with new mats and mattresses was described by Kelly and others (1999) in terms of the proportion of time spent lying as a proportion of 24 hours. The group on mats lay down for 10.5 hours (44% of the observation time) and those on mattresses lay down for 12 hours (50% of the observation time). Cow lying behaviour was described as being an important comfort indicator and significantly different for the two bed types studied.

Limb injuries have been described as accidental, such as from slipping on a floor that is too smooth, or as systematic, such as from fore-knee pressure applied to a hard lying area (Blom, 1983). Systematic injuries were studied in the current work.

Kelly and others (1999) found differences in systematic injury incidences between cows on mats and mattresses, with those on mattresses having fewer injuries. However, there was no direct link shown between systematic injuries sustained to leg joints and milk production quality or quantity.

The softness of a surface has been measured in previous work by plotting impact force against deflection and this means of evaluating comfort was the main focus of this project. The more that a surface deflects on impact, the softer and more comfortable it is, up to a maximum level of softness. If a surface is too compliant it causes a cow standing in a cubicle to be unsteady and uncomfortable.

Nilsson (1988) measured deflection from a 1.5 kN force on 3 dairy cow stall surfaces; concrete, 15 mm thick synthetic rubber mats and 25 mm thick mattresses made from latex-bound coconut fibres covered by polyurethane coated polyamide fabric. The deflection measurements were 0 mm for concrete, 4.3 mm for the rubber mat and 18 mm for the mattress. The most compliant bed, the mattress, resulted in around half the number of severe injuries compared with those from the concrete and rubber mats.

The number of injuries recorded in the herd in the study was 0.3 per leg for the mattress cows and 0.6 per leg for cows on both the rubber mats and concrete.
Irps (1983) showed a curve of force versus deflection in a synthetic rubber mat with tread to help with slip resistance. The maximum deflection was shown as just below 10 mm for a force of 4 kN using a cylindrical test indenter with a 10 cm^2 contact area.

Dumelow (1995) showed minimum and maximum curves of force versus deflection as indicators of limits for hardness (for stability when standing) and softness (for comfort when lying). The penetration of a 120 mm diameter test piece at a 3 kN force is given as a maximum of 30 mm (i.e. more would be too soft) and a minimum of 17.5 mm (i.e. less would be too hard). Dumelow (1995) used the 120 mm diameter test piece as a size close to the actual size of a cow knee (carpal) joint.

Compliance (softness) is not a constant characteristic (Nilsson, 1988). It depends upon material thickness, temperature, humidity, force and, critically, the rate of loading. The rate of loading is different for a cow according to whether she getting up or lying down. For this reason this research project has used results for force against deflection from static and dynamic compression tests since these simulate the actions of getting up and lying down, respectively.

3.0 Equipment and procedures for quasi-static and dynamic compression testing of dairy cow cubicle beds

3.1 Quasi-static compression testing

This work was done in the Mechanical Engineering Department of the University of Glasgow using a Lloyd Instruments LR 30K machine connected to a computer. This test was done to simulate the sustained pressing of a carpal joint by a cow into a cubicle bed on getting up.

The procedure for testing samples of cubicle beds was as follows:

- The machine was switched on and connected to the computer;
- A 30 kN load cell was installed (this load cell comfortably allowed the maximum load taken by a cubicle bed sample to be recorded);
- A 45 mm diameter cylindrical indenter was screwed into the load cell [any size of indenter used in a compression test can be correlated to an actual cow knee joint size of 120 mm (Dumelow, 1995)];
- The mat or mattress sample to be compressed was inserted between the indenter and the bottom plate;
- The compression test was carried out;
- A force/deflection curve was produced by the computer and printed out.

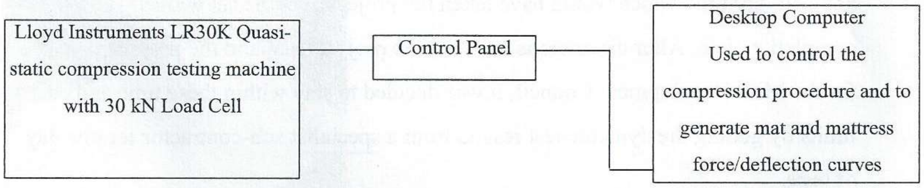


Figure 3.1 Line diagram of quasi-static testing and control arrangement

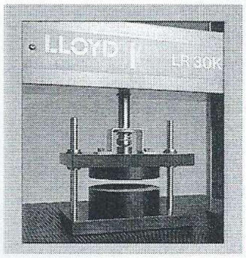


Figure 3.2 Lloyd Instruments LR 30K

3.2 Dynamic compression testing

Dynamic tests were carried out to simulate the action of a cow lying down on a cubicle bed. During the lying down sequence (Herlin, 1994) a cow must eventually make a downward movement of her carpal joint in order to get to the lying position. This action was simulated by dropping an eight kg mass (the carpal joint simulator) onto the cubicle bed surface.

These tests were carried out at ADAS Bridgets, Martyr Worthy, Hampshire by the Centre for Sports Technology Ltd of Greenwich (CST Ltd) which was sub-contracted to the project team because it has expertise in dynamic test procedures. These procedures have been developed for tests done on synthetic surfaces used in the sports and leisure industry and were found to be compatible with the dynamic test objective of this project. The test site was chosen because it was near to CST Ltd and because it had a range of mats and mattresses that were in continuous use for between 3 and 6 years.

The original intention of the project team was to develop a dynamic test machine and use it thereafter at various farm locations. However, sources contacted over a period of months who may been able to build and supply a test machine quoted a price and delivery time which would have taken the project over the set budget and completion date. After discussions between the project team and the project manager for the Milk Development Council, it was decided to stay within these time and cost limits by getting the dynamic test results from a specialist sub-contractor for one day of tests.

The equipment used by CST Ltd included:

- Tripod with an adjustable height;
- Accelerometer with a 60 mm diameter cylindrical indenter on an eight kg drop weight [the 60 mm diameter indenter is the standard size used for impact measurement in synthetic sports surface testing];
- Battery controlled magnet to hold (and drop when required) the eight kg weight;
- Laptop computer for recording results.

Figure 3.3a Eight kg weight used to simulate impacting knee of a dairy cow

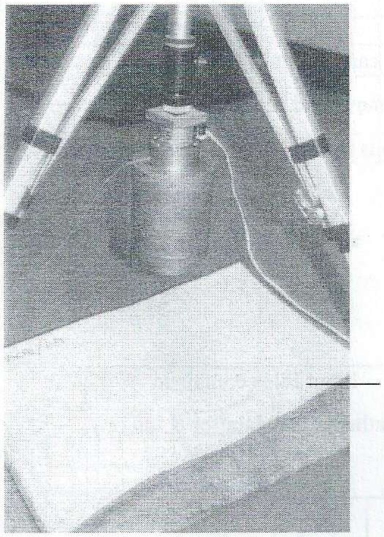


Figure 3.3b Tripod, eight kg weight and accelerometer above a Pasture Mat mattress

4.0 Computer modelling of impact absorption

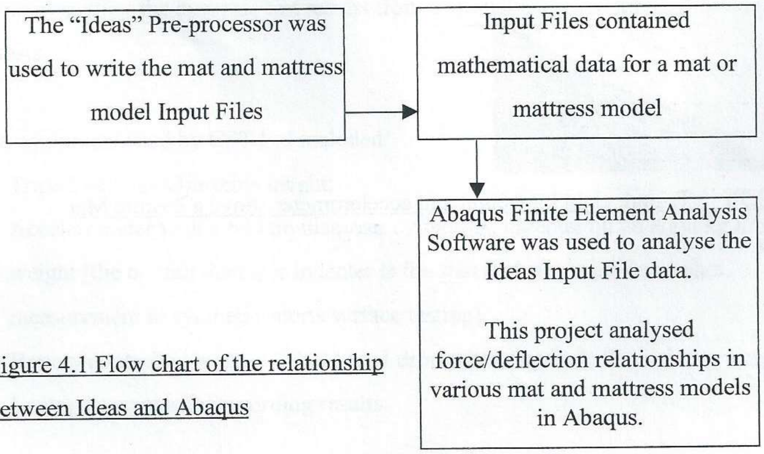
4.1 Finite Element Analysis

The basis of mathematically modelling a mechanical impact on a surface is Finite Element Analysis (FEA). FEA is a method of solving partial differential equations and, in this work, has been applied to calculations for stress and strain values in cubicle mats and mattresses when a cow applies an impact force.

