Mechanical tests and computational models for evaluating the cushioning performance of dairy cow cubicle beds

Gary Tierney

SAC Environment Division

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Abstract

Comfort from dairy cow synthetic beds is quantifiable using animal observation trials, but these are expensive and time-consuming. Finite Element Analysis (FEA) is a computational technique used for engineering stress and deformation analysis. Accelerometric testing is used to test the cushioning offered by athletics tracks and synthetic field sports surfaces. In the current work all three of these research methodologies were used to assess the comfort performance of two commonly used cubicle or free-stall synthetic beds, rubber-crumb mattresses and ethylene vinyl acetate (EVA) mats.

The aim of the animal observation study was to gain primary data on the general health and milk production performance of cows housed in cubicles with the two bed types, as well as on the specific matters of leg-joint injury and lying down and getting up behaviour. The main findings were that cows on rubber-crumb mattresses had fewer leg joint injuries and showed lying behaviour that implied greater comfort, but these advantages did not show up in the milk production data. FEA was used to assess free-stall bed cushioning during the quasi-static push of the getting-up movement of a cow and to predict variation in performance in time or as a result of an altered bed specification. Laboratory quasi-static force-deflection responses of the materials of the two bed types were closely matched in the Abaqus FE code, giving confidence in the integrity of the model. Accelerometric testing was used for the assessment of two further performance criteria vital to a bed purchase decision. First, impact absorption performance during the dynamic lying down movement of a

cow and, second, variation in cushioning performance in time as a result of having been used by a herd for three years. The results from the accelerometric tests showed that the EVA foam cubicle bed was the more time-stable product of the two.

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The Affluent Society (1958)

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Chapter 1.0 Introduction and literature review

1.1 Objectives

A symbiosis between agricultural and mechanical engineering was the impulse for the establishment of the A & M universities in Alabama, Florida and Texas, which have contributed to the knowledge base and economic sustainability of rural communities in America for more than 100 years. This thesis has emerged from a similar agricultural and mechanical engineering connection and proposes two new methods to measure the cushioning performance of two of the best-selling types of dairy cow cubicle bed, rubber-crumb mattresses and ethylene vinyl acetate (EVA) mats.

These two proposed measurement methods of a synthetic bed force-deformation relationship are nonlinear finite element analysis, based upon a quasi-static compression test, and a vertical drop dynamic impact test. By deforming, a floor can reduce the contact stress on a limb by redistributing the load over a larger area and a longer contact period (Webb and Nilsson, 1983).

The quasi-static compression test simulates the push that a cow makes in order to get up from a lying position. The dynamic impact test simulates the drop that a cow makes in order to get into the lying position and has a further application as a method for evaluating the long-term cushioning performance of cubicle beds *in situ*. Upward and downward movements are both a potential cause of injury to the foreknee joint of a cow's leg if the cubicle bed is too stiff; new condition cushioning performance may not necessarily be sustained throughout the 20 year design life of a cubicle house.

Many cubicle bed products are now on the market, with competing manufacturers making claims about good injury-reduction potential, better lying times and even improved milk yield. Loose bedding material such as sand and chopped-straw or sawdust are alternatives to synthetic cushions if laid in sufficient thickness but sand can adversely affect the waste handling system and sand, straw and sawdust all increase materials and labour costs to the farm (Dumelow, 1995). So, the synthetic cubicle bed is an increasingly popular purchase, but what type is a farmer best advised to choose? Is it wise to invest in a higher level of cow comfort in the belief that this will lead to more milk yield? Is new-condition cushioning performance going to be maintained after a number of years of use? This thesis aims to assist farmers in their purchase decisions, by examining these performance criteria. Dairy building design practice includes reference to BS 5502 Part 40: 1990, Buildings and Structures for Agriculture (BSi, 1990), which has guidance on cow cubicle length and width, but there is no stated performance standard for bed surface cushioning.

1.2 Dairy farming fundamentals

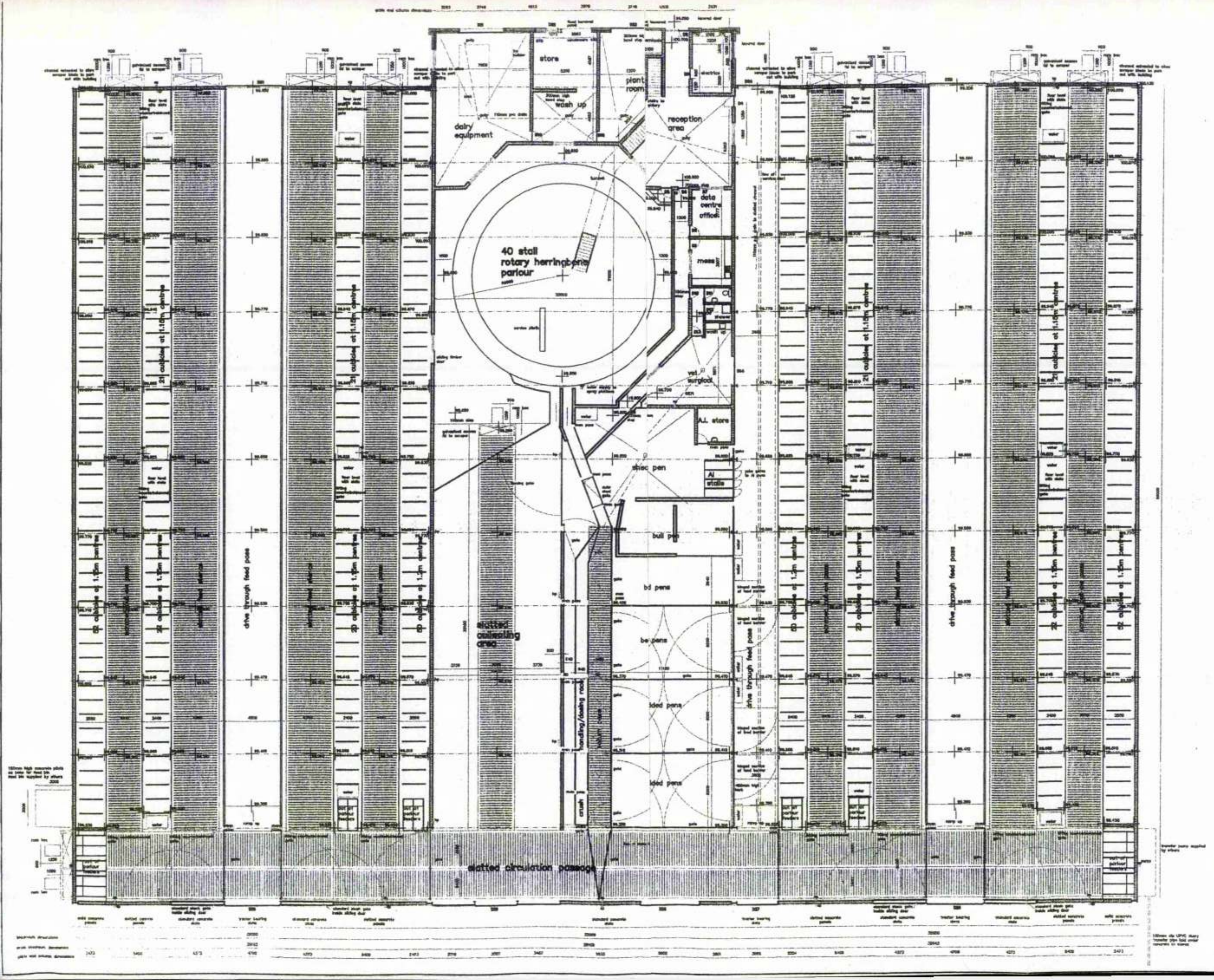
In 2000 the total production of cow's milk in the European Union was 121.2 million tonnes (The Dairy Council, 2001). The average price paid to farmers in the EU in 2000 was 0.30 Euro per kilogram, giving an income from milk sales of approximately 36.36 billion Euro (The Dairy Council, 2001). This implies that the dairy herds are a valuable part of the EU economy and therefore the buildings in which they are managed should foster good health and welfare.

Milking cows are kept inside in Northern Europe during winter because they are not able to withstand harsh weather. In Scotland the traditional cow house is known as a byre, within which a cow is tied in a space in which she is fed and from which her milk is collected. Byre is also the term used in Cumbria, but in more Southern parts of England traditional cow houses are called a mistal or a shippon (Brunskill, 1987). The name of Byres Road in the West End of Glasgow reveals its former dairy buildings use. In Sweden approximately 80% of dairy cows are still kept in tied-stalls (Hultgren, 2001), but in Great Britain the trend towards larger average herd sizes (The Dairy Council, 2001) has seen the increased use of the cubicle housing system. A plan view of a building for 400 cows is shown in *Fig. 1.1* and a sectional view of a cow cubicle from the same building is shown in *Fig. 1.2*. (*Fig. 1.1* and *Fig. 1.2* are reproduced with the permission of SAC, Building Design Services, Auchincruive, Ayr, Scotland).

Free-stall or cubicle housing was invented by two farmers in 1960, working separately, Evans in Great Britain and Owen in the USA (Baxter, 1983). Kelly (1983) stated that roughly 70% of Scottish dairy farms had cows housed in cubicles and this approximate figure was also recorded in 1990 (The Three Milk Marketing Boards in Scotland, 1990). In a 1983 survey of 1005 herds in England (Rowlands *et al.*, 1983) 664 (66%) were in cubicles, 229 (23%) were in tied-stalls and 112 (11%)

were in deep-bedded straw yards. The value of a cow space, whether for the loose or the tied system, is related to its comfort (Colam-Ainsworth et al., 1989). Good cubicle design allows for adequate lying and lunging (the forward and upward movement of the getting up sequence illustrated in *Fig. 1.3*) space and a bed surface that is soft (Faull *et al.*, 1996).

Fig. 1.1 Plan view of a 400-cow dairy unit at Dunleath Estates, Ballywalter, Northern Ireland (Reproduced with the permission of SAC, Building Design Services, Auchincruive, Ayr, Scotland)



BALLYWALTER
Dunleath Estates
Newtownards

sketch plan 1

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Jun 97

b

BUILDING DESIGN UNIT
Auchincruive
AYR, KA6 5HW

SAC

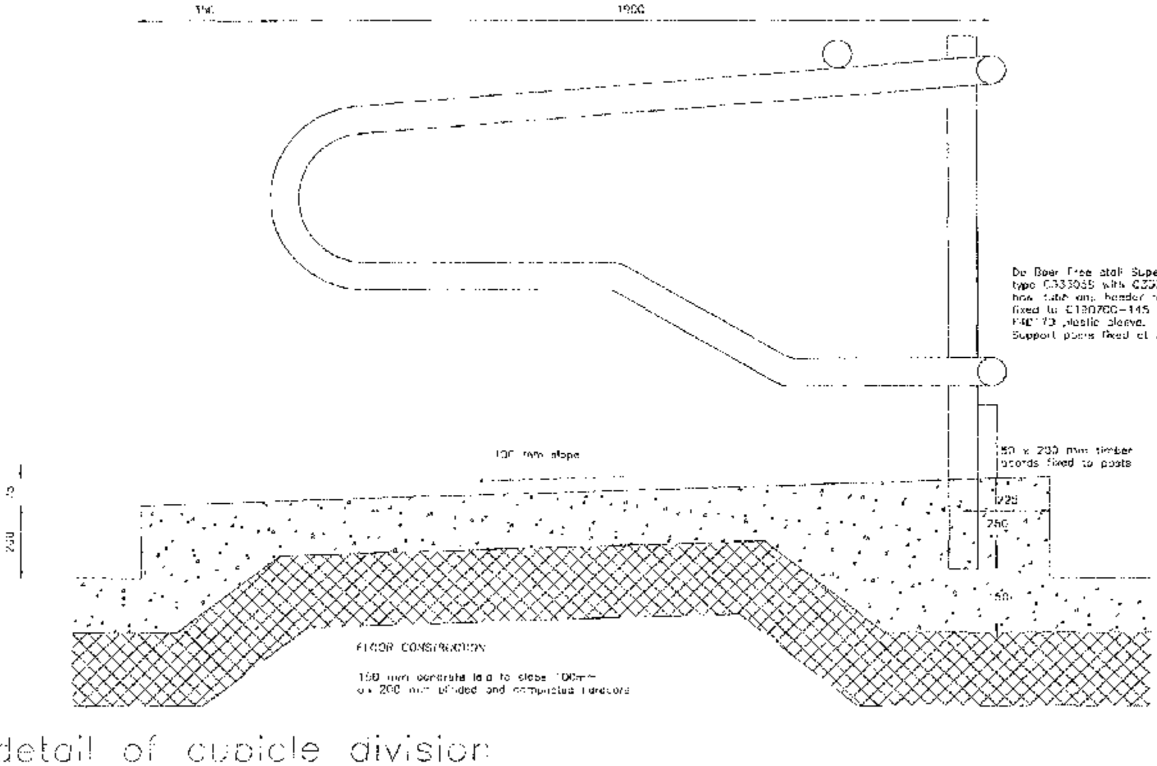


Fig. 1.2 Section view of a cow cubicle at Dunleath Estates, Ballywalter, Northern Ireland (Reproduced with the permission of SAC, Building Design Services, Auchincruive, Ayr, Scotland)

1.3 Dairy cow behaviour as an indicator of comfort in cubicles

Chapter 2 describes a seven month dairy cow behaviour study carried out for the current work at SAC Ayr, Auchincruive, Ayrshire, Scotland and Myerscough College, Lancashire, England, which was the basis for all subsequent work on the measurement of cubicle bed injury reduction potential. Chapter 2 is part of a report written for the Milk Development Council of Great Britain, as MDC Report 96/R6/01. Ethology, the scientific study of an animal's behavioural response to its environment is a legitimate discipline within veterinary medicine (Arave and Albright, 1981).

1.3.1 Comfort indicators

The behaviours indicative of cow comfort include lying and standing. It has been widely stated that cows will have more total lying time on softer bedding and will have discomfort on harder surfaces (Irps, 1983; Herlin, 1997; Haley *et al.*, 2001). Also, lying times are reduced at the changeover from pasture to winter housing (Singh *et al.*, 1993). This reduction in total lying has often been associated with a concurrent reduction in the proportion of lying time spent ruminating. These two behaviours should therefore be greater on softer bedding. Conversely, idling, a term intended to mean standing doing nothing, is rarely seen at pasture; when cows are standing they are usually either ruminating or investigating their surroundings. The idling seen in housed cattle represents a small, but significant proportion of their time.

Table 1.1 describes the stages of sleep in dairy cows as determined by Ruckebusch and Bell (1970). Cows only sleep for short periods. This sleep is characterised by the head/chin resting on the ground, with its end point marked by a sudden jerking of the head (Ruckebusch 1974). These periods of sleep are called sleeping bouts. Singh *et al.* (1993) reported that, for both heifers and cows, maximum sleeping bout length was greater at pasture (4.1h and 4.8h respectively) than immediately post-housing (1.7h for both). Maximum sleeping bout lengths are associated with increased comfort (Singh *et al.*, 1993). Total lying time is also an indicator of comfort, and at pasture heifers and cows have similar lying times of 6.2h and 6.1h. After housing, the lying times increase to 8.9h and 9.9h respectively. As the housing period progresses, night lying, maximum lying time and rumination all increase (Singh *et al.* 1993). Uncomfortable lying areas are more likely to influence day time lying periods than they are night time periods (Dregus *et al.* 1979). Inadequate cubicle comfort is also indicated by the cow standing half in a cubicle, indicating a fear to use the bed (Colam-Ainsworth *et al.* 1989, Leonard *et al.*, 1994, Faull *et al.* 1996). Faull *et al.* (1996) set out a system for scoring comfort in cubicles and a system for scoring cubicle beds. It is important to consider all these factors, in order to gain a broader understanding of cow comfort.

Table 1.1 Stages of sleep in dairy cows (Ruckebusch and Bell, 1970)

Stage	EEG waves	Behaviour
I – awake	rapid, low amplitude	awake and attentive with phases of psycho-sensorial rest
II – somnolence	fuseaux and slow waves	standing or lying, usually progresses from a phase of psycho-sensorial rest
III – sleep	slow waves only	total detachment from surroundings, unresponsive to loud noises, usually (but not always) lying, drooping ears and a resting head are, in 20% of cases associated with this stage
IV - paradoxical sleep	rapid waves	always lying, closed eyelids, resting head, lying on side with at least one hind limb extended

An important issue to discuss is that of research methodology and the value of findings. In the case of determining lying times in herds Metcalf (1998) used a camera shot once a day in a six month study to count the number of cows lying down and standing in a study of cows on cubicle mattresses, cubicle mats and straw yards. No significant differences were found when comparing the three options. Rodenburg *et al.* (1994) had argued previously that this method of observation is of limited value and give the example of an unpublished study at Alfred College, Ontario showing greater use of mattresses when cows were observed continuously compared to when there was a single observation of location and position. The lying time findings reported in the current work were based upon continuous observations in 16 24-hour sessions over the winter months of October 1997 to April 1998.

Soft bedding is preferred by cows instead of a hard concrete floor (Haley *et al.* 2001). Colam-Ainsworth, *et al.* (1989) referred to work by Cermak (1982) that stated that cows lay in cubicles with mats or straw for 14 hours per day while cubicles with concrete resulted in a lying time of only 7 hours per day. This is not surprising considering how little the cows' knees and hocks are protected by skin and tissue. Even when softer beds are further away from feed, cows will make the extra effort to walk and return to the softer bed (Harper, 1983; Irps, 1983). The question is; how soft does a bed have to be to give the cow an optimum level of comfort?

1.3.2 Lying times of dairy cows in cubicles

High producing dairy cows need to optimise their lying time and one of the key factors related to lying time in a cold winter climate housing environment is the type of floor surface in the stall or cubicle. Hill *et al.* (1973) compared the lying times of cows in two groups differentiated by bed surface. Group 1 surfaces were a clay base topped with sawdust and Group 2 surfaces were concrete with no sawdust topping added. Group 1 cows had more total lying time in the 20 month study. The average amount of time spent lying was stated in 1980 to be 7-10 hours per day in bouts, uninterrupted periods of a single behaviour, of approximately 1.5 hours (Arave and Walters, 1980). More recent studies showed that a comfortable cow should be lying down in a cubicle for around 50% of the day. (Haley *et al.*, 2001; Hultgren, 2001; Manninen *et al.*, 2002).

Natzke *et al.* (1982) studied cows given a choice of surface upon which to lie down. These surfaces were: a composite mat of 18 mm thick polyvinyl chloride (PVC) sandwiched by a top layer of nonwoven polyester and a bottom layer of nylon; 18 mm thick rubber mats; jute-backed carpeting; and, 18 mm thick vulcanised rubber mats. The cows selected the composite mats and the vulcanised rubber mats most often and this preference was put down to the greater compliance or softness in those products. Irps (1983) reported that cows preferred soft lying places. Cows prevented from lying down in a controlled study were reported to have reduced plasma concentrations of a growth hormone that is associated with milk yield (Munksgaard and Løvendahl, 1993). Krohn and Munksgaard (1993) reported a shorter mean duration of resting time for cows on concrete flooring compared to cows on rubber mats and that the concrete floor induced a higher frequency of interruptions to the lying down movement. The conclusion from the Krohn and Munksgaard (1993) differences was that concrete was not as comfortable for the animals. In another concrete versus mattress comparison, Pajor *et al.* (2000) reported that lying times were longer for cows on mattresses. Leonard *et al.* (1994) reported that uncomfortable stalls will reduce the time that cows spend lying down and this lack of comfort will be due to the lying area being either too small or too hard. Metcalf (1998) assessed the comfort of three cow groups, one group in straw yards, one in cubicles with mats and one in cubicles with mattresses. The number of animals in each group that were lying and standing was recorded by photograph at a specified time on one day in each month of a six-month study. It was found that there was no difference in lying time and, by inference, comfort levels in the cows in the three bedding systems. This method of gathering comfort data is limited by its 'snapshot' nature. More data are gathered by more intensive observations (Irps, 1983; Krohn and Munksgaard, 1993; Haley *et al.*, 2001; Hultgren, 2001). This is clearly a matter of resource allocation. Irps (1983) observed cows in a study of floor surface preference using video cameras to record behaviour in 14 consecutive days. The lying and standing pattern of 16 young cows was recorded. The animals were free to move between the inside and outside of the housing area and could lie down in places that had straw bedding, sawdust bedding on 'soft' cubicles, a rubber-covered slatted area and a concrete slatted area. The camera recording technique allowed lying and standing positions at hourly intervals to be reported. Krohn and

Munksgaard (1993), Haley *et al.* (2001) and Hultgren (2001) also used video cameras to record lying behaviour data. The high cost of animal observation studies is prohibitive and the current work proposes a method of reducing the cost by setting out a test procedure to measure the long-term cushioning performance of a synthetic cubicle bed.

Haley *et al.* (2001) observed the lying behaviour of cows on rubber-crumb mattresses (Promat Limited, Seaforth, Ontario, Canada) and on concrete, and concluded that the mattress cows were more comfortable. This was inferred from the fact that the cows on mattresses had a total lying time of 14.7 hours per day compared to 10.5 hours per day for cows on concrete. Tucker and Weary (2001) reviewed a number of lying behaviour experiments and concluded that cows prefer to lie down on softer surfaces and spend more time lying down on softer surfaces. Manninen *et al.* (2002) measured the total lying time of cows in deep straw bedding, in stalls with Cloud 9 rubber mats (NRI Industries, Toronto, Canada) and in stalls with 200 mm of sand bedding. The lying times of the cows were similar for the deep straw bedding and the Cloud 9 rubber mats but were significantly lower for the sand bedding. On the matter of injuries to leg joints, sand kept hock lesions to a lower proportion of a cow group compared to a group on rubber-crumb mattresses (Weary and Taszkun, 2000).

Two similar reports of dairy cow lying behaviour in two different floor types offered the same conclusion from a different result in the measurement of lying bout duration (Chaplin *et al.*, 2000; Haley *et al.*, 2001). Chaplin *et al.* (2000) compared the lengths of lying time of two groups of cows. One group on rubber-crumb mattresses and one on ethylene vinyl acetate mats. A major finding was that the maximum length of a lying bout of the cows on mattresses was longer than of the cows on mats. The inference made from this was that the mattress cows lay down for a longer uninterrupted period because they were more comfortable. Haley *et al.* (2001) carried out a similar observation study of behaviour of a group of cows on rubber crumb mattresses and a group on concrete. Again, the length of an uninterrupted lying period was measured. The result was that the cows on concrete lay down longer than the cows on mattresses. But, the inference of Haley *et al.* (2001) was that this meant that the cows on concrete were less comfortable. The explanation given was that the mattress cows were more confident about getting up and down without it being painful than the concrete-based cows. Nilsson (1988) also stated that cows preferred softer floor surfaces but of the cows studied, those on harder beds had longer mean lying period durations.

The clear difference of opinion here about the meaning of lying bout duration indicates the difficulty in animal welfare studies of inferring behaviour to mean something definite. Engineering methodologies such as a quasi-static or a dynamic impact test of the stiffness and compliance of materials have an inherent objectivity and repeatability and are, as such, offered as assistance to animal behaviour experts who study cubicle floor surface effects.

There was overall agreement in Chaplin *et al.* (2000) and Haley *et al.* (2001) that the mattresses (softer product) were more comfortable, based upon other behavioural indicators. The number of hours of lying time per day was longer on the mattresses in both studies. Secondly, standing but not ruminating or eating in the cubicles, low comfort behaviour, was seen more in the cows on the mats in Chaplin *et al.* (2000) and on concrete in Haley *et al.* (2001). Finally, the proportion of the day spent lying on the mattresses was almost the same in the two studies, 50% in Chaplin *et al.* (2000) and 51% in Haley *et al.* (2001).

1.3.3 Lying down and getting up movements

Understanding the movements of a dairy cow when she lies down upon and gets up from a cubicle bed is a major objective of the current work.

When lying down is un-hampered by the floor surface it is one quick movement taking just a few seconds. The movement starts with examination of the lying surface and is followed by kneeling. The time taken to kneel after initial examination is short on an area as comfortable as the summer pasture (Krohn and Munksgaard, 1993). The duration of the complete lying-down movement is significantly longer on concrete floor surfaces than on softer surfaces such as straw bedding and rubber mats. Ladewig and von Borrell (1988) reported a lying down preparation time comparison of 9 seconds for straw bedded yards and 59 seconds for tied-stalls. Also, concrete flooring causes a higher number of interruptions to the lying down movement (Krohn and Munksgaard, 1993). The more comfortable a cubicle bed is, the quicker a cow will lie down (Albright and Arave, 1997; McFarland, 2000).

Hultgren (2001) studied cows in two different tied-stall systems to analyse the way in which cows lay down. The two systems were a solid stall area with a "standard" rubber mat (Mariane Larson AB, Gothenburg, Sweden) and a partially slatted stall area, an ethylene vinyl acetate (EVA) mat in the front and a 740-mm section at the rear that had the rubber slats. The cows in the partially slatted area took 23% less time to lie down, indicating more ease in that movement. Since the lying down time would be based upon the confidence the cow had in the compliance of the receiving surface, it is reasonable to assume that the EVA mat was better for this purpose.

Herlin (1994a) described the downward movement as two separate sequences. Sequence one is the time period from an initial pendulum movement of the head, indicating that the animal is about to lie down, to the moment that the first knee comes into contact with the bed surface. Sequence two is the time taken to move from the end of sequence one to a final lying position. If sequence one included the cow lifting her head for more than ten seconds, this was recorded as an 'intention'. If sequence two was interrupted by the animal getting up from her knees, this was recorded as an 'attempt'. An intention and an attempt in this context are inferred as evidence of discomfort.

Getting up from a cubicle bed is described by Herlin (1994a) with less detail than that for the two getting down sequences. The description was that the getting up process started with a sideways movement of the head and finished when the animal was standing in a balanced position. McFarland (2000) reported that a dairy cow can usually rise in 5-10 seconds by putting her weight on her foreknees, lifting her hindquarters and then getting up onto all four legs. Cows with leg joints that are sore are likely to have trouble with the compression force of the foreknee press. McFarland (2000) cites a cubicle bed being too stiff as one of the reasons why cows will incur swollen carpal joints.

Herlin (1994a) looked for differences in effectiveness in lying down and getting up activity between cows housed in tied-stalls and in cubicles and between primiparous and multiparous cows. Differences were measured from the average number of times a cow got up and down in 24 hours, the time taken to get down and up, in seconds, and the number of intentions per lying down. It is relevant to note that cubicle cows took less time to get down compared to tied-stall cows whilst there was no difference between these two groups in the time to get up. Also, multiparous (older) cows took more time in getting down compared to primiparous cows whilst, again, there was no difference between the multiparous and primiparous groups in the time taken to get up. A difference in getting-up behaviour was noted between two groups when one was kept in a pasture for a few months while the other was indoors in tied-stalls for the duration. The cows that were in tied-stalls had no opportunity for gentle exercise and perhaps as a result of this took longer to get up compared to the cows that had been in a pasture. On this matter of gentle exercise making the cows fitter and better able to get up, there was no such reported benefit in Herlin (1994b) for cubicle cows compared to tied-stall cows. An inference from this is that pasture exercise is better than cubicle house exercise or that the concrete surfaces of a cubicle feeding stance and passageway is not as good for cow leg health as a grass field. Herlin (1994a) results showed that the getting up difference was from the cubicle house cows becoming quicker at getting up after being in the pasture, but the tied-house cows had the same behaviour, no better or worse, in the separate comparisons with pasture-based and cubicle-based cows.

It is evident from the literature that behavioural responses to surfaces can be misleading if not given full attention. Haley *et al.* (2001) found that cows had longer individual lying bouts on concrete compared to cows on rubber-crumb mattresses, which suggests more comfort on concrete. But the full behavioural picture revealed that the cows on the concrete stood up for almost twice as long in an individual standing bout (80 minutes for concrete; 48 minutes for mattresses; $p<0.001$). Also, cows on concrete had a significantly longer total length of standing time in a day (12.9 hours for concrete; 11.0 hours for mattresses; $p<0.001$) and a lesser total length of lying time in a day (10.4 hours for concrete; 12.3 hours for mattresses; $p<0.001$). These behaviours suggest that the cows did not enjoy getting up and down and the likelihood is that the pain endured from the concrete stiffness was the reason, an inference backed up by the other behavioural aspects. Nilsson (1988) determined a variety of lying times for cows on different bed types and observed that there were shorter mean lying periods on the softer beds in the study. However, it was concluded that the length of lying period should not be used as an evaluation of the wellbeing of the animals.

It may be that getting up is generally less of a problem for a cow compared to lying down. It is clear from the findings of Herlin (1994a) that the getting up movement is an entirely different biomechanics matter compared to getting down. The 'sequence two' time period of a cow when lying down was recorded as much shorter than 'sequence one'. That is to be expected as sequence two is the time between a knee hovering above the bed surface to the point of impact and at that stage the movement will be quick. Dynamic impact attenuation of synthetic sports surfaces is measured in international standard tests and is suggested here as being analogous to sequence two of the lying down movement of a dairy cow. A valuable future assessment of cubicle bed types may be to time sequence one in the lying down movement of a cow in a pasture and in various mats and mattresses. Herlin (1994a) described a sequence one comparison. The shortest time of four groups, indicating more confidence in the surface, was that of cows housed in cubicles and given time in a pasture, with the other three being kept in cubicles or tied stalls throughout the study or partly in tied stalls and a pasture. The hypothesis did not include different cubicle bed types though and the detail of the rubber mat used in the studies was not reported.

Phillips (1993) described the lying down and getting up movements of cows as two seven-stage movements. Stages five and six of the getting up movement show positions that will cause a quasi-static compression force to be exerted upon the knee joints. Given this, there is scope for further consideration of the getting up activity as a quasi-static compression force interface between the knee joint and the bed surface. Stages three and four of the getting down movement illustrate that there is a drop of one knee that will cause a dynamic impact force to be incurred by that joint.

The quasi-static push of getting up and the dynamic impact of getting down are described in the current work as two major potential causes of injury in dairy cows in cubicle housing, if the surface is not adequately compliant.

Essen-Gustavsson (1986) discussed the benefit of movement to all animals by stating that physical activity causes muscles to improve their capacity to oxidise fats and carbohydrates and, in so doing, decrease the concentration of lactic acid during an activity. Therefore, the fact that dairy cows in tied-stalls move around much less than they do in loose housing and in the summer pasture may cause their leg muscles to be much less effective. But cows prevented from lying down in a controlled study were reported to have reduced plasma concentrations of a growth hormone that is associated with milk yield (Munksgaard and Løvendahl, 1993). So, perhaps reduced movement for longer is a benefit to the milk production process as long as the cows are comfortable and uninjured when they do get up and down.

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 *et al.*, 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. *Fig. 1.3* illustrates the sequence of a dairy cow lying down and getting up as illustrated by 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.

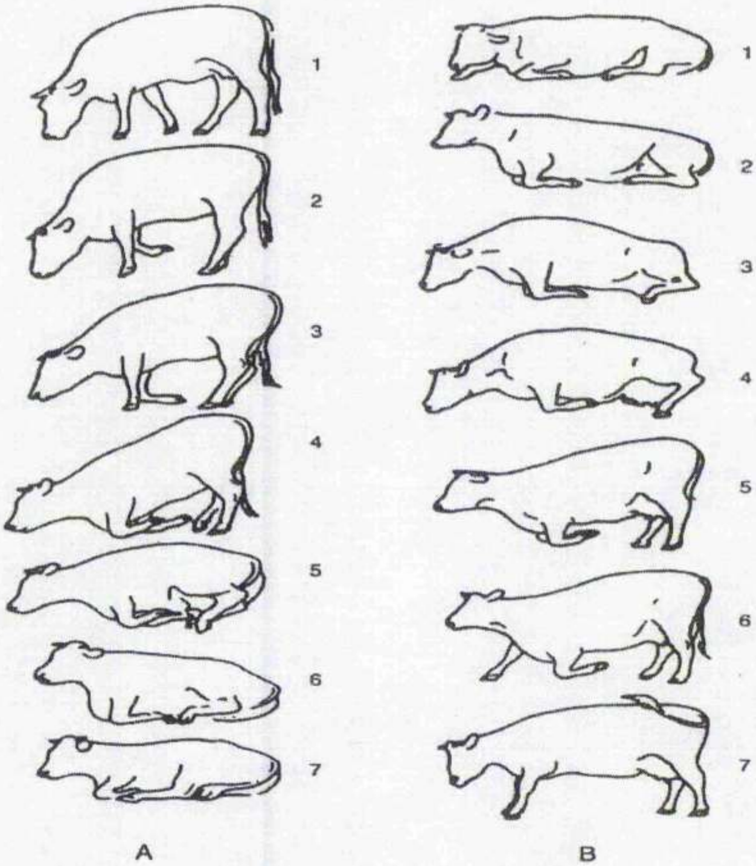


Fig. 1.3 The sequence of a dairy cow lying down (A) and getting up (B) (Fraser and Broom, 1990).

Lying behaviour of cows in cubicles with new EVA mats and rubber-crumb mattresses is described in Chapter 2 in terms of the proportion of time spent lying in 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.

1.3.4 Knee injuries sustained in unsuitable cubicle beds

The foreknee or knee in dairy cows is not the same joint as the knee in humans, but the term 'knee', as applied to animals, has been accepted by veterinary science and is a well-understood reference (Sisson and Grossman, 1975). The knee in animals consists of a composite of joints known as the carpal joints, of which there are three major constituents. These are, the *radio-carpal* formed by the distal end of the radius and the proximal row of the carpus; the *intercarpal* formed between two rows of the carpus; and, the *carpo-metacarpal* formed between the distal row of the carpus and the proximal ends of the metacarpal bones. Three synovial sacs or bursae, containing a lubricating fluid, correspond to the three major carpal joints, the largest of which is the radio-carpal sac (Sisson and Grossman, 1975). Injury to the knee of a cow, induced by compression forces, ranges from the relatively minor matter of hair being removed from the outer surface area to the more serious swollen joint or *adventitious bursae* (Gustafson, 1993).