Manual finite element calculations are difficult enough when dealing with linear elastic materials, such as concrete or steel, but are almost impossible when dealing with hyperelastic materials like ethylene vinyl acetate or rubber. Therefore, the computer software is essential. Hyperelasticity implies that the material will still return to its original state on unloading even when a large deformation has occurred during loading.

4.2 Ideas and Abaqus

The materials modelling in this project has been carried out in two separate, but related, computer aided engineering systems: Abaqus and Ideas. Ideas is the preprocessor (for model development) and Abaqus is the FEA post-processor (for analysis of results).



The "Ideas" Pre-processor was used to write the mat and mattress model Input Files

Input Files contained mathematical data for a mat or mattress model

Abaqus Finite Element Analysis Software was used to analyse the Ideas Input File data.

This project analysed force/deflection relationships in various mat and mattress models in Abaqus.

Figure 4.1 Flow chart of the relationship between Ideas and Abaqus

The Abaqus FEA software has been used for this project at the University of Glasgow under licence from HKS Inc. of Providence, Rhode Island, USA. Its particular value is as a results generator or post-processor called Abaqus/Post. In Abaqus/Post, graphics are presented which show the simulated action of a body impacting on a surface. That is, in the current work, a carpal joint hitting a mat or mattress.

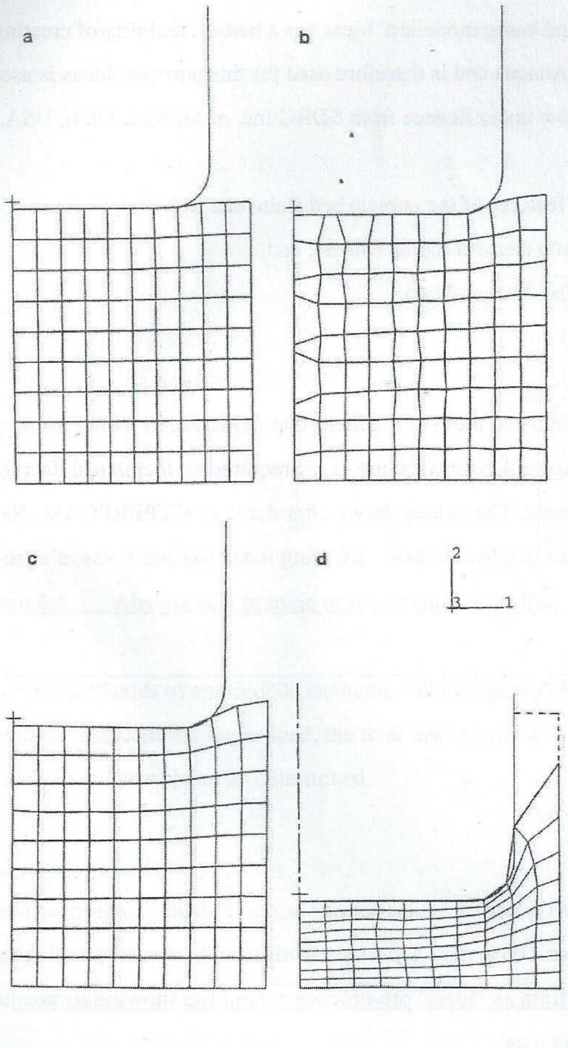


Figure 4.2 Abaqus/Post images of the progressively deforming shape of a hyperelastic material (such as a dairy cow mat or mattress) under compressive load (Thomson and others, 1999)

The results displayed in Abaqus/Post were dependent upon the quality of the fundamental modelling data written into the Ideas pre-processor. Finite element analysis is set up by creating a mesh of 'elements' (rectangular blocks) which, as a whole, make up the material being modelled. Ideas has a better capability of creating such a mesh compared to Abaqus and is therefore used for this purpose. Ideas is used at the University of Glasgow under licence from SDRC Inc. of Milford, Ohio, USA.

In summary, the essential features of the cubicle bed finite element analysis were:

- an input file for the finite element model (Ideas); and,
- an output file for results (Abaqus/Post).

4.2.1 The Input File

The input file is used to create the mesh of elements that represent, in model form, the material to be analysed. Figure 4.3 shows some of the required mathematical data for analysis of the mat or mattress. The values shown after the line 'HYPERFOAM, N=1' are for initial shear modulus (μ), hyperelastic stiffening index (α) and Poisson's ratio (ν), respectively.

```
*MATERIAL, NAME=EVA
**
*HYPERFOAM, N=1
0.48E6, 0.4, 0.2
*DENSITY
1000
**
```

Figure 4.3 An extract from an 'Ideas' pre-processor input file showing some of the Maxibed mat modelling data

Individual elements are created in the model by co-ordinated corner points called nodes. Figure 4.4 shows the elements of the Maxibed mat model illustrated in Abaqus/Post. The model is of the knee (carpus) contact area of the cubicle bed.

ABAQUS

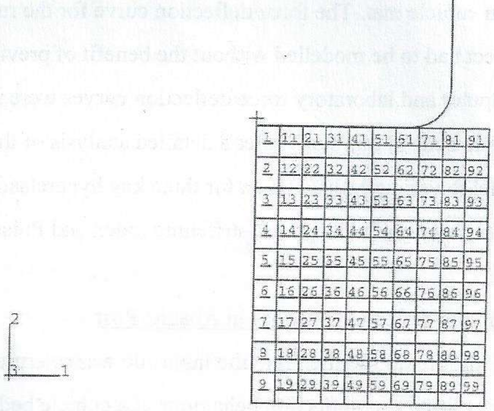


Figure 4.4 Abaqus/post graphic of the 'elements' of the Maxibed mat model

By creating a series of continuous elements and evaluating the extent of their individual displacement under load, the total displacement of the structure (a mat or mattress in this work) can be determined.

4.2.2 Abaqus/Post

Abaqus carried out the mechanical impact analysis and the results were viewed in Abaqus/Post where the forces and stresses in a typical cow movement were simulated in impact stages.

Force/deflection curve generation in Abaqus/Post became the primary task in order to verify the ability of the computer to simulate a compressed mat or mattress. That is, a sample of a cubicle bed material was compressed in a Lloyd Instruments 30 kN quasi-static testing machine and a force/deflection curve of this compression was extracted. Abaqus had to yield the same curve for confidence of its modelling reliability in this context.

This innovative work in agricultural engineering proved to be a time-consuming process. Previous work in matching curves for ethylene vinyl acetate foam materials was analysed and this was the basis of successfully creating a model for the EVA foam cubicle mat. The force/deflection curve for the rubber crumb mattress in this project had to be modelled without the benefit of previous similar work. However, computer and laboratory force/deflection curves were successfully matched for both cubicle beds in this study after a detailed analysis of the reaction of the computer model to various values given for three key hyperelastic engineering constants of initial shear modulus, power-stiffening index and Poisson's ratio.