Eskebo (1966) reported that cows incurred foreknee injuries due to being introduced to harder lying surfaces after a period of having a soft bed area. Also, Eskebo (1966) referred to a 1953 study (Heizer *et al.*, 1953) that stated that foreknee injuries in cattle in buildings were of significance. Albright and Alliston (1971) cited injury to cattle feet and legs as being a source of major costs to the dairy industry in terms of veterinary treatment. Limb injuries have been described as accidental, such as from slipping on a floor that is too smooth, or as systematic, such as from foreknee pressure applied to a hard lying area (Blom, 1983). Chapter 2 of the current work describes differences in systematic injury incidences between cows on EVA mats and rubber-crumb 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.

Webb and Nilsson (1983) discussed in detail the topic of flooring and injury to animal limbs. Coverage was given to physical and psychological effects of inadequate floors and a key area of discussion was interaction between limbs and floors and the mechanical stress levels that lead to damaged tissue. Reference was made to measuring the mechanical properties of tissue and the use of FEA by Schock *et al.* (1980) to simulate the effect of soft tissue indentations made by floors used in pig housing. Webb and Nilsson (1983) proposed that research in the field of flooring and injury to animal limbs should find a physiological measure of tissue damage to quantify injury levels and a standardised protocol for assessing the injury levels likely to arise from a given floor specification. Webb and Nilsson (1983) referred to

Walberg (1978) as having found fewer injuries in cows when exposed to softer floor surfaces. Blom (1983) stated that Nygaard (1979) found significantly fewer injures in cows on floors that had a smooth surface compared to the number found in cows exposed to a rough surface area. Nygaard (1979) had also cited floor temperature as a significant cause of injury, with 50% more limb lesions occurring from being a colder floor (Blom, 1983).

Pressure injuries to dairy cow foreknees are systematic in the main (Blom, 1983). Some accidental damage may occur such as banging into gates or slipping on a walkway surface that has too little grip for a cow's hooves. But, since lying down and getting up is a significant proportion of the day for the dairy cow, the system has to be optimised. In a comparison of tied-stall and loose housing, more foreknee injuries were prevalent in the tied-stall cows. However, the types of bed surface used in the two systems in the study are not reported. Blom (1983) stated that even minor injuries to the cow foreknee are of importance as an indication of a sub-optimal environment.

Swollen and bruised knees are commonly associated with cubicle bed materials. Knees are injured on hard surfaces when the cow initiates the lying down motion. Most rubber mats and mattresses prevent swollen knees, but concrete does not (Rodenburg and House, 2000). It seems that hock joints are affected by the roughness of the surface in mats and mattresses, but knees are not. This could form part of a future study of the friction characteristic of synthetic cubicle beds.

Rodenburg and House (2000) reported a low incidence of swollen knees on mattresses and rubber mats but more minor knee joint lesions are not reported. It may be that the cow hock joint is more prone to swelling than the knee joint because its biology is closer to that of a human knee. The hock does not appear to receive the same extent of quasi-static compression force and dynamic impact force that a knee does in cubicle getting up and down movements (Fraser and Broom, 1990; Phillips, 1993). Krohn and Munksgaard (1993) found more injuries in the knee joints of a cow group in tied-stalls compared to a group in free-stalls. This was probably because of lack of exercise. However, the bed surfaces in the study groups were of various types and thicknesses, and these may have been a contributory factor.

1.4 Hyperfoams

Rubber crumb and EVA foam beds for dairy cows have compression load responses that are characteristic of hyperelastic materials, also known as hyperfoams. That is, a stress-strain curve for a sample of each bed type compressed by a perpendicular force shows a nonlinear relationship. Chapter 3 describes the fundamental properties of hyperelastic materials used in rubber and foam cubicle bed manufacturing. The high elasticity of rubber arises from its molecular structure (Gent, 1992). Because the molecules are long and flexible, they assume random shapes under Brownian thermal motion and on receiving an applied force they straighten out. But, when the force is released they spring back to the random configuration.

The use of hyperelasticity in models of analysis of engineered products such as rubber-crumb mattresses and EVA foam mats is fairly novel and material property data are still relatively scarce. This is largely because even the simple laboratory experiments needed to determine the full non-linear-elastic constitutive tensor are not trivial, and may require uniaxial, bi-axial, planar and volumetric deformations (Ogden, 1984). Indeed, the materials often have a high volume fraction of air-filled open-cell cavities. The constitutive response of such voided materials is then not only non-linear and time-dependent but is even dependent on the sign of the hydrostatic component of the stress tensor. In essence, tensile loading causes stretching of the cavity walls while compression causes elastic buckling and collapse of the cavity and, ultimately, 'bottoming out' and a loss of cushioning. Given laboratory-scale material samples, this pressure-sensitive response can be determined and both Miller *et al.* (2000) and Mills and Gilchrist (2000) described such tests in the context of sports engineering.

Fortunately, there are factors that mitigate the difficulty in materials modelling in particular cases such as that for cubicle beds. Here, the impact loads are predominantly compressive and a full hyperelastic test programme may not be necessary to infer a material model that yields useful results. Adopting the practice used in continuum damage mechanics by which a material with a heterogeneous microstructure is modelled as a homogeneous continuum, Thomson *et al.* (1999) developed first-order hyperfoam models that are a good fit to the aggregate response of hyperelastic cushioning systems commonly used in sports engineering applications. A similar approach is developed in the current work in the context of agricultural engineering.

1.5 Cubicle bed cushioning performance measurement methods

The measurement of performance on the basis of a laboratory test programme is difficult and frequently contentious since it relies on the inherently subjective practice of extrapolating (Tipp and Watson, 1982). Chapters 4, 5 and 6 describe performance measurement methods for cubicle bed cushioning and constitute the key outcomes of the thesis, nonlinear finite element analysis, based upon a quasi-static compression test, and a vertical drop dynamic impact test. The methods discussed are intended to allow others to repeat the procedures and engage in discussion for the purposes of improvement and to pursue an agreement on a standard method of measurement of cubicle bed cushioning.

The impact absorption of rubber-crumb mattresses and ethylene vinyl acetate (EVA) mats were investigated and the findings were published by the Milk Development Council of Great Britain to help dairy farmers with cubicle synthetic bed investment decisions (MDC Report 97/R6/13). This work followed on from MDC Report 96/R6/01, which concluded that rubber crumb mattresses caused less knee and hock damage than ethylene vinyl acetate mats in a seven-month study. Previous studies by Underwood *et al.* (1995) and House *et al.* (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 softness or, termed more correctly, compliance.

The softness of a surface has been measured in previous work by plotting impact force against deflection (Irps, 1983; Nilsson, 1988) and this method of evaluating comfort was carried out for Chapter 4 of the current work. 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). An alternative determination of measuring softness was set out by Løken (1978), which involved pushing steel spherical indenters of 20 mm, 50 mm and 100 mm diameter into 18 mm thick rubber bed samples and recording the penetration depth (mm) and the resistance pressure (MPa). Løken (1978) stated that better research methods for testing cattle floor properties should positively contribute to solving the problem of environmental injury.

Nilsson (1988) measured surface deflection from a 1.5 kN normal force on a range of dairy cow stall beds; 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 (average) 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 severe injuries recorded in the herd in the study was 0.35 per leg for the mattress cows and 0.58 and 0.59 per leg for cows on concrete and rubber matting respectively. Nilsson (1988) classified severe injuries as a small but open or half-healed wound, an open wound, a deep wound or a large inflamed wound.

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. Løken (1978) stated that the same material tested with a fast load rate will be judged to be harder than if tested by a slower procedure. The rate of loading is clearly different for a cow according to whether she is 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.

McKnight *et al.* (1996) devised a pressure test of cubicle beds using a 23 cm^2 indenter that was pressed into the surface to a depth of 2.5 mm. The results were that the animal comfort mat required 186.1 kPa and the "hard" or "regular" rubber mat required 873.3 kPa. This reported difference in stiffness of the two beds tested was not put in the context of a maximum or minimum stiffness or compliance as had been done by Nilsson (1988). An agreed test standard methodology is required to allow designers and manufacturers to know what specification is needed for cows to be safe and unharmed in the lying down and getting up movements in cubicles. Rodenburg and House (2000) called for the development of a standardised compression test for cubicle beds, stating that such a test could be beneficial in future research.

McFarland (2000) suggested a knee test of a cubicle bed to determine its suitability for the dynamic motion of a cow lying down. The procedure is described as a stockman or cubicle designer kneeling on the surface to see how well it conforms to the dynamic impact. If it feels suitably compliant then it should be good for the animal. This 'try-it-for-yourself' approach was advocated by Baxter (1983) as the best way of finding out what the animal's built environment is really like, when the user of a space and a designer of that space are not able to communicate in the normal way. That said, perhaps agricultural engineering design can be more scientific. A human knee has a patella and a cow's foreknee does not. Also, there is an inherent subjectivity to 'feeling'. Any method of improving dairy cow welfare is to be encouraged, but objective methods for determining the optimum mechanical specification for cubicle beds are needed.

The main objective of the current work is to propose two engineering test methodologies for use in new applications to help predict how well dairy cow cubicle beds can minimize cow knee joint injury by cushioning compression forces exerted by the animal's getting up and lying down movements. The two test methods are modeling the beds as hyperfoams in the Abaqus finite element code as a simulation of the quasi-static getting-up 'push' and measuring peak acceleration from an impact test as a simulation of cow's dynamic lying-down 'drop' movement. A cow obviously has to get up from and down upon a free-stall bed surface many times in the design life of a cubicle house and this means that measuring cushioning performance is required for beds in a new and used condition. Both of the test methods described can be used to measure short-term and long-term cushioning performance.

1.5.1 Measuring quasi-static cushioning performance of cubicle beds via uniaxial compression load tests

A cow rising from a mattress or mat must make a sustained push into the bed volume. This is a quasi-static process and was simulated in the current work in laboratory conditions. Samples of new mats and mattresses were subjected to quasi-static compression testing using a Lloyds Instruments Ltd LR 30K machine in a mechanical engineering laboratory of the University of Glasgow. The information gained was the force versus deflection relationship for two cubicle bed material samples and is discussed in Chapter 4. Sonck *et al.* (2000) measured quasi-static loading in cubicle beds by pressing a 120 mm diameter steel hemisphere into a bed surface via a pneumatic cylinder, which exerted a force of 2 kN for 5 seconds. Uniaxial tests do not yield the full reality of three-dimensional behaviour of hyperelastic materials under compression load (Miller *et al.*, 2000). However, they do allow a benchmark to be set for computer manipulation (Thomson *et al.*, 1999). Benchmark test results for each of the two cow bed types investigated in the current work were gained for further analysis using computer modelling.

1.5.2 Evaluating quasi-static cushioning performance of cubicle beds via finite element analysis

Chapter 5 describes finite element analyses (FEA) performed using Abaqus/Explicit Version 5.8 (HKS, 1998a; HKS, 1998b; HKS, 1998c), a nonlinear FEA package that allows modelling of compression loads on a surface. FEA has been applied to a variety of problems in areas such as engineering, biology and medical research (Ankersen, 1999). Therefore, it was considered to be a useful tool in investigating the properties of hyperelastic materials used to minimise impact injury to the foreknee joint of a dairy cow. The requirement of Chapter 5 was to use Abaqus/Explicit (HKS, 1998b) to derive the hyperfoam material constants of initial shear modulus, hyperelastic stiffening index and Poisson's ratio by matching force-deflection curves to those plotted from benchmark quasi-static compression tests. The initial shear modulus and the power-stiffening index were set at values established by Thomson *et al.* (1999) for tests done on hyperelastic materials used in sports shoes and, thereafter, incremental adjustments were made until a good match between quasi-static compression and computer-simulated force-deflection curves was observed. Mills and Gilchrist (2000) described a procedure to fit uniaxial test force-deflection curve data with a computer simulation using two values each for both the hyperelastic stiffening index and the initial shear modulus for low density polymer foams. Thomson *et al.* (2001) matched the quasi-static response of a treadmill running surface to a constitutive model with an initial shear modulus $\mu = 2$ MPa and a power-stiffening index $\alpha = -25$.

1.5.3 Measuring dynamic impact cushioning performance in cubicle beds

Dynamic impact forces are surprisingly large and, for example, humans generate heelstrike forces of the order of three times their bodyweight when simply walking on paved level surfaces (Clarke *et al.*, 1983). The descending process of a dairy cow getting onto a cubicle bed is a dynamic one and a test procedure for measuring cushioning performance of cubicle beds must take this into account. Natzke (1982) reported that a group of cows, given a choice of synthetic bed surfaces, chose the softer beds on offer. However, the compressibility of these softer beds, 18 mm thick composite mats and 18 mm thick vulcanised rubber mats, reduced in the first six months of use, although no description is given of how compressibility was assessed.

This showed the importance of long-term performance in products that are generally purchased for a life of 5-10 years.

Dumelow (1995) stated cushioning performance to be an important factor in the suitability of cubicle beds. But, the point was made that this is a property that will change with use and a laboratory-based method for determining long-term cushioning was described. A 120 mm diameter steel hemisphere was mounted on a ramming mechanism, which impacted upon bed test samples from 5,000 and 30,000 times, to simulate a number of years of use. The range of mats tested showed varying levels of maintained effectiveness in time. The experimental findings reported were based upon laboratory experiments and the opinion was expressed that a farm-based test of cushioning performance would have been desirable.

Hansen and Strom (2000) described the importance of measuring short-term and long-term cushioning performance, describing long-term performance as elasticity. Softness was measured by pressing an artificial knee into a range of bed types to simulate the force exerted when a cow lies down. But, the compression action described, at a constant rate of 6 mms^{-1}, is that of the quasi-static push of a cow when she gets up from the lying position. The method of evaluation is a valid one, but not for the lying down movement. Elasticity or long-term performance is stated, with good reason, by Hansen and Strom (2000) to be neglected in the literature and this aspect was measured by compressing the bed samples 1,000 times with a force of 4.5 kN. Hansen and Strom (2000) found that rubber-crumb mattresses had an unsatisfactory long-term cushioning performance, with a deep hollow forming on the bed surface.

This literature study led to one of the main objectives of the current work, to find a standard method for measuring both short-term and long-term dynamic impact cushioning performance, on-site or in the laboratory, quickly and cost-effectively.

1.5.4 Candidate methodologies for measuring dynamic impact in cubicle beds

A series of dynamic impact tests was carried out for Chapter 6 by dropping a mass onto a cubicle bed 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 maximum acceleration for a given drop height and mass, maximum force for a given drop height and mass and the force versus deflection relationship.

The main references for this area of concern are from the measurement of the impact cushioning of sports and playground surfaces. A review follows of three published dynamic impact force measurement tests for the sports and leisure industry:

- Deutsches Institut für Normung (DIN) 18032 Sport Halls - Halls for Gymnastics, Games and Multi-purpose Use Part 2 - Floors for Sporting Activities - Testing Requirements;

- BS EN 1177: 1998 Impact Absorbing Playground Surfacing – Safety Requirements and Test Methods;
- NF P90-104 Sports grounds - Determination of Sporting Qualities - Comfort and Performance – Accelerometric Method.

1.5.4.1 Deutsches Institut für Normung (DIN) 18032 Sport Halls - Halls for Gymnastics, Games and Multi-purpose Use Part 2 - Floors for Sporting Activities - Testing Requirements (DIN, 1995)

This test is also known as the Berlin Athlete Test. The apparatus and procedure must conform to the requirements of DIN 18032 Part 2 Section 5.2. A mass of 20 kg is dropped on to an anvil of 100 mm diameter. The anvil transmits the load through a spring to a test foot with a spherical base resting on the synthetic surface. The foot is fitted with a force transducer that enables the peak force during impact to be recorded. This peak force is compared to that obtained when an impact is recorded for a concrete floor and the percentage force reduction is calculated for the synthetic surface.

Force Reduction (%) = $[(1 - F_S/F_C) \times 100]$

F_S is the peak force recorded on the synthetic surface;

F_C is the peak force recorded on concrete.

A floor surface is deemed to satisfy if the force reduction value, relative to concrete, is between 40% and 65% (+/- 5%). DIN 18032 could be used in dairy cow cubicle bed impact absorption measurement but has not been used in the primary research of the current work.

1.5.4.2 BS EN 1177:1998 Impact Absorbing Playground Surfacing – Safety Requirements and Test Methods (BSi, 1998).

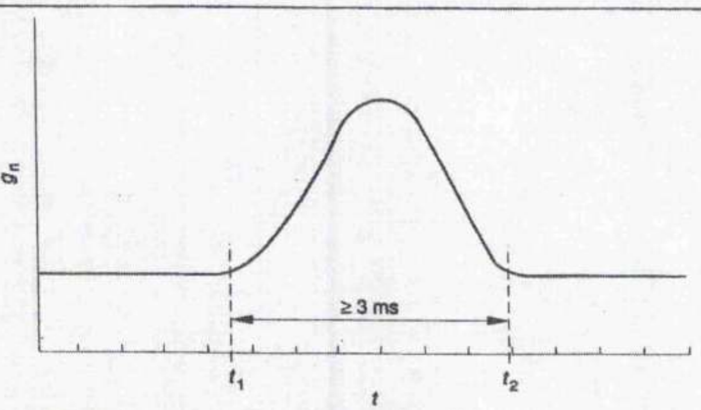
This test principle is one that determines an injury risk to the head of a child when an impact is made on a surface. The risk is expressed as a Head Injury Criterion (HIC) value and the critical value for HIC is 1000. Above 1000 is too high for safety.

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 1.4).

The test procedure of BS EN 1177:1998 is not applicable to cubicle bed testing. A dairy cow knee fall height is fixed and the BS EN 1177:1998 procedure requires a few different fall heights to be used in a test to determine the maximum height of a play apparatus above the surface.

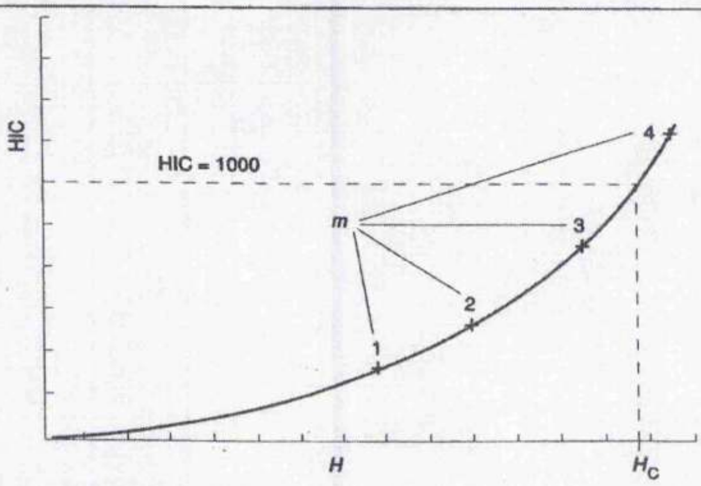
Typical examples of trace of acceleration against time and curve of HIC values against drop height



g_n acceleration

t time

Figure C.1 Typical trace of acceleration against time



m Impact measurements

H Drop height

H_c Critical fall height

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

Fig. 1.4 BS EN 1177:1998 Figures C1 and C2 illustrating impact test results for contact time (Fig. C1) and Head Injury Criterion (Fig. C2) used to determine the Critical Height for a playground surface for children

1.5.4.3 NF P90-104 (1992) Sports grounds - Determination of Sporting Qualities - Comfort and Performance – Accelerometric Method (AFNOR, 1992).

NF P90-104 (AFNOR, 1992) has been adapted for use in the current work as a new method for testing the cushioning performance of dairy cow cubicle beds.

The principle, as described in Chapter 6, 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 first integration with respect to time yields a value for the peak velocity of the falling mass and the second integration gives the maximum deformation of the surface.

The measurement of the maximum acceleration (ms^{-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} (ms^{-2}) × mass (kg) = F_{max} (N)
- Higher F_{max} ⇒ stiffer surface ⇒ higher injury potential
- Lower F_{max} ⇒ more compliant surface ⇒ lower injury potential

The drop height is determined according to the dynamic fall distance of an adult dairy cow when she is getting onto a cubicle bed.

Chapter 2.0 Observation study of cows on rubber-crumb mattresses and EVA mats in two dairy farms

2.1 Design of the experiment

The objective was to identify any differences in cow health, welfare and production levels when housed on either rubber-crumb beds (mattresses) or ethylene vinyl acetate (EVA) beds (mats) for the winter of 1997-1998. The experiment was replicated at SAC Ayr, Auchincruive, Ayrshire and Myerscough College, Lancashire. The cubicle layout was similar in both dairy units, with clear-span portal frame buildings for a three-section cow housing area and a herringbone parlour. The cubicle divisions at Auchincruive were the Dutch Comfort type and the length and breadth of the cubicle beds were 2.2 m and 1.15 m respectively. The cubicle divisions at Myerscough were the Mushroom type with a bed length and breadth of 2.3 m and 1.2 m respectively.

At each site 58 cows were divided into two groups and housed on either rubber-crumb mattresses (Pasture B.V. "Pasture Mat"; Group 1) or EVA mats (Cow Comfort "Maxibed"; Group 2). Details are shown as *Fig. 2.1a* and a photograph of the layout prepared at SAC Ayr is shown as *Fig. 2.1b*. The suppliers of the beds were:

Pasture Mat	Maxibed
Fullwoodhead Dairy Supplies Ltd.	Cow Comfort UK Ltd.
River Place	Isle of Man Farm
Paddockholm Industrial Estate	Meadow Lane
Kilbirnie	Croston
Ayrshire	Lancashire
Scotland	England

The 75 mm thick Pasture Mat (rubber-crumb mattress) was made up of a series of tubes of rubber crumbs sewn inside a polyester inner mattress which was covered by a heavier outer cover of non-woven polypropylene. The 50 mm thick Cow Comfort Maxibed (EVA mat) was made from ethylene vinyl acetate. Both cubicle bed types were covered in a thin layer of sawdust as is common management practice, with care being taken by staff at both farms to ensure that similar amounts were added to each bed.

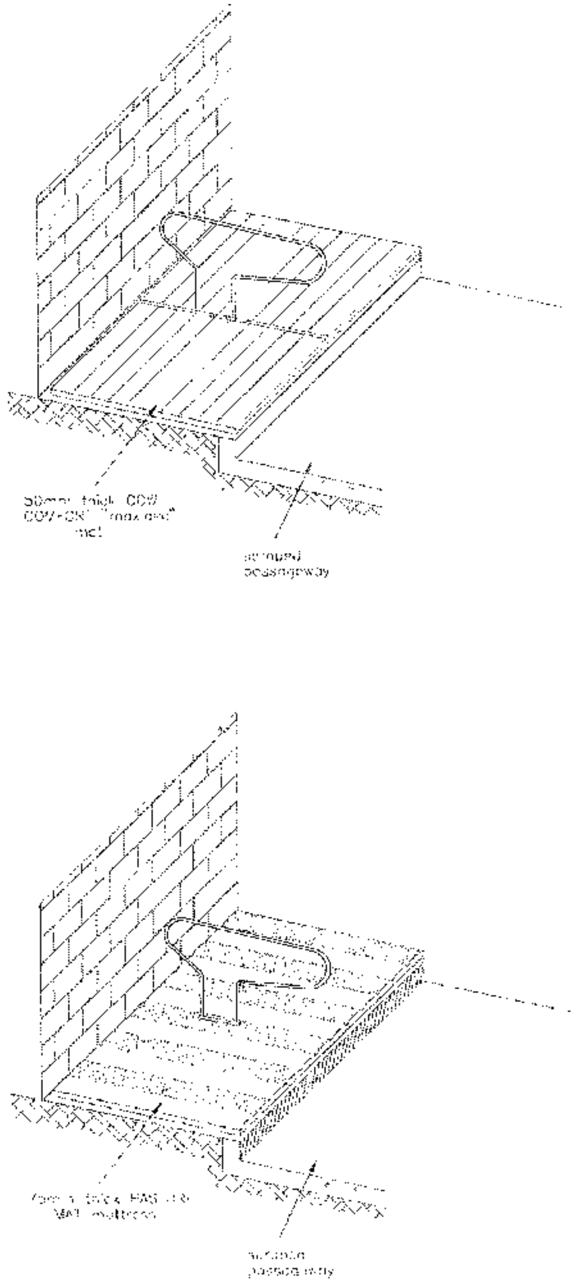


Fig. 2.1a Cow Comfort Maxibed EVA mat and Pasture Mat Rubber-crumb mattress detail showing the 'Mushroom' cubicle division used at Myerscough College

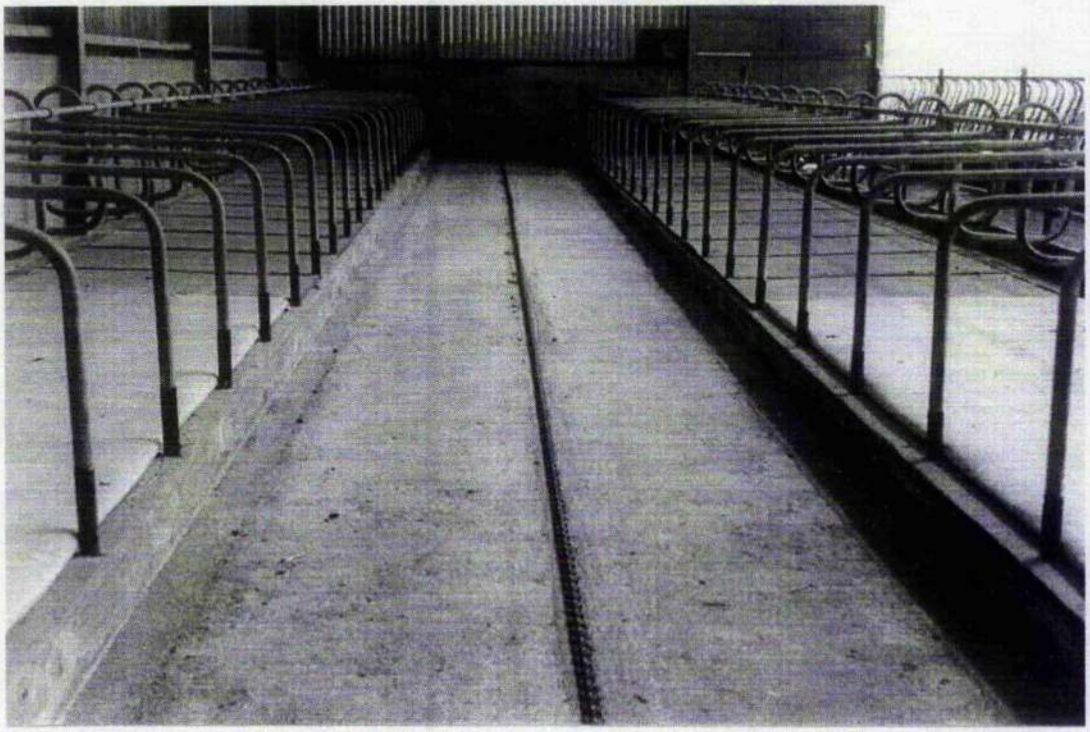


Fig. 2.1b Cow Comfort Maxibed EVA mat and Pasture Mat Rubber-crumb mattress layout with the 'Dutch Supercomfort' cubicle division used at SAC Ayr

These cubicle beds are representative of products on the market with the EVA mat being around 30% cheaper than the rubber-crumb mattress at the time of purchase for the trial.

Each group of 29 cows comprised 15 autumn-calved "core" cows and 14 summer-calved "fillers". After week 6, at both sites, the summer-calving filler cows were replaced by early lactation, late-autumn-calvers and the groups then remained constant throughout the remainder of the housing period.

At Auchincruive the herd included both Holstein-Friesians and Ayrshires, whereas at Myerscough there were only Holstein-Friesians. The two groups at each site were matched for lactation number, days post-calving, breed, and previous lameness history. At Auchincruive all cows were housed immediately after grass but at Myerscough the cows were allowed a transition period of about one week prior to the trial. During the transition period the Myerscough cows were housed at night, grouped randomly and allowed access to pasture during the day. Hence, for both groups, the beginning of the trial marked the onset of winter housing period.

2.2 Materials and methods

2.2.1 Milk yield

The milk yield of each cow in the trial (all cows were milked twice per day) was recorded on a daily basis at each site. The individual daily yield was the total milk from two milkings starting with the afternoon milking. If only one milking was recorded for any reason it was discarded.

2.2.2 Milk composition

Individual cow butterfat percentages, protein percentages and somatic cell counts were obtained from the monthly National Milk Records sampling at Myerscough and the Scottish Milk Records Association at Auchincruive.

2.2.3 Feed

The weight of feed offered to the cow groups once or twice daily *ad libitum* was recorded, the refusals were weighed weekly and a mean weekly feed intake was determined for the mattress and mat groups.

The detail of the feed offered at Auchincruive was as follows:

40 kg per head of first cut silage (DM ~ 22%)

plus 6 kg per head of supergrains (DM ~ 22%)

plus 3 kg per head of barley (DM ~ 85%)

plus for the first 100 days of the trial 3 kg per head of concentrates

for the remainder of the trial $^1/_2$ kg per head of concentrates

The detail of the feed offered at Myerscough was as follows:

40 kg per head of first cut silage (DM ~ 21.5%)

plus 8 kg per head of maize silage (DM ~ 29%)

plus 3.5 kg per head of caustic treated wheat

plus 2 kg per head of 40% protein meal

plus 0.12 kg per head of minerals

2.2.4 Weights and body condition score

Weighing and Body Condition Scoring were always done after evening milking at Auchincruive and after morning milking at Myerscough. Weights were recorded as the cows returned from the parlour into the handling area via a crush with a weigh platform. Body condition scoring was carried out on a score range of '0' to '5' in accordance with the standard practice established by Mulvaney (1977).

The fat at the tailhead and loin were assessed using the scale from 0 (very poor) to 5 (grossly fat) with half scores in between to give an eleven point scale. Any tightness or mobility of the skin was determined at these two main areas and the assessment was done by feeling the amount of fat, a visual assessment not being considered sufficiently accurate.

2.2.5 Subjective scoring for hock/knee injury, dirtiness and locomotion

Cows were weighed and scored just before the trial and fortnightly thereafter, from the beginning of October 1997 until April 1998. This gave sixteen scores for each core cow in the study. The scoring was carried out by the same person at all times, the sawdust bedding was applied in the same quantities and cubicles were cleaned in the same way for both mattress and mat cows at each site.

2.2.5.1 Hock and knee injury score

The knees and hocks of each cow were scored in order to establish a pattern for the conditions of these joints in the housing time spent going onto and getting up from the cubicle beds. The scoring system for knee and hock injury was specifically developed for use in this study but closely based on the method described by Gustafson (1993):

0 = no lesions observed;

1 = bare, pale areas;

2 = bare, red areas;

3 = occurrence of serum and/or sore scabs;

4 = open, infected wounds;

5 = adventitious bursae ('big', or swollen, knee/hock).

2.2.5.2 Dirtiness score

Four areas of the cow, body, rear, udder, legs (*Fig. 2.2*) were scored for dirtiness on a scale of 1 to 3, with half points, based on work done by Bergsten and Pettersson (1992):

1 = perfectly clean;

2 = quite dirty;

3 = very dirty.

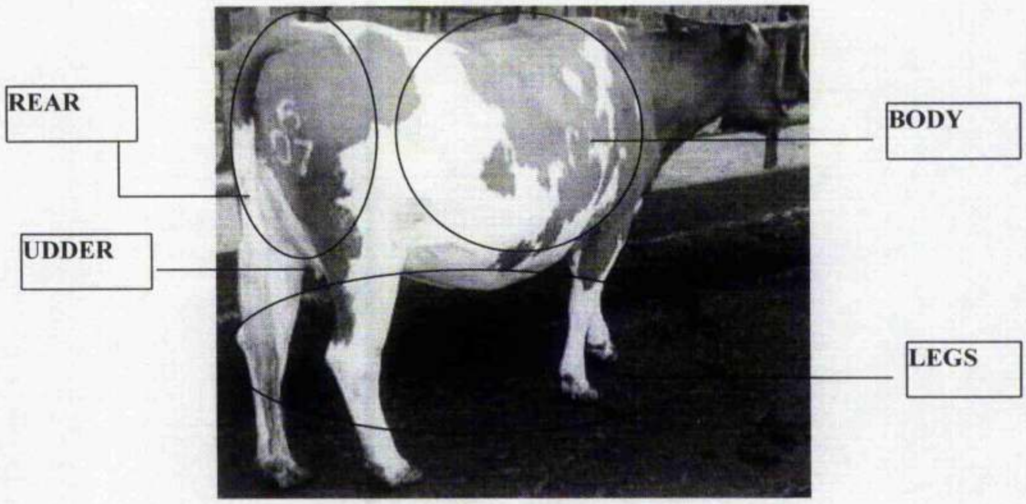


Fig. 2.2 Body, rear, udder and legs of a cow as used in dirtiness scoring

2.2.5.3 Locomotion score

Cows were scored on a scale of 1 to 5, with half-points, as described by Manson and Leaver (1988):

1 = walking freely and soundly, no unevenness or tenderness;

2 = walking 'short' (<75% tracking up). May have uneven gait and appear tender, possibly with downward extension of the head;

3 = slight lameness, not affecting normal behaviour;

4 = obvious lameness, affecting normal behaviour;

5 = severe lameness, difficulty rising.

2.2.6 Clinical lameness

The abbreviations used in chapter 2 in the context of dairy cow clinical lameness have the meanings listed below:

N.LAME	the number of cows which went lame at least once.
WEEKS LAME	total number of weeks lame per cow.
N.EVENTS	the number of lameness events per cow.

Cows with a locomotion score of 3 or greater were considered to be clinically lame and the incidence and prevalence were defined by several parameters. These were: the number of cows that went lame at least once during the trial (N.LAME); total number of weeks lame per cow (WEEKS LAME); and the number of lameness events per cow during the trial (N.EVENTS). A locomotion score 3 or greater was defined as a new lameness event if it was preceded by two scores of less than 3 (i.e. 4 lameness-free weeks). No distinction was made regarding the site or cause of lameness.