4.3 Force/deflection analysis in Abaqus/Post

The information written into the input file was interpreted by Abaqus to show the impact force and deflection behaviour of a cubicle bed material. The primary task was to match computer results with laboratory quasi-static uni-axial compression tests in order to derive the engineering constants, initial shear modulus ('μ' in the input file), power-stiffening index ('α') and Poisson's ratio ('ν'), for the rubber crumb and EVA beds. This was analogous to work done on training shoe cushioning (Thomson and others, 1999).

The physical compression tests were carried out using a Lloyd's Instruments LR30K Universal Testing Frame fitted with a 5 kN load cell and a 45 mm diameter steel indenter, which simulates the knee joint compression of a dairy cow. 45 mm is a smaller diameter than that of an adult dairy cow but it was possible to adapt the force and deflection results for this diameter to those that would result from using a diameter more like the 120 mm diameter of a cow joint (Dumelow, 1995). The deflection of the mat or mattress sample was controlled by a computer and force/deflection curves were printed out. Figure 4.5 shows the force/deflection curves for the EVA Maxibed mat and the rubber-crumb Pasture Mat mattress.

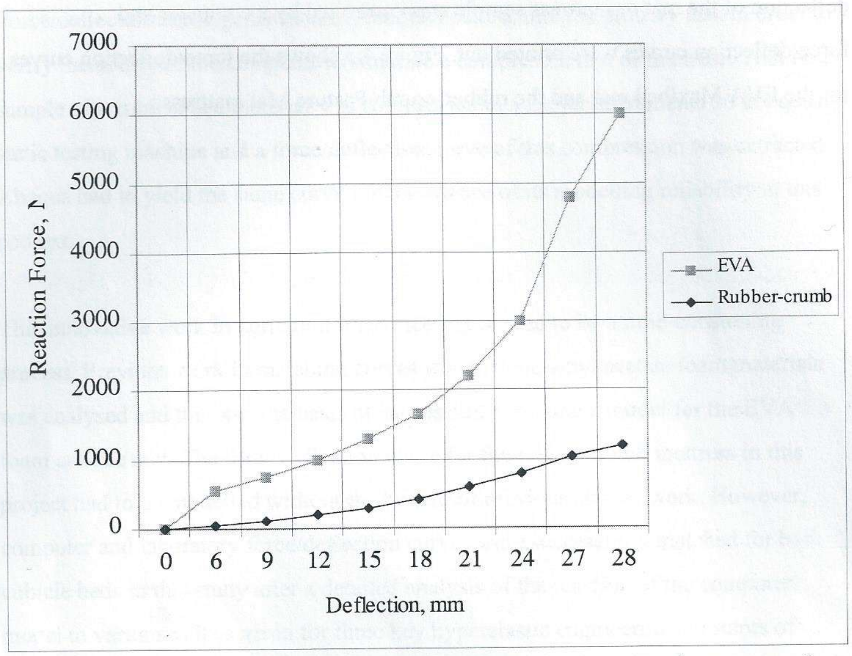


Figure 4.5 Quasi-static compression test Force/Deflection curve for new samples of an EVA Maxibed mat and a Rubber-Crumb Pasture Mat mattress

The compression tests that produced the force/deflection curves were the basis, therefore, for the Abaqus modelling. The steel indenter was the 'knee' and was modelled as a rigid surface connected to a reference node, node 1000, which was displaced in the –2 direction (Figure 4.4) to bring the knee onto the cubicle bed model and compress the elements (Thomson and others, 1999).

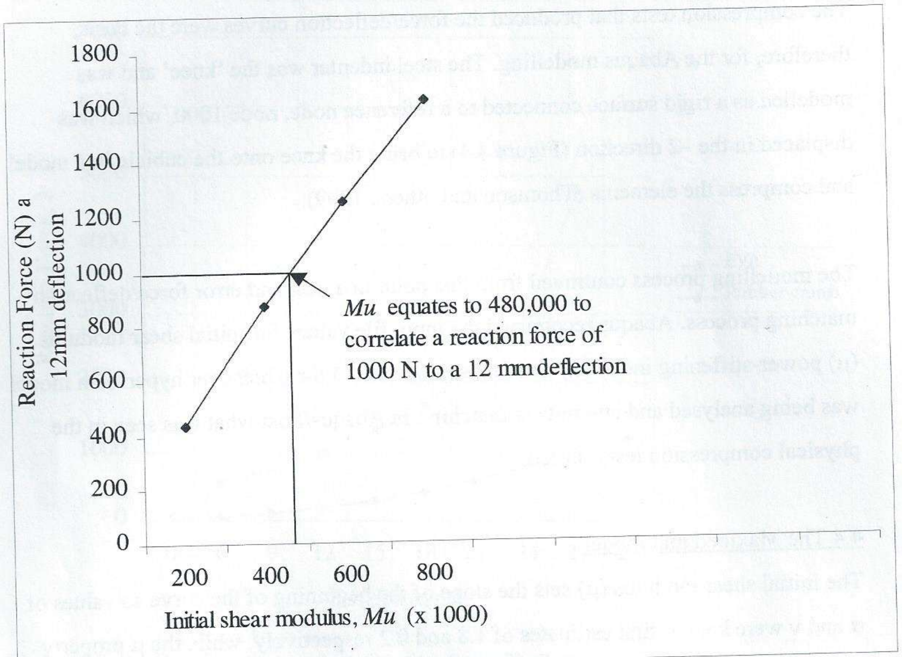
The modelling process continued from this point in a trial and error force/deflection matching process. Abaqus recognised the input file values for initial shear modulus (μ) power-stiffening index (α) and Poisson's ratio (ν) for whichever hyperfoam model was being analysed and attempts at matching in Abaqus/Post what was seen in the physical compression tests started.

4.4 The Maxibed mat model

The initial shear modulus (μ) sets the slope of the beginning of the curve so values of α and ν were kept at first estimates of 1.8 and 0.2 respectively, while the μ property was altered in stages to determine its matching value for the beginning of the physical compression curve. The first four values of μ tried were 0.2×10^6, 0.4×10^6, 0.6×10^6 and 0.8×10^6. These were used to produce force/deflection curves in Abaqus and were plotted in a straight-line graph against values of reaction force at 12 mm. 12 mm was chosen as the point at which the curve starts to bend.

The laboratory curve showed a reaction force of 1000N at 12 mm deflection and the aim in the computer model was to find the μ value, in the straight-line μ values plotted against reaction force at 12 mm deflection, which correlated to a reaction force of 1000N.

Figure 4.6 shows that the value of μ found to correlate to a reaction force of 1000N at 12 mm deflection was 480,000.



Mu equates to 480,000 to correlate a reaction force of 1000 N to a 12 mm deflection

Figure 4.6 Curve of Reaction Force at 12 mm deflection for four Maxibed Mat computer models with four different values for Initial Shear Modulus

The laboratory force/deflection curve for the Maxibed mat had a reaction force of 1000 N at 12 mm deflection and this had to be matched in the computer model. This was achieved by finding the correct value of μ for the finite element analysis.

The second stage of this matching process was to re-run the input file with the newly established value for μ of 0.48×10^6 in place and again produce a force/deflection curve in Abaqus/Post. This time the requirement was to find a matching value for the power-stiffening index, α, which sets the upper part of the curve. The matching value was found to be 0.4.