2.2.7 Behaviour

The abbreviations used in chapter 2 in the context of dairy cow lying and standing behaviour have the meanings listed below.

L-scan	lying, recorded by scan sampling
LR/L	proportion of lying time spent ruminating
SO	idling (standing, doing nothing)
logSO	log transformed idling
SO(C)/SO	proportion of idling time spent in cubicles
S½	standing half-in cubicles with back feet in passageway
logS½	log transformed S½
L-TOTAL	total lying time, recorded by event sampling
L-BOUTS	number of lying bouts over 24h
L-MAX	maximum bout length
L-MIN	minimum bout length
L-AV	average bout length

The lying, standing, feeding, drinking and ruminating behaviour pattern of 15 core cows in each group was recorded every 15 minutes for 24 hours at weeks 0, 2, 4, and 6 post-housing on both sites. After the week 6 observation, when the summer-calving filler cows were replaced by late-autumn-calvers, behavioural observations were made at week 8 on both sites and then at weeks 16 and 24 at Auchincruive, and weeks 14 and 22 at Myerscough. For the purposes of analysis, weeks 14 and 22 at Myerscough then corresponded to weeks 16 and 24, respectively, of the Auchincruive data.

In addition, lying time was recorded in more detail at each behavioural observation by event sampling, recording the exact time that each cow lay down or rose from lying, and the cubicle that she used.

2.3 Analysis

Statistical tests were performed using Genstat for Windows Version 5.3.3.2, unless otherwise stated, and the effects investigated throughout were; herd (Auchincruive or Myerscough), group (mattress or mat) and herd*group interaction. The level of significance used in the analysis was $p = 0.05$.

2.3.1 Milk yield

The daily milk yield results were tabulated for each cow and an average milk yield per cow was worked out for each group. Although individual results for each cow were obtained the study was undertaken to observe the two groups as a whole and so the statistical analysis was carried out on the average milk yield figures per cow/ week for each group.

The statistical tests were performed using the Unistat Statistical Package version 4.007. To do the appropriate tests it was necessary for the results to be normally distributed. To test for normal distribution, a one sample Kolmogorov-Smirnov Test: Normal was carried out. All the data that showed a normal distribution were analysed by analysis of variance (ANOVA).

2.3.2 Milk composition

The monthly milk composition results were tabulated for each cow and an average butterfat and protein percentage for each group at each site was determined.

As with the milk yield results the statistical analysis was conducted on the average butterfat and protein content per cow per month for each group.

2.3.3 Feed

The feed amount offered to the mattress and mat cow groups at each site was recorded and the amount eaten by each group was determined from what remained at the end of each week. The changes in intake over the trial period has been determined for each group on this basis and has been illustrated in *Fig. 2.6a* and 2.*6b* in the results section of Chapter 2.

2.3.4 Weights and body condition score

The average, maximum and minimum weights were calculated for each cow in the trial. ANOVA was then carried out for the Auchincruive and Myerscough herds and the mattress and mat groups for both herds. Also, any herd/group interaction was established. Weight change was calculated by taking the minimum weight from the maximum weight for each cow and this parameter was also analysed by ANOVA to determine if there were differences between the herds and groups. ANOVA was used to determine any differences in the average, maximum and minimum body condition scores of the cows in the trial.

2.3.5 Subjective scoring for hock/knee injury, dirtiness and locomotion

All subjective scores were transformed logarithmically to give a normal distribution (log SCORE = $\log_{10}$ (SCORE+1)). The average, maximum and minimum scores recorded for each cow during the trial were analysed by ANOVA (General Linear Model).

2.3.5.1 Hock and knee injury score

The fortnightly scoring was split into categories of injury from 0, injury-free joints, to 10, adventitious bursae on both knees (i.e. two scores of 5). The total number of injury observations was isolated for each cow and the mattress and mat groups were compared on this basis using ANOVA in regression.

2.3.5.2 Dirtiness score

The scores were analysed using ANOVA for the average and maximum total body dirtiness and udder dirtiness scores. Each cow in the trial was scored fortnightly and the mattress and mat cow grouped average and maximum scores were then compared for a significance of difference.

2.3.5.3 Locomotion score

In addition to analysis of average and maximum scores during the trial, pre-trial locomotion scores were also compared to check for pre-existing differences.

2.3.6 Clinical lameness

N.LAME was binomially distributed (cows had either been lame or not lame during the period of the trial) and therefore was analysed by logistic regression.

The data for N.EVENTS and WEEKS LAME both followed a Poisson distribution (count data with discrete intervals and no upper limit) and so were analysed using Generalised Linear Regression, specifying a Poisson distribution and a canonical link function.

2.3.7 Behaviour

The behaviours analysed were: lying (L-scan), proportion of lying time spent ruminating (LR/L), idling (SO; standing, doing nothing), proportion of idling time spent in cubicles (SO(C)/SO), and standing half-in cubicles with back feet in the passageway (S½). Each behaviour was expressed as a proportion of the time observed in cubicles as during milking time they were not free to engage in lying, standing half-in cubicles, or idling in cubicles.

SO and S½ data were skewed and so were transformed logarithmically before analysis. The remaining behavioural data were normally distributed and did not require transformation.

Event sampled lying behaviour was characterised by: total lying time over 24h (L-TOTAL); number of lying bouts over 24h (L-BOUTS); maximum bout length (L-MAX); minimum bout length (L-MIN); and average bout length (L-AV).

All behavioural data were analysed by split-plot ANOVA (repeated measures ANOVA) with group and week of scoring as treatment effects, herd as whole plots, group as sub-plots and individual cows as blocks.

2.4 Results

2.4.1 Milk yield

The average milk yield at Myerscough was marginally, but not significantly, higher on the mats than the mattresses (Table 2.1). The reverse was the case at Auchincruive with mattress cows giving a slightly higher average yield. Statistically the milk yield results showed that there was no significant difference between the groups (mattresses and mats), P = 0.5699 at Myerscough and P = 0.9206 at Auchincruive. The average milk yield for the herd at Myerscough was higher than that at Auchincruive.

Table 2.1 Daily average and maximum milk yield (litres) per cow in each group

	Auchincruive		Myerscough	
	Mattress	Mat	Mattress	Mat
Average milk yield	24.7	24.4	29.2	30.3
Maximum milk yield	30.0	29.9	33.3	33.9

2.4.2 Milk composition

At both sites the butterfat percentage was higher on the Mattresses than on the mats (Table 2.2), although, again, this was not a significant difference. Myerscough, P = 0.1779 and Auchincruive, P = 0.4152.

Table 2.2 Average and maximum butterfat content (%) for milk yield in each group

	Auchincruive		Myerscough	
	Mattress	Mat	Mattress	Mat
Average butterfat	4.03	3.89	4.18	4.06
Maximum butterfat	4.51	4.23	4.37	4.30

As with the butterfat results the protein averages were again higher at both sites on the mattresses (Table 2.3) although the maximum percentage at Auchincruive was higher on the mats. This did not prove to be significant.

Table 2.3 Average and maximum protein content (%) for milk yield in each group

	Auchincruive		Myerscough	
	Mattress	Mat	Mattress	Mat
Average protein	3.06	2.99	3.29	3.22
Maximun protein	2.95	3.29	3.42	3.27

Using the NMR and SMRA data individual somatic cell count records were analysed and there were no significant differences between the mattress and mat cows in terms of average, maximum and minimum somatic cell count levels. All somatic cell count levels were at a satisfactory level (*Fig. 2.3, 2.4* and *2.5*).

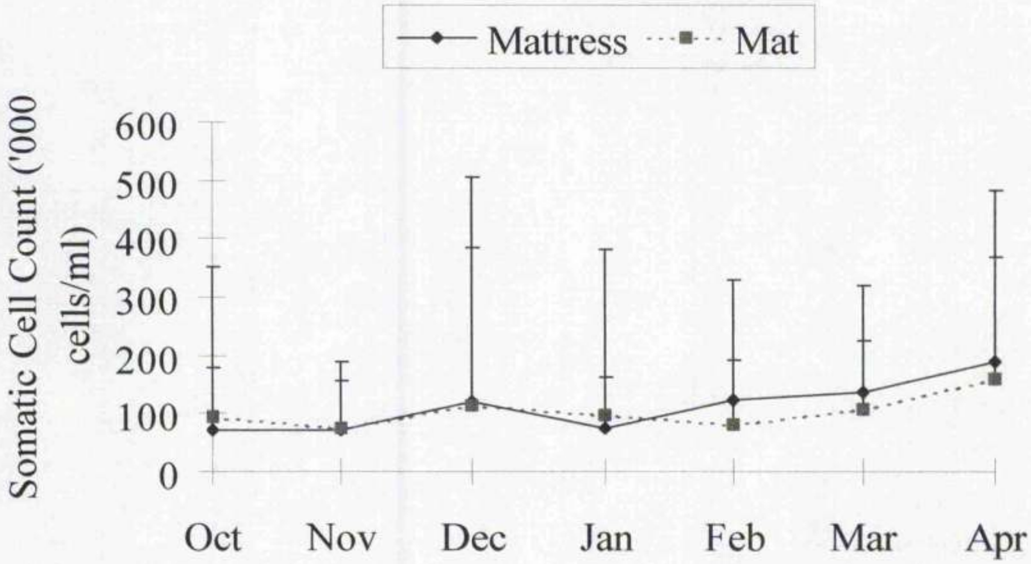


Fig. 2.3 Mean monthly somatic cell counts (± SE) for the two groups (Auchincruive and Myerscough data pooled), October 1997 to April 1998

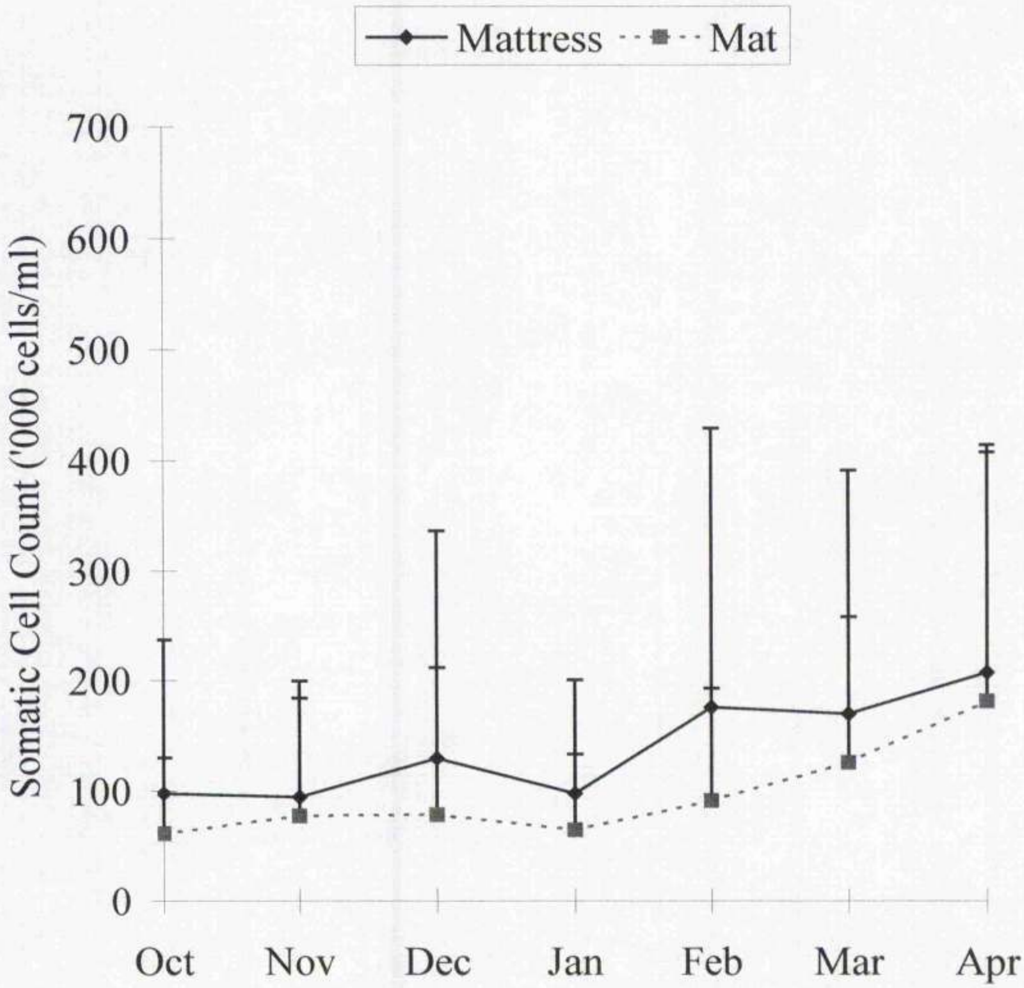


Fig. 2.4 Comparison of somatic cell counts from October '97 to April '98 for groups at Auchincruive

(Note: The bars represent the standard error)

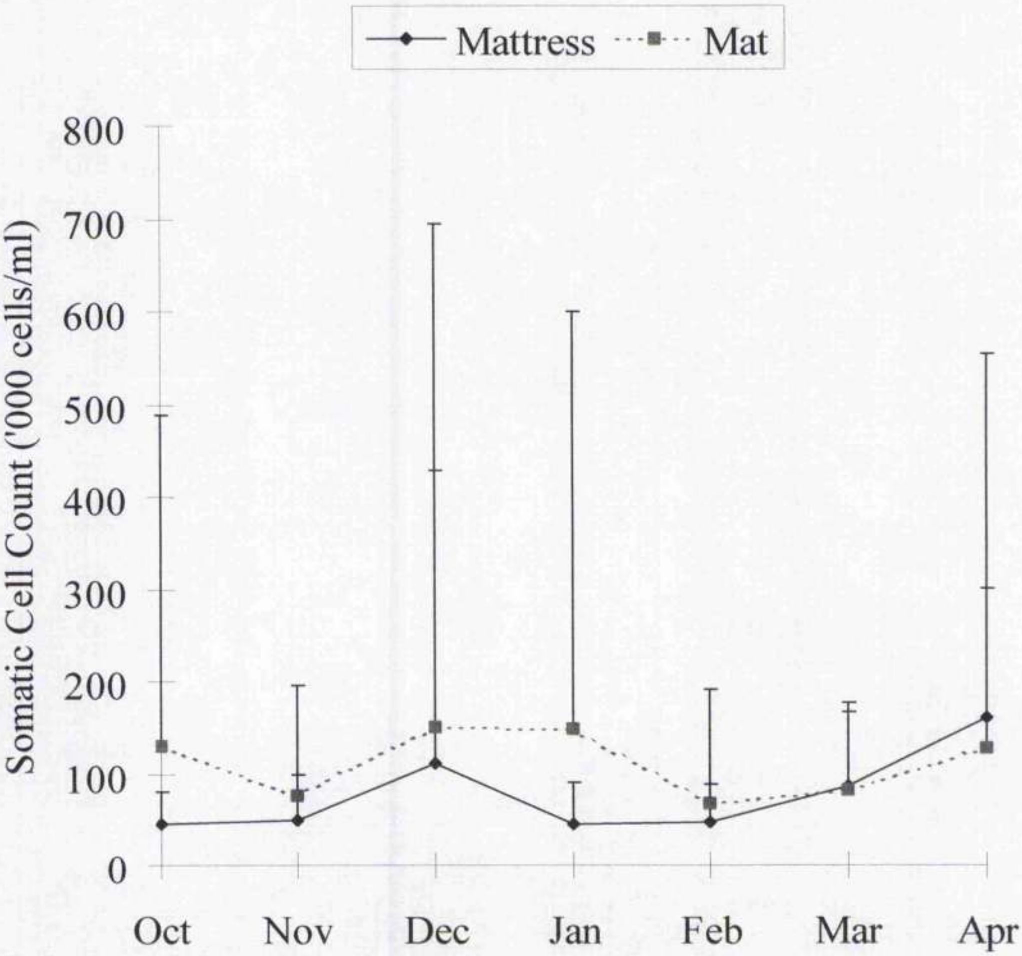


Fig. 2.5 Comparison of somatic cell counts from October '97 to April '98 for groups at Myerscough

(Note: The bars represent the standard error)

2.4.3 Feed

Fig. 2.6a and *2.6b* show the weekly intake of feed for the mattress and mat groups at each site. The average weekly intake of the mattress and mat groups was 10,619 kg and 10,367 kg freshweight, respectively, taking the Auchincruive and Myerscough herds together. As there was a total of 58 cows in each group, this difference equates to approximately 4.3 kg/cow per week. The feed at Auchincruive consisted of 15 kg DM/cow/day for the first 100 days of the trial and 12 kg DM/cow/day for the remaining time. The complete diet feed at Myerscough consisted of 13 kg DM/cow/day for the trial period.

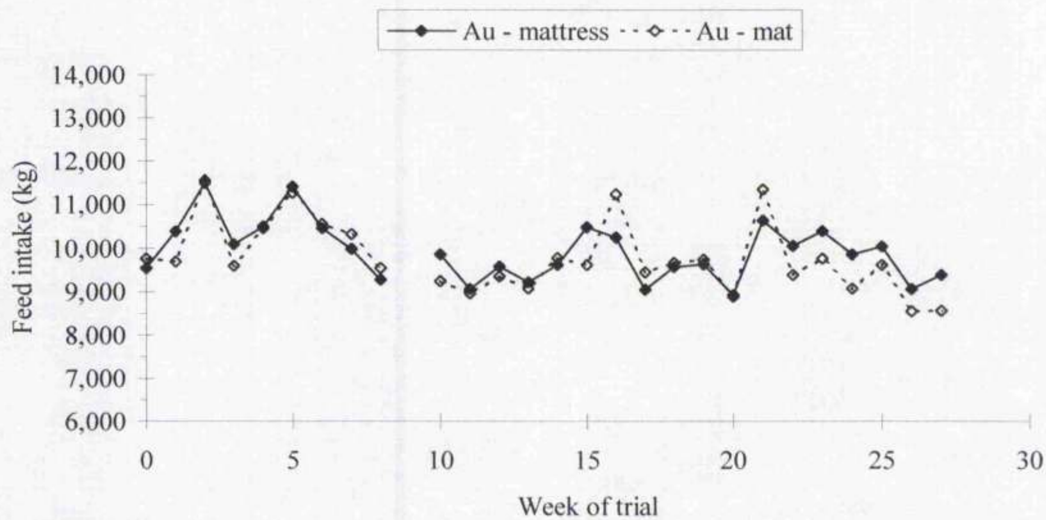


Fig. 2.6a Feed intake of trial cows at Auchincruive

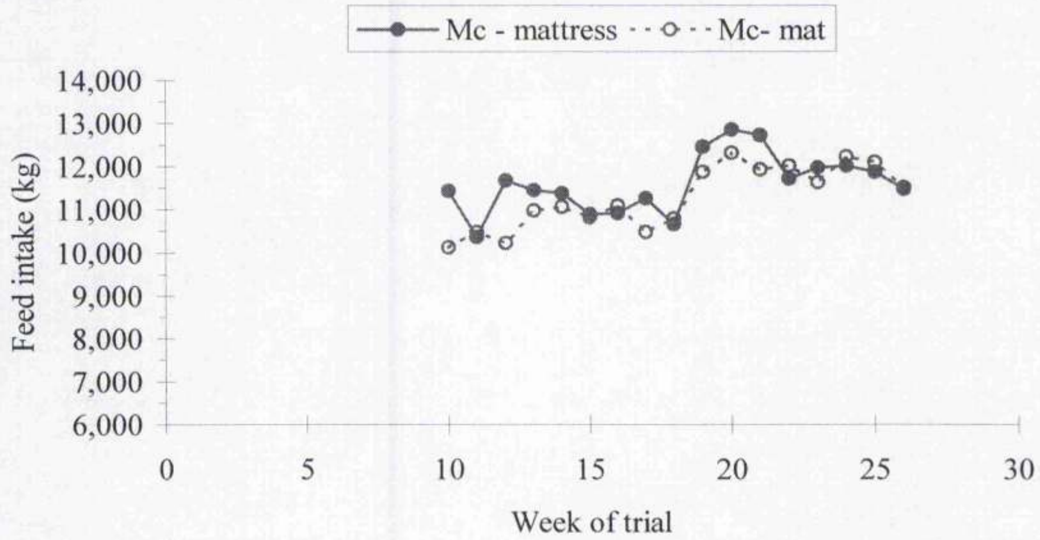


Fig. 2.6b Feed intake of trial cows at Myerscough

2.4.4 Weights

Weight loss (the difference between maximum and minimum weight) in the cows during the trial period was measured (Table 2.4). There were no significant differences between the mattress and mat cows in terms of weight change ($P = 0.436$).

Table 2.4 Weight change (kg) in the trial cows

	Auchincruive		Myerscough	
	Mattress	Mat	Mattress	Mat
Weight change	49.9	47.8	39.5	48.5

2.4.5 Body condition score

Body condition average, minimum and maximum scores are given in table 2.5 in terms of herd and group mean. There were no significant differences between the body condition scores of the mattress and mat cows. ($P = 0.827$ for the mean average score; $P = 0.422$ for the mean minimum score; and, $P = 0.254$ for the mean maximum score). The Myerscough herd had higher average ($P < 0.001$) and minimum scores ($P < 0.001$) but there was no difference ($P = 0.762$) in the mean maximum score.

Table 2.5 Body condition scores

	Auchincruive		Myerscough	
	Mattress	Mat	Mattress	Mat
Average score	2.4	2.4	2.5	2.5
Minimum score	2.0	1.9	2.2	2.3
Maximum score	2.9	2.8	2.9	2.8

2.4.6 Hock and knee injury score

The average injury scores for hocks and knees on rubber-crumb mattresses and EVA mats were compared at the two farms (Table 2.6). The average hock injury scores were lower for cows on rubber-crumb mattresses compared to those on EVA mats at SAC Ayr ($P < 0.001$). The average knee injury scores for the two bed-type groups at SAC Ayr were also significantly different ($P = 0.026$) in favour of the cows on mattresses. At Myerscough there were no significant differences between the two bed-type groups in terms of either average hock ($P = 0.951$) or average knee ($P = 0.505$) injury scores. The average hock and knee injury scores for both bed-type groups at both farms were at the lower end of the scale used in the injury assessment. The analysis of injury scores showed that there was a statistically significant difference in the incidence of minor hock and knee problems (Table 2.6) between the mattress and mat cows at SAC Ayr. The results showed that there was a lower average score in the mattress group. Injury to dairy cow hocks and knees are common in the winter housing period and the full range of injuries, from the minor 'bare, pale area' to the severe 'adventitious bursae', were observed in the trial in cows on both types of cubicle bed. However, injury scores of 0 or 1 are indicative of a positive cow reaction to a mattress or mat (Table 2.7) and at SAC Ayr a higher proportion of rubber-crumb mattress cows had the 0 or 1 score for both knee and hock injury. The incidences of knee and hock injury scores of 0 or 1 in the rubber-crumb mattress and EVA mat cows at Myerscough were similar.

Table 2.6 Rubber-crumb mattress and ethylene vinyl acetate (EVA) mat comparison for average hock and knee injury scores

	Cows on rubber-crumb mattresses	Cows on EVA mats	S.E.D.	*p*
SAC Ayr				
Average hock injury score	1.04	1.44	0.106	< 0.001
Average knee injury score	0.37	0.52	0.068	0.026
Myerscough				
Average hock injury score	0.39	0.38	0.119	0.951
Average knee injury score	0.16	0.20	0.068	0.505

Table 2.7 Rubber-crumb mattress and ethylene vinyl acetate (EVA) mat proportions of hock and knee injury scores of 0 or 1 in SAC Ayr and Myerscough cows

	Number of injury scores of 0 or 1 (indicators of no injury or low injury)			
	Hock		Knee	
Cubicle bed type	Possible	Actual	Possible	Actual
SAC Ayr cows				
Rubber-crumb mattress	471	163 (35%)	476	378 (79%)
Ethylene vinyl acetate (EVA) mat	469	114 (24%)	471	292 (62%)
Myerscough cows				
Rubber-crumb mattress	458	379 (83%)	458	436 (95%)
Ethylene vinyl acetate (EVA) mat	459	359 (78%)	459	428 (93%)

2.4.7 Dirtiness score

The average total dirtiness scores showed that there was no significant difference between the scores of mattress and mat cows (p = 0.074). Taking all cows on mattresses and comparing them to those on mats there was no significant difference (p = 0.463) between the maximum total dirtiness scores (Table 2.8).

Table 2.8 Total body dirtiness scores

	Auchincruive		Myerscough	
	Mattress	Mat	Mattress	Mat
Average score	6.2	6.0	5.7	5.6
Maximum score	7.5	7.5	6.6	6.4

However, examination of specific areas showed that there was a significant difference in average udder dirtiness scores between the mattress and mat cows when those at both Auchincruive and Myerscough are considered ($p = 0.042$) with the udders of the cows on mats being cleaner (Table 2.9). The maximum udder dirtiness scores showed that there was no significant difference between the mattress and mat cows ($p = 0.147$).

Table 2.9 Udder dirtiness scores

	Auchincruive		Myerscough	
	Mattress	Mat	Mattress	Mat
Average score	1.5	1.4	1.3	1.2
Maximum score	2.0	1.9	1.6	1.6

2.4.8 Locomotion score

There was no difference between the mattress and mat groups at both sites before the trial commenced, $p = 0.062$, although there was a difference between the Auchincruive and Myerscough herds. Pre-trial scores for the new fillers at Week 8 were significantly different between herds, $p < 0.001$, (Table 2.10).

Table 2.10 Mean pre-trial locomotion scores

	Auchincruive	Myerscough
Pre-housing	1.61	1.71
Week 8 (new fillers)	1.58	1.91

Average scores for the trial period were consistently higher at Myerscough than at Auchincruive but there was no difference in the maximum scores.

There were no significant differences between the mattress and mat cows in terms of locomotion scores. Average score, p = 0.403; maximum score, p = 0.345; minimum score, p = 0.793, (Table 2.11).

Table 2.11 Locomotion scores of groups in the trial period

	Auchincruive		Myerscough	
	Mattress	Mat	Mattress	Mat
Average	0.66	0.70	0.77	0.81
Maximum	1.21	1.36	1.23	1.25
Minimum	0.32	0.28	0.53	0.55

2.4.9 Clinical lameness

There was no difference in the number of cows which went lame at least once, (N.LAME), either between the groups or between the herds and no difference in the number of lameness events per cow, (N.EVENTS), between herds (p = 0.128). Mattress cows appeared to have more lameness events than those on mats (p = 0.063), although the interaction between group and herd was more significant (p = 0.019). The total number of weeks lame per cow, (WEEKS LAME), did not differ either between herds (p = 0.101) or between groups (p = 0.266) but, again, the interaction was significant (p = 0.013, *Fig. 2.7*).

Fig. 2.7 shows the number of cows which had a given number of weeks lame. The lowest number of weeks lame for all four groups in the trial was 0 and the highest number of weeks lame was 8 (found in the Auchincruive Mat group).

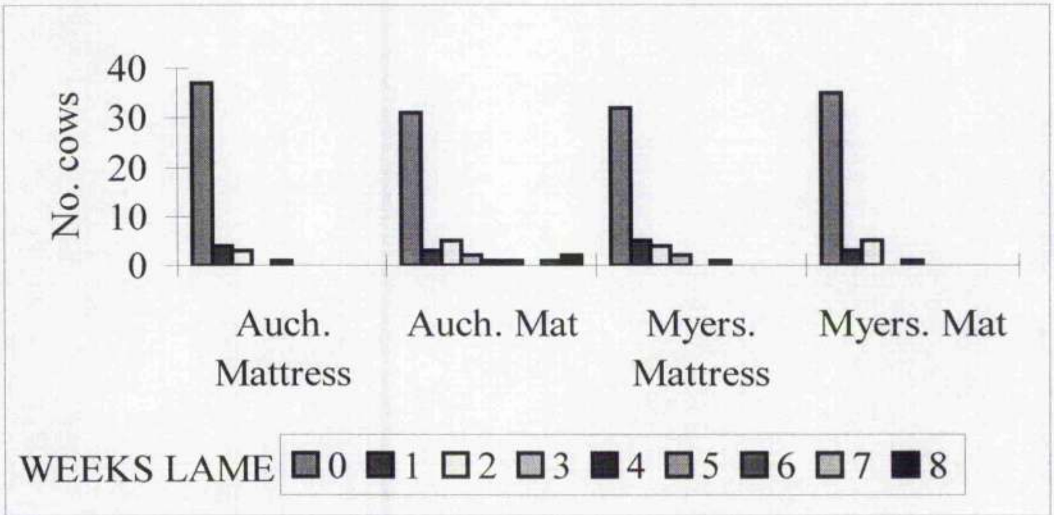


Fig. 2.7 Effect of interaction between group and herd on WEEKS LAME

2.4.10 Behaviour

Mattress cows had longer lying times and longer periods of ruminating while lying which indicates greater comfort levels. Also, the mattress cows spent less of their time standing doing nothing.

Fig. 2.8a – 2.8e illustrate the change in each of the behaviours investigated, for the core cows of the two groups. The two herds (Auchincruive and Myerscough) differed only in lying time scanned (L-scan), lying and ruminating as a proportion of total lying time (LR/L) and standing half-in a cubicle (logS½).

The variation over time was highly significant ($p \leq 0.001$) for all behaviours and in each behaviour, with the exception of standing half-in a cubicle, the variation was different between the two groups ($p < 0.05$).

Overall, Mattress cows had a greater proportion of lying time scanned (L-scan) (0.50 vs. 0.44, $p = 0.004$) and lying and ruminating as a proportion of total lying time (LR/L) (0.58 vs. 0.50, $p < 0.001$). Also, mattress cows had less time idling (SO) (0.10 vs. 0.13, $p < 0.001$) and less time idling in a cubicle as a proportion of total idling time (SO(C)/SO) (0.05 vs. 0.07, $p = 0.004$).

Fig. 2.8a The change over time and the effect of group for lying

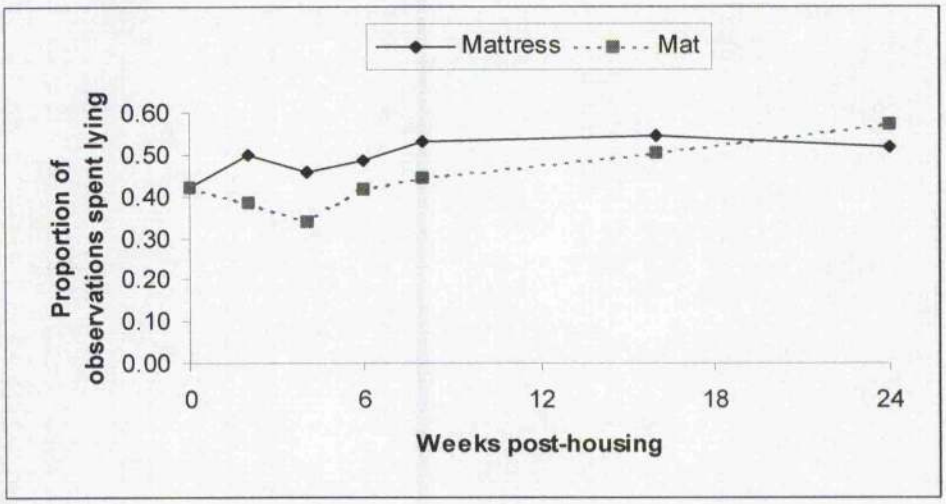


Fig. 2.8b The change over time and the effect of group for lying-ruminating as a proportion of total lying

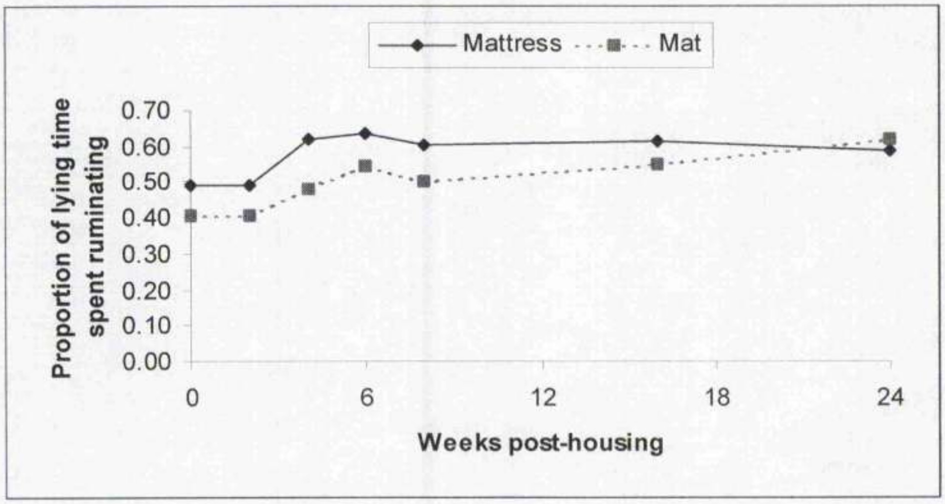


Fig. 2.8c The change over time and the effect of group for idling

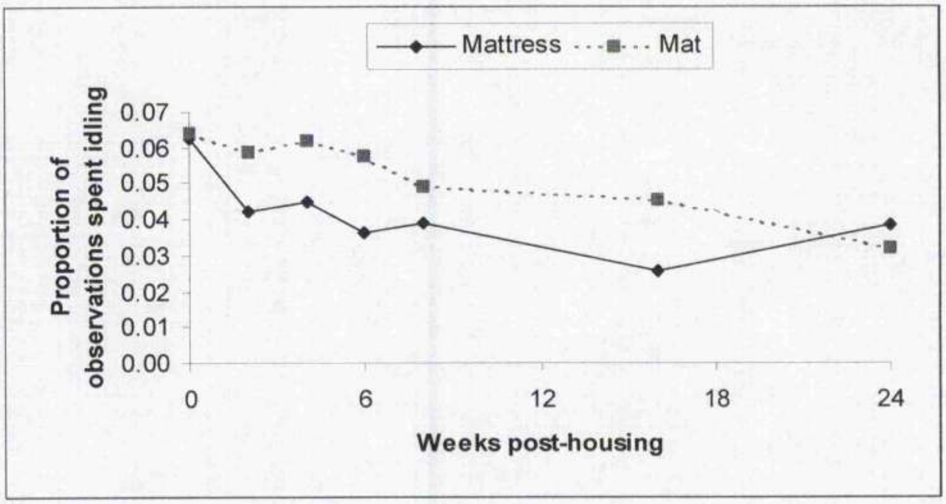


Fig. 2.8d The change over time and the effect of group for idling in cubicles as a proportion of total idling