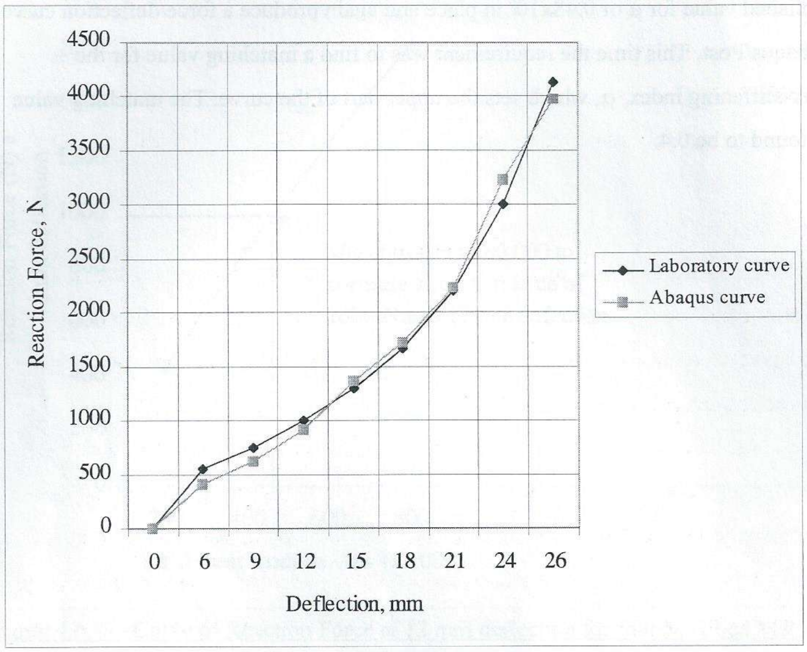


Figure 4.7 Closely matching curves from laboratory quasi-static compression testing and from an Abaqus computer simulation for the Maxibed EVA mat

4.5 The Pasture Mat mattress model

The above process was repeated for the Pasture Mat mattress model. The behaviour under load of the mattress was different and the corresponding values for μ and α were different. That is, for the Pasture Mat mattress the Abaqus values of μ and α that produced a match for the laboratory curve for the Pasture Mat were more difficult to find.

An innovative approach was taken in the matching process. Instead of inputting values of μ and α on a trial-and-error basis, as for the Maxibed model, the Abaqus programme capability showed its worth when it was 'asked' to find the required values after the target curve values were installed in the programme. That is, the known values for stress and strain (these are related mechanical properties to force and deflection) from the laboratory curve were manually inserted in the model input file and this produced the desired matching effect. The project team viewed this successful matching as major benefit of the work and look forward to using the skills developed in further modelling work that can help farmers with product information.

The matching values of α and μ for the pasture mat mattress were produced by Abaqus in 3 estimates for 3 programme runs (N=3). These were:

	μ	α	ν
1.	32300.3	3.08710	0.20
2.	3857.35	3.04830	0.20
3.	96716.1	-2.04928	02.0

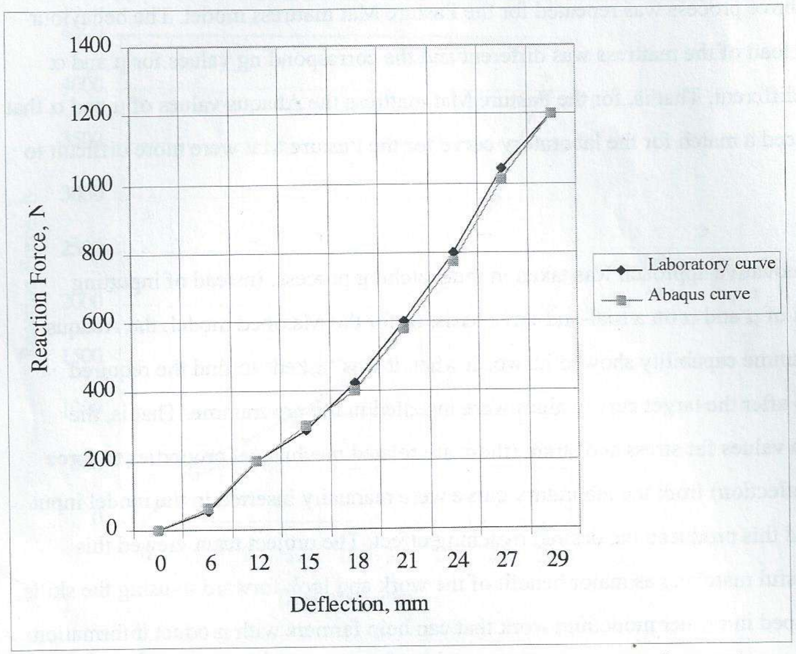


Figure 4.8 Closely matching curves from quasi-static compression testing and from an Abaqus computer simulation for the Pasture Mat rubber-crumb mattress

4.6 The value of successful computer modelling

The force-deflection responses of the materials of the two bed types were successfully modeled in Abaqus FEA. This gave confidence in the ability of the model to predict the effect of changes in, for example, rubber-crumb thickness and density, two properties that were expected to change after prolonged use.

Test results from impact tests showed that a new rubber-crumb bed is more compliant than a new EVA bed and is, therefore, more likely to prevent leg-joint injury. However dynamic impact testing of three-year-old beds suggested that the rubber-crumb type was less compliant than EVA and this reduced compliance of the rubber-crumb mattress was accompanied by an increase in density and a reduced thickness. This was simulated in Abaqus by reducing the rubber-crumb model thickness by 50% and looking at the force-deflection response. This. curve confirmed a reduced softness or compliance compared to the full-thickness rubber-crumb mattress.

This means that Abaqus can be used quickly, cost-effectively and with confidence to estimate the effect of a range of rubber-crumb mattress and EVA mat specifications.

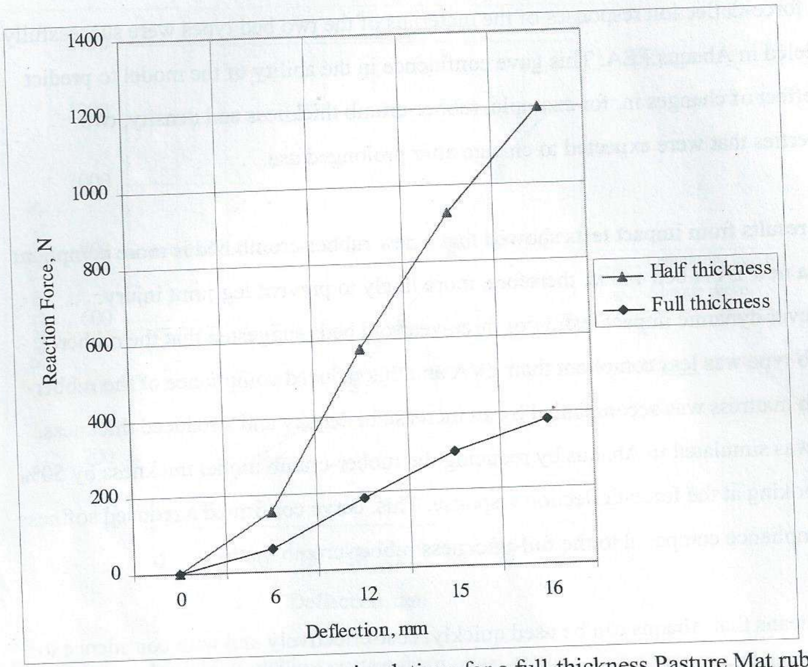


Figure 4.9 Abaqus computer simulations for a full-thickness Pasture Mat rubber-crumb mattress compared to one compressed to half-thickness

The full-thickness Pasture Mat was tested in a mechanical engineering laboratory. The reduced thickness (because it had compacted with use) Pasture Mat was tested in place in a dairy house cubicle. The full-thickness Pasture Mat was found to be softer. Figure 4.9 is the computer model illustration of the hardening of the Pasture Mat in time and verifies the success of the finite element analysis carried out.

5.0 Impact absorption comparison of cubicle bed products from quasi-static compression testing

5.1 Force/deflection curves as a measure of cubicle bed softness

Nilsson (1988) set out two curves of maximum and minimum softness in a dairy cow cubicle. The curves were set after measurement of bed surface deflection for a given impact force with a laboratory test indenter of 100 mm and consideration of cow preferences in a behavioural study. The theory described is that a cow requires softness for knee force peaks during the actions of getting up and down and some stability while she is standing. These curves are shown as figure 5.1 adapted for the 45 mm diameter indenter used in this project.