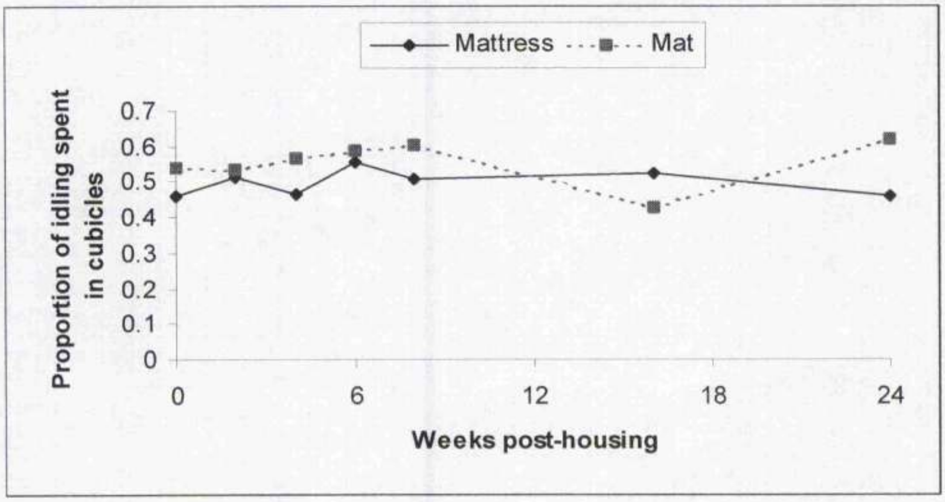
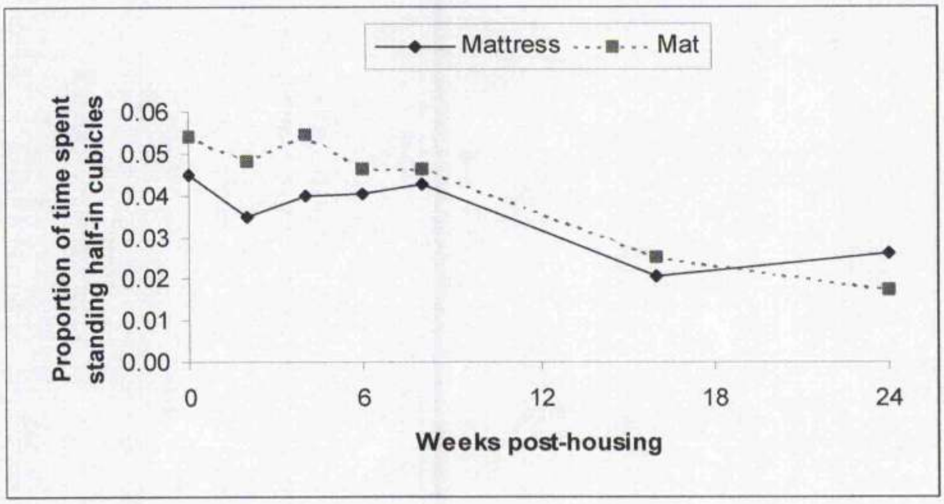


Fig. 2.8e The change over time and the effect of group for standing half-in cubicles



2.5 Discussion

2.5.1 Lying and idling time

Lying time and the proportion of lying time spent ruminating were greater in the mattress group suggesting that this bedding was more comfortable for cows, although reduced lying times associated with the onset of housing were seen in both groups. Likewise, idling was greater in the mat group and greatest in the initial week of housing for both groups, suggesting that it is indicative of unsettled behaviour. However, this apparent higher level of comfort, a good thing from an animal welfare point of view, did not have any effect on milk production levels, butterfat percentages or protein percentages.

The proportion of idling time spent in cubicles might suggest that cows are motivated to lie down but unwilling to do so because of discomfort and this may be a possible explanation for the reduction in total lying. However, there was no difference between the groups in this parameter and neither did standing half-in cubicles vary between the groups. It may be that these two behaviours were more closely related to cubicle design than to the softness of the bedding.

The Group*Week interaction effect, which was seen for all the behaviours except standing half in a cubicle (logS½), was largely due to the observations made in week 24, when the differences between the groups were reversed. This reversal (*Fig. 2.8a*) may have been due to the mat cows increasingly finding their cubicle bed option comfortable, while the mattress cows stayed at a consistent level of comfort.

2.5.2 Injury to hocks and knees

Leg injuries can result from causes other than kneeling or rising. They may, result from contact with the cubicle division or the handling gates or from abrasion with, rather than impact upon, the cubicle bed. They may also result from infection. The statistical analysis ensures that such specific, single instances are insignificant. Differences in the hock and knee injury scores in the SAC Ayr and Myerscough herds may have been partly due to the necessarily subjective nature of the scoring system. Different cubicle divisions at the two sites may also have been a factor. The cubicle divisions at SAC Ayr were the Dutch 'Supercomfort' type, which had a back leg at the passageway edge of the cubicle, whereas those at Myerscough were the 'Mushroom' type with two legs near the middle of the cubicle length. However, neither of these factors affected the relative differences between rubber-crumb mattresses and EVA mats since, within one site, the mattress and mat cows were housed in cubicles with the same type of divider.

The analysis of injury scores showed that there was a statistically significant difference in the incidence of minor hock and knee problems between the mattress and mat cows at SAC Ayr. The results showed that there was a lower average score in the mattress group. However, Chaplin *et al.* (2000) analysed this same data for major injuries, injury score '5', and found no significant difference between the mattress and mat groups at either farm. This would imply that, at least for the range of products that are within the Nilsson (1988) softness and hardness limits, selection should not be based on the risk of major injury but on factors such as unit cost and the risk of minor injuries. The second of these two factors, if sustained in the longer-term, is likely to have an adverse effect on cow comfort and health.

Previous injury research has suggested that concrete cubicle beds are harmful to cows and that mattresses and mats improve things. For example, Underwood *et al.* (1995) tested recycled rubber tyre mattresses in a dairy unit for 84 cows in tie-stalls and stated that mattresses greatly reduced the incidence of leg and udder injuries. McFarland and Gamroth (1994) stated that the main purpose of the cubicle bed is to provide a cushion layer. Rodenburg *et al.* (1994) reported on a test of mattresses and mats for hock injury scores where 0 was the best condition (no swelling, no hair loss) and 3 was the worst (swelling, hair off), concluding that swelling incidences were less for mattresses but that hair loss was similar for both mattresses and mats. House *et al.* (1994) reported on the use of rubber-filled mattresses in Canada and gave results for hock injuries that suggested a reduction in injury levels in a 130-cow herd after the installation of mattresses.

2.5.3 Feed intake

It was not possible to analyse the feed intake records on a statistical basis but the feed intake was higher in the Myerscough herd than at Auchincruive and mattress cows at both sites had higher intake levels than mat cows. The cows at Myerscough were heavier overall than those at Auchincruive since there is a mix of Ayrshires and Holstein-Friesians in the latter herd and only Holstein-Friesians in the former. However, the key consideration is any variation between the mattress and mat groups at each site so the difference in cow type and size between sites is not a factor.

Weight change in cows is important because it reflects their performance over the lactation period. Also, cows tend to lose weight at the beginning of lactation because their feed intake cannot make up for the demands of milk production. Cows that are not 'doing well' may be expected to lose more weight (Livesey *et al.*, 1997) and this may be a good indicator of the type of cubicle bed suited to cows in early lactation.

2.5.4 Locomotion

Locomotion scores were lower at the beginning of the trial as cows were only recently calved and had not been housed. The transition period at Myerscough could be responsible for the pre-trial herd difference. Also, there was a large number of heifers in the Auchincruive herd. Heifers do not usually have a history of lameness and their mobility is often better than that of older cows.

Overall, mattress cows had a lower average locomotion score and this was mediated by a lower minimum score. This was not accompanied by a difference in maximum score which suggests that the same number of cows went lame in each group. There were more cows with uneven gait in the mat group. This slight unsoundness could be due to the greater standing time of the mat cows.

The interaction between group and herd seen for N.EVENTS and WEEKS LAME was due to a few, persistently lame cows in the Auchincruive Mat group which had repeated incidents of lameness. These were not all older cows with a history of lameness and there were equal numbers of old cows on the trial which did not become lame. As this effect was not mirrored in the Myerscough Mat group, it is questionable whether it can be entirely attributed to the bedding type since there are many factors which cause lameness. It was not possible to undertake a full series of hoof examinations for all cows on the trial so we cannot speculate as to its cause. Hence no differences were found in clinical lameness between the mattress and mat groups.

2.5.5 Cow dirtiness

Environmental mastitis is recognised as being a key concern to farmers and milk buyers and research indicates that udder health is threatened by the teat orifice remaining open for many hours after milking (Schultze *et al.*, 1983). Hence udder cleanliness is a major area of concern for the dairy industry. Rodenburg *et al.* (1994) compared cleanliness scores in 6 herds on mattresses and 12 herds on mats and generally found that mattress cows were cleaner than mat cows. However, they did not analyse their data statistically and they recognised that there were different management practices such as stall cleaning and bedding-up frequency. Britten (1994) discussed a cow bed that attempted to provide both the cushioning of a deep layer of sawdust and the cleanliness of a plastic or rubber surface. This cow 'pillow' was described as an inert envelope of polypropylene around the filling of sawdust, thus containing the potential breeding medium for bacteria.

In this experiment the herd management at the two sites was very similar and statistical analysis has been applied. The results show that the average udder cleanliness was better for the mat cows. Total dirtiness, whole body dirtiness, may be affected by diet. That is, perhaps a low D.M. diet leads to dirtier cows. Other possible factors of influence are the efficiency of the automatic scrapers, the weather if the animals have to wait outside, and the provision of brushes and mutual grooming.

2.5.6 Milk records

The milk records showed that there was no difference between the yields of the cows on mattresses and mats at either site. Taking this result on its own would favour mats because they cost less than mattresses. But, it could be argued that, in the long term, an increase in total milk production could arise as a consequence of longer life due to better comfort levels that have been shown in the mattress cows in this one-winter study. Further work in this area of concern is essential if a reliable conclusion is to be made regarding comfort levels and milk production.

Chapter 3.0 Physical and engineering properties of hyperelastic materials used in dairy cow cubicle bed manufacture

Chapter 3 is a review of the engineering properties of hyperelastic and hyperfoam materials. These properties are the basis of any cushioning offered by dairy cow cubicle beds. The Ogden (1984) hyperelastic strain energy function is encoded into Abaqus/Explicit (HKS, 1998), which has been used in the current work to assess the cushioning performance of the cubicle bed types under investigation.

Deformation mechanics is the branch of engineering most concerned with the response of solid objects to external loads. It therefore provides the theoretical framework for predicting the behaviour of a cow cubicle mat loaded by the mass of an animal. Engineers are familiar with the mechanics of linear-elastic materials but it is hoped that the current work will be of use to a wider readership that may include animal behaviourists and other non-engineers. Therefore, it is appropriate to present some basic concepts before moving to the advanced theory of the deformation of non-linear hyperelastic polymer mats.

Three aspects of the deformation of a cubicle bed render elementary linear-elastic deformation theory inadequate:

- the multi-axial nature of deformation in a three-dimensional bodies;
- deformations that are large enough to produce geometric non-linearity in the governing equations;
- the sigmoid shape of the force-displacement response of the materials and the consequent material non-linearity.

3.1 The mechanics of solids and structures

3.1.1 Stress and the ultimate tensile stress (UTS)

All materials break when subjected to a sufficiently large force. Prior to breaking, they deform in a manner that differs according to the nature of the material. The deformation may be too small to view with the naked eye, but it occurs nonetheless. If engineers are to design successful structures, they must be able to predict this deformation and determine the maximum load that the structure can sustain without failing. To gain such information, it is necessary to physically test materials under controlled laboratory conditions. The simplest laboratory test is the uniaxial test, in which a specimen is subject to simple tension (pulled between the grips of the testing machine) or compression (pushed, usually between flat platens). The former is more common with ductile materials, such as structural steels, while the latter is more common with brittle materials, such as concrete. In the current work, uniaxial compression tests were used to determine the elastic constants required for computational models of the EVA foam and rubber-crumb cubicle beds.

Intuitively, steel is stronger than wood but a paper clip will break at a lower load than a large tree trunk. To compare materials, as opposed to structures, it is necessary to compare specimens of equal size. However this is not always possible. A large metal specimen may be impractical while a small wooden specimen may contain features such as knots that make the sample unrepresentative of the whole tree. To assess the severity of an applied force (F) on specimens of different cross-sectional area (A) and so assess how close they are to breaking, the applied force is divided by the area to give a stress (σ)

$$\sigma = \frac{F}{A} \tag{3.1}$$

On this basis, it is observed that every material has a characteristic ultimate tensile stress (UTS) at which fracture occurs. As it is stretched, the area of a tensile specimen will reduce from an initial value ^{o}A to a current value A. Stress can be defined as either F/^{o}A (the nominal or engineering stress) or F/A (the true or Cauchy stress). The terms 'engineering' and 'true' are historical rather than meaningful. In the current work, the Cauchy stress will be used.

3.1.2 Stretch and strain

Uniaxial tensile specimens often stretch by an amount that is proportional to both the applied force (or stress) and to the length of the test specimen. To allow specimens of different lengths to be compared, the current length L of the deformed specimen is divided by its initial length ^{o}L, to give the stretch ratio λ. Materials such as soft biological tissue and some polymers may reach stretch ratios of 3 or 4 before they break but, for metals, the stretch ratio at the point of fracture is of the order of 1.001.

Since an un-deformed specimen has a stretch ratio of 1, all of the deformation in a metal is described in the 4th significant figure. This is unsatisfactory in calculations that are necessarily rounded to a few significant figures. What is required is a measure in which all of the deformation is described in, ideally, the first significant figure. Such a deformation measure is called a strain and the simplest of many possible strain measures is, in the uniaxial case

$$\varepsilon = \lambda - 1 \quad = \frac{e}{{}^{o}L} \tag{3.2}$$

where e is the extension of the specimen. This is the nominal or engineering strain. An alternative strain measure is

$$\varepsilon = \ln \lambda \tag{3.3}$$

which is the true, logarithmic or Biot's strain. For small strains, these give the same value and the second of these terms will be used in the current work. None of these terms contain more information than the stretch ratio, they are simply a method of improving the robustness of numerical calculations.

3.1.3 Uniaxial linear elasticity and the elastic modulus

Provided the load is not too large, a structural material will return to its un-deformed condition when the load is removed. Such a material is said to be elastic. The stress and strain are proportional, almost until the elastic limit is reached. This proportionality is expressed in Hooke's Law (Robert Hooke 1635-1703)

$$\sigma \propto \varepsilon \tag{3.4}$$

$$\sigma = E{*}\varepsilon \tag{3.5}$$

The constant of proportionality E, is Young's modulus or the elastic modulus. Like the UTS, E is a characteristic of the material. Up to the limit of proportionality, such materials are said to be linear elastic. Beyond the elastic limit, or yield point, steels do not recover their original shape but this plastic deformation is not relevant to the study of hyperfoams.

3.1.4 Multiaxial deformation

Under uniaxial loading a specimen reduces or increases in cross-section as the tensile or compressive load is applied. Therefore, it is useful to regard the stresses and strains in each direction of multi-axial deformation as components of a 3-dimensional stress and strain state. To describe fully the stress and strain states requires several components and so neither can be a scalar (zero order tensor), which has one component, nor indeed a vector (first order tensor), which has three components. Both stress and strain are examples of second order tensors or matrices, denoted $\underline{\underline{\sigma}}$ and $\underline{\underline{\varepsilon}}$ in Gibb's notation. They each have nine components, and can be written in matrix notation, thus

$$\begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

and

$$\begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix}$$

Figure 3.1 shows the stress tensor components in 3-dimensions.