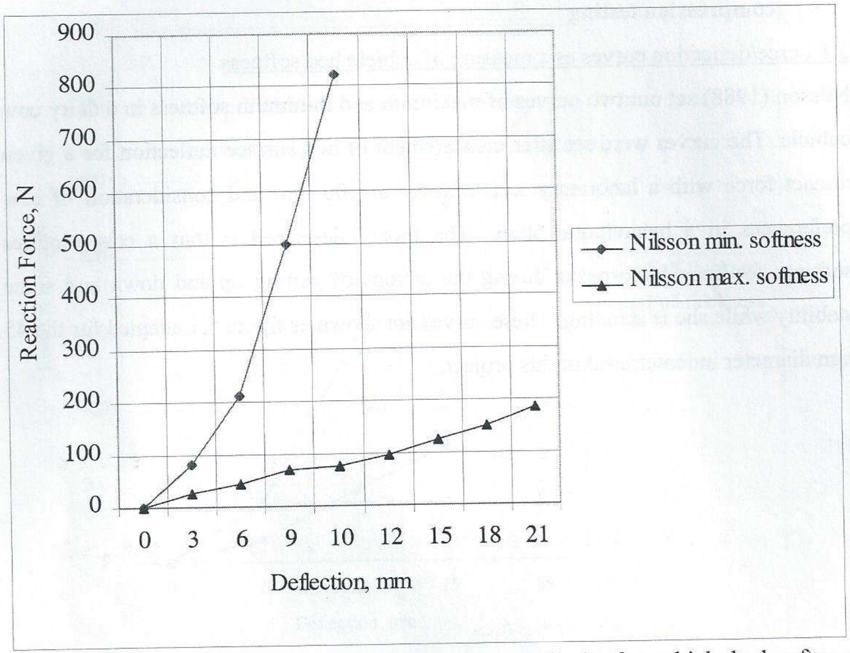


Figure 5.1 Nilsson (1988) upper and lower curve limits for cubicle bed softness for a 45 mm diameter indenter

Figure 5.1 is a graph of cubicle bed surface deflection for a given impact force. The upper and lower limits were set out by Nilsson (1988) and have been used in this project as part of the evaluation of softness / hardness in cubicle beds. See Figures 5.2 and 5.3.

Cubicle bed surfaces can be set against the upper curve as a softness minimum and the lower curve as a hardness minimum.

Comparison must be done with the indenter size in mind. Dumelow (1995) adapted Nilsson's curves for a 120 mm diameter spherical indenter because he argued that it was nearer to the average size of an adult dairy cow knee. The adaptation is done using the following equation:

$$F_2 = F_1 \text{ x } [(3R_2 - d)/(3R_1 - d)]$$

Where: F1 = the impact force for a given deflection with indenter size 1 (100 mm);
F2 = the impact force for a given deflection with indenter size 2 (120 mm);
R1 = indenter 1 radius;
R2 = indenter 2 radius;
d = deflection.

Dumelow (1995) showed that a number of synthetic beds are not within the comfort range set out by Nilsson's curves. They were essentially too hard.

For the current work Nilsson's comfort curves have been adapted for a 45 mm indenter used in quasi-static compression tests. The force versus deflection curves produced are compared to Nilsson's upper and lower limit.

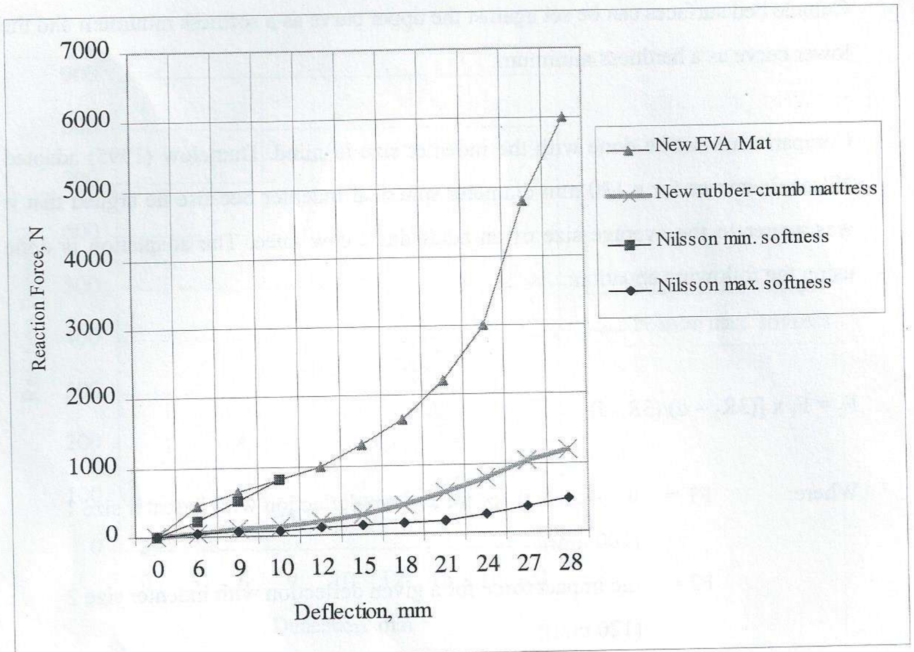


Figure 5.2 Maxibed EVA mat and Pasture Mat rubber-crumb mattress compared to Nilsson (1988) upper and lower softness limits for a 45 mm diameter indenter

NB: The curve for minimum softness from Nilsson (1988) has deflection values up to, but not greater than, 10 mm.

The Maxibed curve, Figure 5.2, shows it to be close to the minimum softness limit of Nilsson's two curves. That is, any harder would be too hard for the lying down comfort of a cow.

The Pasture Mat mattress curve, Figure 5.2, shows that, according to Nilsson's parameters, it is close to the softness maximum. That is, any softer and it would be too soft for the stability of a standing cow.

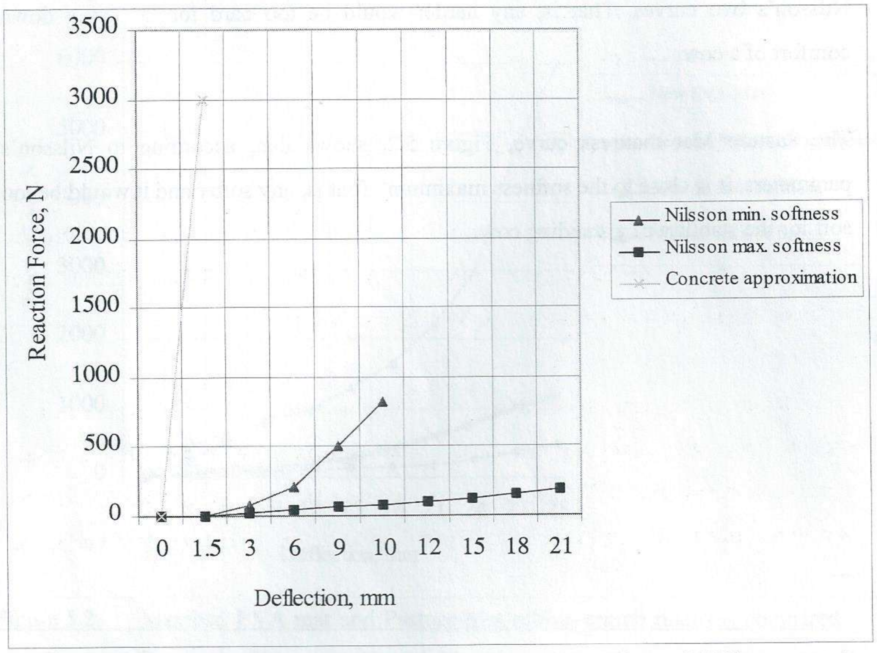


Figure 5.3 A concrete cubicle bed softness compared to Nilsson (1988) upper and lower limits

To illustrate the importance of having a soft top to a cubicle bed, a reinforced concrete approximate force/deflection relationship is shown in figure 5.3. Concrete is well outside the comfort range.

5.2 Dairy cow bed quasi-static standard test

A quasi-static test can be carried out for any cubicle bed sample and compared to the Nilsson (1988) limits. This is a simulation of the cow's upward movement where she compresses the mat or mattress in a sustained push. The test indenter diameter must be known and correlated to those used by Nilsson (1988).

A limitation to this test, as a measure of whether or not a cubicle bed is comfortable enough for lying and standing, is that static compression machines are not able to test a mat or mattress in-situ. Therefore, the testing is confined to samples in a laboratory situation. However, this is still useful information for a farmer considering an investment.

A site based dynamic impact test, that can be used to evaluate new and aged mats and mattresses, is described in Section 7.0.

6.0 Dynamic impact testing of cubicle beds

6.1 Dynamic impact load testing of surfaces via Association Francaise de Normalisation NF P90-104 – Determination of Sports Qualities: Comfort and Performance – Accelerometric Method

This procedure was used in this project to determine the impact absorption properties of new and aged cubicle beds. The test recorded a response from a mat or mattress in terms of a maximum acceleration of a weight (knee simulator) when it was dropped from a height of 174 mm. The test is based upon the principle that a higher recorded peak acceleration implies a harder or less compliant surface.

The cubicles at the farm used for the tests have been occupied in an all year round housing system for a number of years. Therefore, the beds have had more use than at other locations where summer time grazing is practised.

There were 4 mats and mattresses tested:

		Year installed	**Continuously used**
Used Maxibed mat	Tested in place	1997	Yes
Used Pasture Mat mattress	Tested in place	1997	Yes
New Maxibed mat	Tested in laboratory	-	-
New Pasture Mat mattress	Tested in laboratory	-	-

Table 6.1 Cubicle mats and mattresses used for dynamic impact test procedure

The test apparatus included:

- A tripod with an adjustable height;
- An accelerometer with a 60 mm diameter cylindrical indenter on an eight kg drop-weight;
- A battery-operated electromagnet to hold and subsequently release the eight kg weight;
- A laptop computer for recording the results.

See Figures 3.3a and 3.3b in Section 3.0 for photographic images of the dynamic impact test apparatus.

The test procedure was:

1. The tripod was set up to give a drop height of 174 mm, established by making a few trial drops, as that required to produce 2000 N. Dumelow (1995) suggested that 2000 N is the force generated by the knee joint of a 600 kg descending cow;
2. The magnet was engaged to hold the eight kilogram mass above the impact point then released to allow the drop-weight to impact upon the cubicle bed;
3. The accelerometer signal was passed to the computer for calculation of the maximum acceleration and hence the peak force;
4. Steps two-four repeated for the number of test drops required.

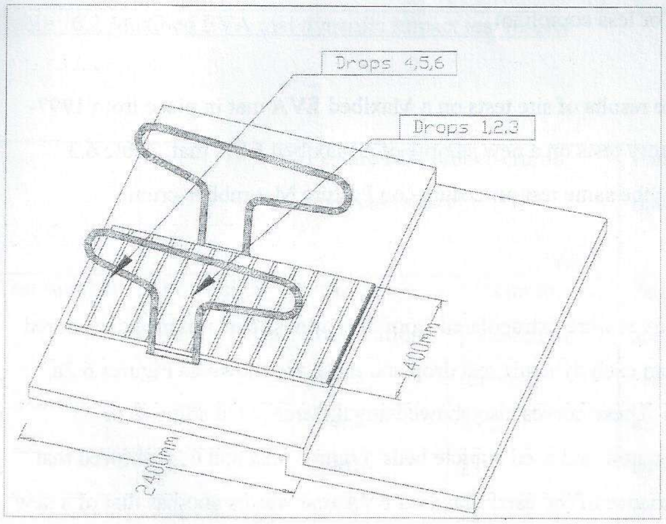


Figure 6.1 Impact test drop points

The drop points 1, 2 and 3 shown in Figure 6.1 were in the area of the cubicle mat or mattress that normally received the dynamic impact of a knee joint (carpus) when a cow lay down. Therefore, this area had been well used and so the long-term impact performance test had to take place at these points.

Drop points 4, 5 and 6 were in an area of the bed that did not normally receive a knee joint impact and was used in this test to give an indication of 'un-used' or short-term impact resistance performance.

6.2 Dynamic impact test results

Peak acceleration, force and deflection were recorded for a drop. Test drop points 1,2 and 3, shown in Figure 6.1, were for the area of the bed normally hit by a descending cow. Points 4,5 and 6 were for an un-used area at the front of the cubicle. These two different areas of the cubicle bed were tested to determine the impact properties of an old and an 'as-new' bed.

Peak acceleration is an indication of hardness. It is a measurement of the rate at which the eight kilogram mass used in test came to rest after it hit the cubicle bed surface. The higher the peak acceleration, the quicker the mass came to rest because the surface was harder or less compliant.

Table 6.2 shows the results of site tests on a Maxibed EVA mat in place from 1997-2000 and of laboratory tests on a new sample of a Maxibed EVA mat. Table 6.3 shows the results of the same test procedures on Pasture Mat rubber-crumb mattresses.

Force/deflection curves were extrapolated from the softness performance data stored in the computer from each dynamic test drop and these are shown as Figures 6.2a, 6.2b, 6.3a and 6.3b. These curves also showed any differences in softness or compliance between new and used cubicle beds. Figures 6.2a and 6.2b showed that the softness performance of the used Maxibed EVA mat was as good as that of a new one. Figures 6.3a and 6.3b showed that the Pasture Mat rubber-crumb mattress became significantly harder after use between 1997 and 2000.

		Maxibed EVA mat (new)		Maxibed EVA mat (4th year)	
Test number	Drop height (mm)	Peak acceleration (m/s^2)	Maximum penetration (mm)	Peak acceleration (m/s^2)	Maximum penetration (mm)
1	174	237.9	11.3	255.1	13.1
2	174	244.0	11.9	258.7	13.0
3	174	243.9	12.0	258.6	13.1
	average	242.0	11.7	257.0	13.1

Table 6.2 Maxibed EVA mat dynamic impact test results

		Pasture Mat rubber-crumb mattress (new)		Pasture Mat rubber-crumb mattress (4th year)	
Test number	Drop height (mm)	Peak acceleration (m/s^2)	Maximum penetration (mm)	Peak acceleration (m/s^2)	Maximum penetration (mm)
1	174	204.5	25.2	489.1	11.7
2	174	228.8	23.8	499.0	11.5
3	174	240.8	22.7	507.5	11.9
	average	225	23.9	498.5	11.7

Table 6.3 Pasture Mat rubber-crumb mattress dynamic impact test results

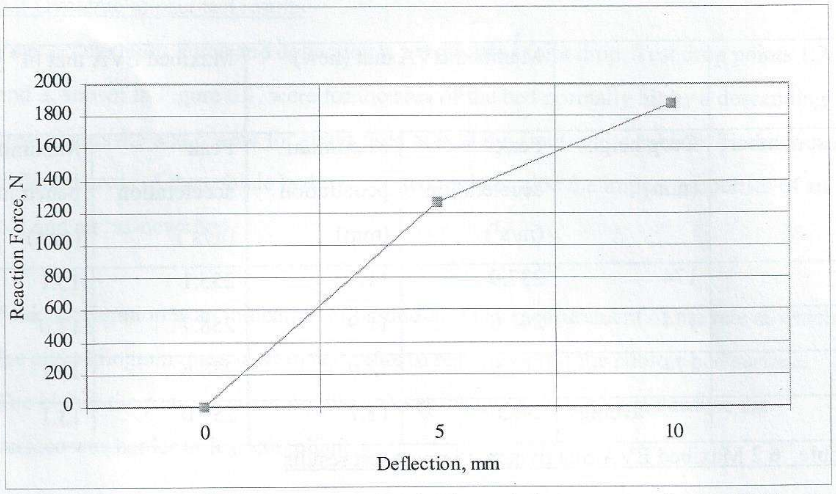


Figure 6.2a Force/deflection curve for the dynamic impact test of a new EVA Maxibed sample

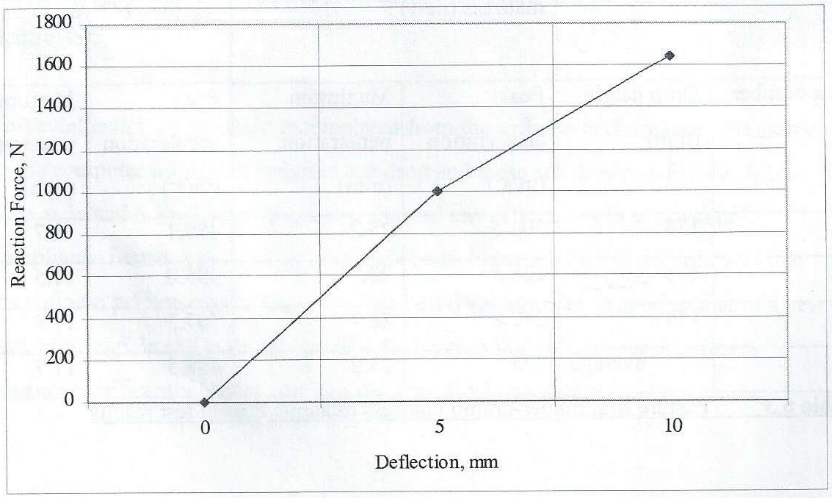


Figure 6.2b Force/deflection curve for the dynamic impact test of an EVA Maxibed mat in place in a cubicle from 1997-2000

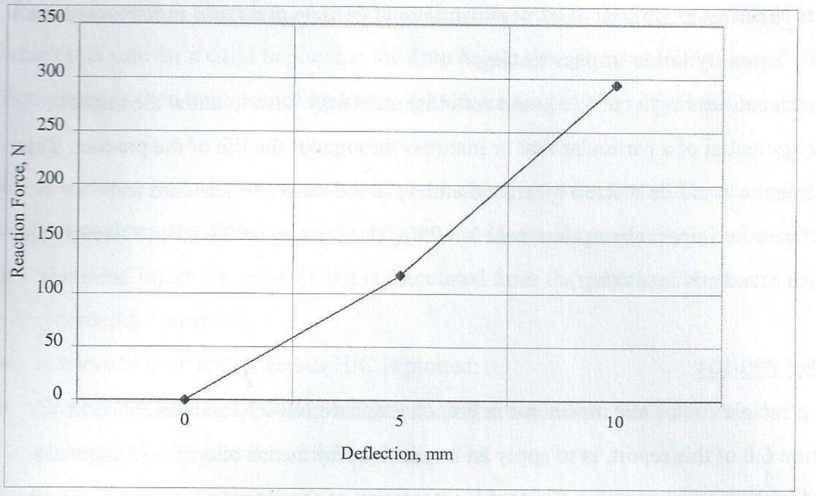


Figure 6.3a Force/deflection curve for the dynamic impact test of a new Pasture Mat rubber-crumb mattress sample

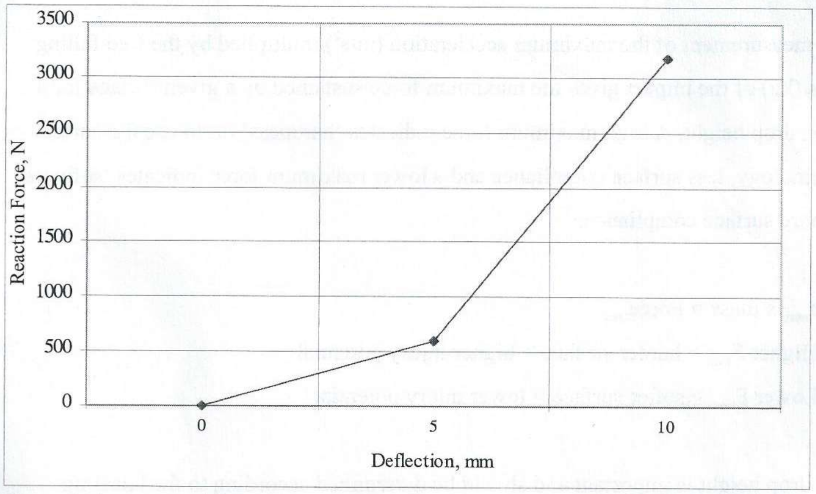


Figure 6.3b Force/deflection curve for the dynamic impact test of a Pasture Mat rubber-crumb mattress in place in a cubicle from 1997-2000

NB: Figure 6.3a shows that approximately 300 N of force was required to produce a mattress surface deflection of 10 mm. Figure 6.3b shows that approximately 3000 N of force was required for a surface deflection of 10 mm. This indicates a significantly increased hardness level in the used mattress.

7.0 Minimum standards of performance of cubicle mats and mattresses based upon dynamic impact testing

Farmers considering a cubicle house refurbishment may wish to know the impact injury potential of a particular mat or mattress throughout the life of the product. This information could be offered by manufacturers in the form of a standard test certificate for impact absorption from NF P90-104 (France) or BS EN1177:1998 (The British Standards Institution).

7.1 NF P90-104

The principle of this test, as set out in French Standard NF-P90 and described in Section 6.0 of this report, is to apply an impact load by means of a free-falling mass fitted with an accelerometer. By double integration of the record of acceleration with respect to time, the force-deflection characteristic of the surface under test can be gained.

The measurement of the maximum acceleration (m/s^2) multiplied by the free-falling mass (kg) of the impact gives the maximum force sustained by a given surface for a given drop height. A high maximum force indicates 'hardness' or, to use the correct terminology, less surface compliance and a lower maximum force indicates 'softness' or more surface compliance.

- a_{max} x mass = $Force_{max}$
- Higher F_{max} > harder surface > higher injury potential
- Lower F_{max} > softer surface > lower injury potential

The drop height is important and should be determined according to the kneeling distance of an adult dairy cow.

7.2 Critical fall height test for playground surfaces (BS EN 1177:1998)

This test principle is one that determines an injury risk to the head of a child when an impact is made on a surface. The risk is expressed as a Head Injury Criterion (HIC) value and the critical value for HIC is 1000. Above 1000 is too high for safety.

The requirement is, therefore, to determine the maximum height above a surface at which it is safe for a child to play i.e. the drop height that gives an HIC value of 1000. Equipment is then built according to that maximum height (the critical fall height).

- A surface is tested with at least 4 drops of a headform made at different heights;
- The peak acceleration experienced by the headform due to gravity is recorded;
- The Head Injury Criterion (HIC) is calculated from the peak acceleration recorded for each drop;
- A curve of drop height versus HIC is plotted;
- Critical fall height is the drop height which corresponds to HIC=1000 on the plotted curve (Figure 7.1 of this report).

Typical examples of trace of acceleration against time and curve of HIC values against drop height

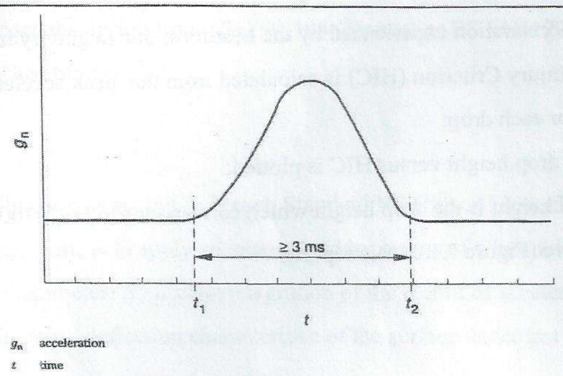


Figure C.1 Typical trace of acceleration against time

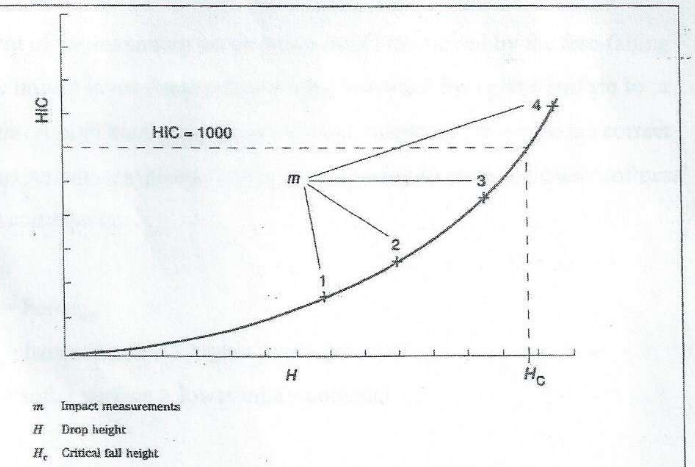


Figure C.2 Typical curve of HIC values against drop height

Figure 7.1 Curves from BS EN 1177:1998 that illustrate an example of impact test results used to determine the Critical Height for a playground surface for children

7.3 Dairy cow bed dynamic impact standard test proposal

The test procedure of BS EN 1177:1998 is not required in cubicle bed testing because the fall height is fixed (the cow knee fall height).

A mat or mattress can be tested at a farm according to NF-P90, described in Section 6.0, and the maximum acceleration recorded for a cow knee drop height. The maximum force can be calculated from maximum acceleration if the impacting mass is known.

A mat or mattress that is known, from field trials, research literature and farmer experience, to be good at minimising systematic injury in cows can be said to be the benchmark for acceptable impact injury reduction potential. The maximum acceleration recorded on it, for the cow knee drop height, will be the indicator of minimum compliance or softness. Comparisons of other new and aged products can be made against this benchmark using the same test procedure.

- Fall height is fixed according to knee fall height;
- Peak acceleration is variable according to the surface;
- Surfaces are tested for peak acceleration from the cow knee fall height and those that are within a close range of the peak acceleration that equates to that of the benchmark cubicle bed may be deemed to satisfy.

Observation work carried out at SAC Auchincruive and at Myerscough College in 1997 and 1998, MDC Report 96/R6/01, revealed that cows housed in cubicles with new Pasture Mat mattresses had better lying times and fewer injuries than those in cubicles with new Maxibed mats. Quasi-static tests were carried out in this work on new Pasture Mat and Maxibed samples that showed the Pasture Mat to be the softer of the two types. Nilsson (1988) set standard softness and hardness limits for cubicle beds that showed a new Pasture Mat sample to be well within these limits and a new Maxibed sample to be on the borderline of "too hard".

These findings from three different research projects suggest that a new Pasture Mat is a satisfactory cubicle bed and new Pasture Mat softness has been evaluated in terms of dynamic impact peak acceleration to give a benchmark for cubicle bed softness performance. The new Pasture Mat NF-P90 peak "a" value established was 225 m/s^2 and this is proposed as a softness datum.

For comparison to this dynamic impact tests were carried out on a 4th year Pasture Mat and Maxibed and a new Maxibed. The results are shown in tables 6.2 and 6.3.

The new Pasture Mat (225 m/s^2), the new Maxibed (242 m/s^2) and the 4th year Maxibed (257 m/s^2) could all be deemed to satisfy the proposed dynamic impact softness test. However, the 4th year Pasture Mat (498.5 m/s^2) is unsatisfactory. This suggests that the rubber-crumbs in the Pasture Mat tested have compacted into a dense mass of rubber. The Maxibed was shown by these tests to be a more stable product.

Further work to establish an international procedure for an accelerometer test for animal beds is necessary.

8.0 Discussion

8.1 Injury to hocks and knees

This study was done because it was known from previous work that dairy cows sustain varying levels of impact injury according to the type of cubicle surface they get to lie upon.

Kelly and others (1999) reported in MDC research report 96/R6/01 that there was a significant difference between mattress and mat groups, ($P=0.009$), in terms of the number of injury-free cows (cows which scored '0') with the mattress cows faring better. However, when comparing mattresses and mats in terms of specific injury levels there were no significant differences found.

The carpal joint (knee) injury results were similar to the hock results. There was a significant difference between the mattress and mat groups in terms of the incidence of cows

uninjured (0 scores), with the mattress cows doing better, ($P < 0.001$). The results for scores of >1 also showed that there was a significant difference between the mattress and mat cows, again with the mattress cows faring better, ($P < 0.001$). For scores of 5 (either knee swollen) and 10 (both knees swollen) there was no significant difference.

8.2 Static and dynamic impact testing in injury prediction

To understand more about the influence of hardness on joint injury this project looked at cubicle mat and mattress tests of static and dynamic compression. Static compression tests were carried out in laboratory conditions on samples of a new Pasture Mat rubber-crumb mattress and a Maxibed ethylene vinyl acetate mat. This was a simulation of the getting up action of a cow and the forces generated were recorded. Dynamic impact tests of these cubicle beds were carried out at a farm (well-used beds) and in laboratory conditions (new samples) to simulate downward movement and to establish any variation in hardness in the long term. The results suggested that the Pasture Mat mattress crumbs had compacted and the effect of this was to make the bed harder than it was when new. The performance of the Maxibed in the long term was more stable with the new and old beds tested showing similar impact absorption responses.

8.3 Finite Element Analysis software and cost-saving injury prediction research

The expense of setting up tests of cubicle beds was considered in the study and a computer model of a Pasture Mat and a Maxibed, based upon Abaqus Finite Element Analysis software, was designed to help avoid high research costs in the future. In this model, the injury reduction potential can be simulated for short and long term periods of use.

8.4 Further work in this area of research

Long term performance information is essential to farmers when making a purchase decision. Further work is needed to make computer simulation models of other mats and mattresses and to develop further the standard impact test proposed in Section 7.0 for on-farm performance ratings to be carried out.

9.0 Conclusions

The findings of this project were as follows:

- future impact testing of cubicle beds of any type and age can be tested by quick and cost-effective analysis using the computer model;
- future impact testing of cubicle beds of any type and age can be tested by quick and cost-effective analysis using an international standard test of softness as set out in this report;
- new EVA mat injury reduction performance was shown to be matched by a 4th year equivalent which suggested that these beds are a reliable long-term investment;
- new rubber-crumb mattresses showed the best short-term injury reduction performance but a significantly reduced long-term performance.

The causes and prevention of injury to knees and hocks in dairy cows has been studied for many years. Synthetic cubicle beds have been found to be an excellent addition to a dairy house. This work has added to the body of information on this topic by showing results from computer modelling and from laboratory and farm mechanical tests.

10.0 Farmer / Practical Recommendations

Recommendations to farmers are:

! Consider the variation in comfort performance of a mat or mattress over time before agreeing a purchase;

! Ask the supplier if dynamic impact and static test results are available for their product and how they compare to the proposed standard of softness described in this report;

! Ask the supplier to include a three-year check of bed softness using the dynamic test described in this report.

11.0 References

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