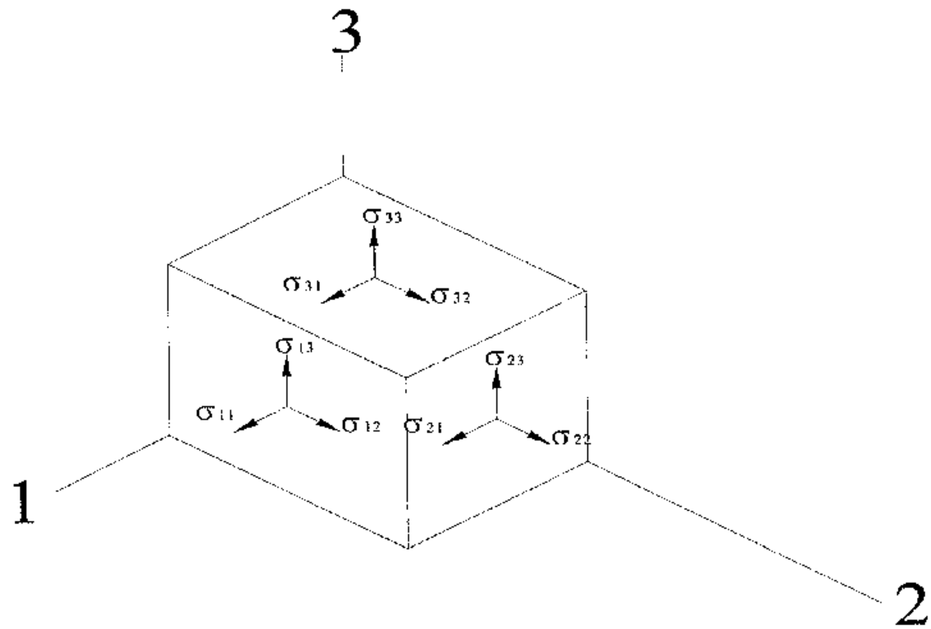


Fig. 3.1 The stress tensor components

Matrix notation is an efficient way of setting out a large number of linear simultaneous equations, such as are generated by finite element analysis. In most situations, both the stress and strain tensors are symmetric, each with six independent components. Thus, while a uniaxial stress σ_{11} produces a positive (i.e. tensile) strain ε_{11}, it also produces negative (i.e. compressive) strains ε_{22} and ε_{33} in the other two directions. These components are generally smaller than ε_{11} and the ratio $\varepsilon_{22}/\varepsilon_{11}$ is the material constant, Poisson's ratio, ν. For an isotropic material, one in which the behaviour is the same in all directions

$$\nu = -\frac{\varepsilon_{22}}{\varepsilon_{11}} = -\frac{\varepsilon_{33}}{\varepsilon_{11}} \tag{3.6}$$

in which the – sign is introduced so that the two strains, with different signs, result in a positive ν. In multi-axial loading

$$\varepsilon_{11} = 1/E\times(\sigma_{11} - \nu\times(\sigma_{22} + \sigma_{33})) \tag{3.7}$$

$$\varepsilon_{22} = 1/E\times(\sigma_{22} - \nu\times(\sigma_{33} + \sigma_{11})) \tag{3.8}$$

$$\varepsilon_{33} = 1/E\times(\sigma_{33} - \nu\times(\sigma_{11} + \sigma_{22})) \tag{3.9}$$

Although both stress and strain are tensors, it is convenient to adopt Voigt's notation and write them in a column format. Equations 3.7, 3.8 and 3.9 and the three corresponding shear expressions can then be written as

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{12} \\ \varepsilon_{13} \\ \varepsilon_{23} \end{bmatrix} = \begin{bmatrix} 1/E & -\nu/E & -\nu/e & 0 & 0 & 0 \\ -\nu/E & 1/E & -\nu/E & 0 & 0 & 0 \\ -\nu/E & -\nu/E & 1/E & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/(2\times G) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/(2\times G) & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/(2\times G) \end{bmatrix} \times \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{bmatrix} \quad (3.10)$$

where G is the shear modulus. G is also an elastic constant but E is usually called the elastic modulus. In compact form

$$[\varepsilon] = [C] \times [\sigma] \quad (3.11)$$

where $[\varepsilon]$ is the matrix of strains, $[\sigma]$ is the stress matrix and $[C]$ is the compliance matrix of the material.

E, ν and G are all elastic constants but for an isotropic material only two of these are independent and any one of them is expressible in terms of the other two via the relation

$$E = 2\times G\times(1 + \nu) \quad (3.12)$$

The 3-dimensional linear elastic constitutive equations may then be expressed in a number of alternative but equivalent forms. In particular, they may be inverted to give:

$$[\sigma] = [E] \times [\varepsilon] \tag{3.13}$$

where

$$[E] = [C]^{(-1)} \tag{3.14}$$

$$= \begin{bmatrix} \lambda+2G & \lambda & \lambda & 0 & 0 & 0 \\ \lambda & \lambda+2\times G & \lambda & 0 & 0 & 0 \\ \lambda & \lambda & \lambda+2\times G & 0 & 0 & 0 \\ 0 & 0 & 0 & 2\times G & 0 & 0 \\ 0 & 0 & 0 & 0 & 2\times G & 0 \\ 0 & 0 & 0 & 0 & 0 & 2\times G \end{bmatrix} \tag{3.15}$$

is the stiffness matrix and

$$\lambda = (E\times\nu)/((1+\nu)\times(1-2\nu)) \tag{3.16}$$

[E] or $[C]^{-1}$, the inverse of the compliance matrix, is also described as the stiffness matrix. Compliance and stiffness are the technically correct terms for cushioning performance in structures designed for the purpose, such as cubicle beds, as opposed to softness and hardness.

λ and G are alternative elastic constants called Lamé's constants (in Lamé's original notation G is denoted μ). Table 3.1 shows additional inter-relationships between the elastic constants for such a material.

Table 3.1 Elastic constant inter-relations for materials conforming to Hooke's Law (Engineering Fundamentals, 2001)

$E =$	$2\mu(1+\nu)$	$3k(1-2\nu)$	$\lambda(1+\nu)(1-2\nu)/\nu$	$9k\mu/(3k+\mu)$	$\mu(3\lambda+2\mu)/(\lambda+\mu)$	$9k(k-\lambda)/(3k-\lambda)$
$\nu =$	$(E-2\mu)/2\mu$	$(3k-E)/6k$	$2\lambda/(E+\lambda+R)$	$(3k-2\mu)/(6k+2\mu)$	$\lambda/2(\lambda+\mu)$	$\lambda/(3k-\lambda)$
$\mu =$	$E/2(1+\nu)$	$3kE/(9k-E)$	$(E-3\lambda+R)/4$	$3k(1-2\nu)/2(1+\nu)$	$\lambda(1-2\nu)/2\nu$	$3/2(k-\lambda)$
$k =$	$E/3(1-2\nu)$	$E\mu/[3(3\mu-E)]$	$(E+3\lambda+R)/6$	$[2\mu(1+\nu)]/[3(1-2\nu)]$	$\lambda(1+\nu)/3\nu$	$(3\lambda+2\mu)/3$
$\lambda =$	$E\nu/[(1+\nu)(1-2\nu)]$	$\mu(E-2\mu)/(3\mu-E)$	$3k(3k-E)/(9k-E)$	$2\mu\nu/(1-2\nu)$	$3k\nu/(1+\nu)$	$(3k-2\mu)/3k$

In Table 3.1, k is the bulk modulus, the ratio of the current volume to the initial volume, and so a measure of compressibility, λ is the 2nd Lamé constant and $R = (E^2+9\lambda^2+2E\lambda)^{0.5}$. λ is also commonly used to represent stretch ratio in the Ogden (1984) strain energy function, but the two meanings are not connected.

3.1.5 Elastic strain energy

The work done or energy expended when a variable force F extends a specimen by an amount e is found from:

$$W = \int F \times de \qquad (3.17)$$

$$= \int \sigma \times A \times L \times d\varepsilon \qquad (3.18)$$

$$\Rightarrow \quad W/(A \times L) = \int \sigma \times d\varepsilon \qquad (3.19)$$

$$\Rightarrow \quad W/V = \int \sigma \times d\varepsilon \qquad (3.20)$$

where V = A×L is the current volume of the specimen. W/V is the work done per unit volume of material, i.e. the energy density.

W/V is the 'true' energy density, in contrast to the nominal energy density $W/{}^{0}V$. Nominal quantities may seem less natural for large deformations but they are perfectly valid quantities that can be built into a constitutive model. The only requirement is that the terms $A \times {}^{o}L$ or ${}^{o}A \times L$, which do not give a valid volume measure, do not arise. In short, the stress and strain measures must be work conjugates.

Since elastic strain is recovered on unloading, so too, in theory, is the elastic strain energy of a linear elastic material. They are therefore conservative and, since they return to the original shape along the same line on a σ-ε plot, there is no loss of energy in the form of a hysteresis loop.

3.2 Geometric non-linearity.

The deformation of engineering structures under service loads is usually small enough for the shape to be almost unchanged by the load. It then doesn't matter whether the calculation of stresses and strains is based on the initial or the deformed configuration. However with the elastomeric materials from which cow cubicle mats are made, the initial and deformed shapes are very different and the strain value will depend significantly on the shape used as the basis for calculation. Such large deformation leads to geometric non-linearity in the governing equations. However the 3-dimensional stress and strain tensors in sub-chapter 3.1 are only applicable to linear problems and when both the translational and rotational deformations are small. If either of these conditions is violated a more general measure of deformation is needed.

The shape of a body may be denoted by the set of points in space occupied by the particles of material. Each particle may be denoted by its initial position vector $^{\circ}\underline{x}$ relative to some origin, i.e. its position vector at time t = 0. In 3-dimensions, $^{\circ}\underline{x}$ has the components [$^{\circ}x_1$, $^{\circ}x_2$ and $^{\circ}x_3$].

The clock may be started at any suitable time but, if the body is elastic, it is convenient to regard t = 0 as the un-deformed shape. This provides a natural reference state from which the deformation may be measured. At some later time, the particles occupy 'current' positions $\underline{x}$, which are functions of $^{o}\underline{x}$ and so the deformation can be represented as

$$\underline{x} = \underline{x}(^{o}\underline{x}) \tag{3.21}$$

('$\underline{x}$ is a function of $^{o}\underline{x}$')

Figure 3.2 shows the displacement vector $\underline{u}$ connecting the t = o and t = t (initial and current) position vectors $^{o}\underline{x}$ and $\underline{x}$.

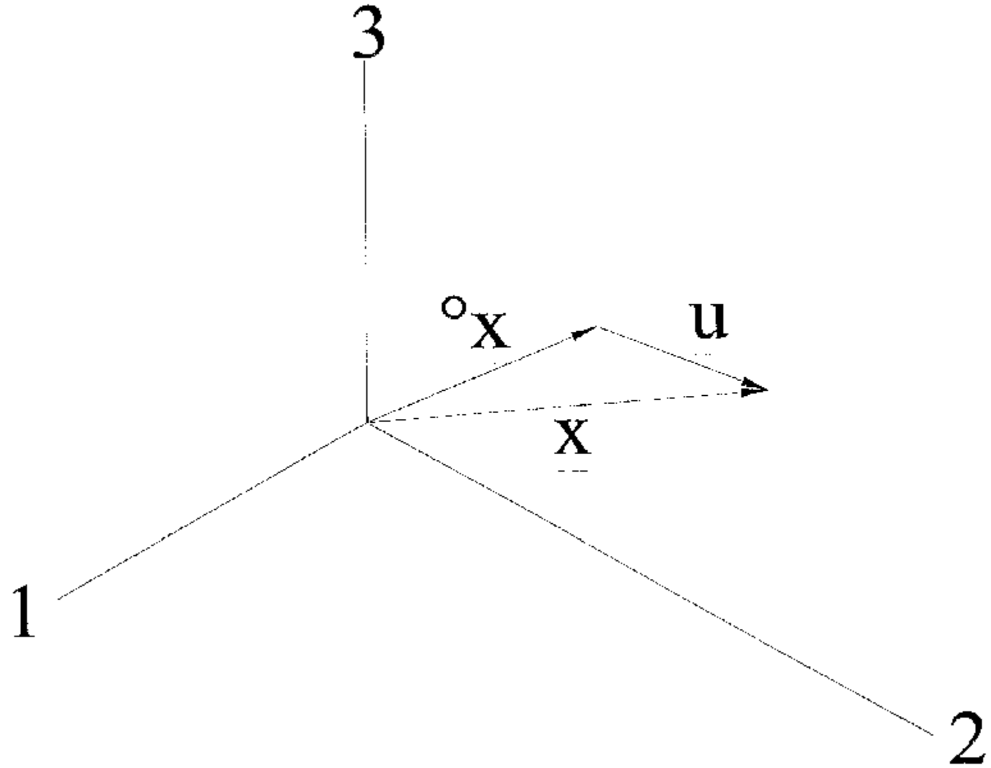


Fig. 3.2 The displacement vector $\underline{u}$ connecting the initial and current position vectors $^{o}\underline{x}$ and $\underline{x}$

This is called the material or Lagrangian description of the deformation. In most cases, it can be inverted to give

$$^{\circ}\underline{x} = {}^{\circ}\underline{x}(\underline{x}) \qquad (3.22)$$

('$^{\circ}\underline{x}$ is a function of $\underline{x}$').

This is the spatial or Eulerian description.

The stress in a body is related to the strain and hence to the stretch, i.e. the change in separation $\underline{dx}$ between two neighbouring particles (as opposed to the displacement of a single particle). This can be expressed by the ratio $\underline{\underline{\nabla x}} = \underline{dx}/{}^{\circ}\underline{dx}$, the ratio of the current separation to the initial separation. $\underline{\underline{\nabla x}}$ is a second-order tensor that defines the deformation gradient and leads to a definition for strain in 3-space. Since $\underline{dx}$ and $^{\circ}\underline{dx}$ are vectors, each with three components, then the deformation gradient has nine independent components.

The deformation gradient contains all of the information about the stretching and rotation of the body and is generally non-symmetrical, which makes it more difficult to manipulate. However it can be factorised

$$[\underline{dx}/{}^{\circ}\underline{dx}] \quad = \quad [R]\times[U] \quad \text{or} \quad [V]\times[R] \qquad (3.23)$$

in which [R] is an orthogonal matrix and so represents a rotation. [U] and [V] therefore represent the stretching component of the deformation and are called the right and left stretch tensors respectively. Either can be used as the basis for a strain measure. However, it is perhaps simpler to depart from small deformation uniaxial theory at the expression

$$\varepsilon = \lambda - 1 \tag{3.24}$$

where

$$\lambda = dx/{}^{\circ}dx \tag{3.25}$$

is the stretch ratio in an infinitesimal neighbourhood. For large deformations in 3-space, the differential is now a vector $\underline{dx}$ and an efficient method of extracting a scalar stretch ratio is to take the dot product or inner product, which is to square the vector and then take the square root to isolate its magnitude. This gives

$$\lambda^{(2)} = (\underline{dx} \bullet \underline{dx}) / ({}^{\circ}\underline{dx} \bullet {}^{\circ}\underline{dx}) \tag{3.26}$$

which can be shown to be

$$\lambda^{(2)} = [{}^{\circ}n]^{T} \times [\nabla x]^{T} \times [\nabla x] \times [{}^{\circ}n] \tag{3.27}$$

where $[{}^{\circ}n] = {}^{\circ}\underline{n}$ is a unit vector in the direction of ${}^{\circ}\underline{dx}$. When given a specific ${}^{\circ}\underline{n}$, this equation gives the corresponding stretch ratio. Alternatively, allowing ${}^{0}\underline{n}$ to vary through all possible values and searching for stationary values of λ (maxima or minima) gives the principal stretches, λ_1, λ_2 and λ_3. Physically, these are the stretch ratios along the principal axes of the ellipsoid into which an initially spherical volume of material deforms.

Even in the uniaxial case, there are two different measures of strain. They are both functions of the stretch ratio λ and, in general

$$\varepsilon = \varepsilon(\lambda) \tag{3.28}$$

This cannot be any arbitrary function however but there are options. For example Green's strain is

$$\varepsilon g = {}^{1}/_{2} \times (\lambda^{(2)} - 1) \tag{3.29}$$

This can be used for small deformations in 1-dimension but it is an unnecessary complication then. In contrast, the familiar strain $(\lambda-1)$ and $\ln\lambda$ do not generalise well to large deformations and so εg becomes essential. A physical picture of Green's strain can be gained by noting that

$$\varepsilon g = {}^{1}/_{2} \times (\lambda^{(2)} - 1) \tag{3.30}$$

$$= {}^{1}/_{2} \times (dx^{(2)} - {}^{o}dx^{(2)})/{}^{o}dx^{(2)} \tag{3.31}$$

Thus εg is a measure of the change in the squared length of the line element (normalised with respect to the square of the initial length). The same physical picture is retained in 3-dimensions but in that context the line elements are vectors. It can also be shown that

$$\varepsilon g_{ij} = {}^{1}/_{2} \times (\partial u_k/^{\circ}\partial x_i \times \partial u_k/^{\circ}\partial x_j + \partial u_j/^{\circ}\partial x_i + \partial u_i/^{\circ}\partial x_j) \qquad (3.32)$$

Green's strain is then called *Lagrangian* strain since the differentials are with respect to Lagrangian co-ordinates. If the displacement gradients are small, the second order term drops out and $\underline{\underline{\varepsilon g}}$ reduces to the small strain tensor $\underline{\underline{\varepsilon}}$. The second order form is also exact, and not an approximation to some higher-order function.

As noted, $\underline{\underline{\varepsilon g}}$ is only one of a number of strain measures that are suitable for large deformations, i.e. for finite strains rather than infinitesimal strains. All of the useful large strain measures share the "normalised squared length" feature when written in terms of the line element and they all show the second order term when written in terms of the displacement gradients. They all reduce to the small strain definitions when the deformation is small.

3.3 Material non-linearity and hyperelasticity

Hyperelastic materials, typically rubber-like polymers, belong to a class of material that is important in applications ranging from vehicle suspensions to artificial heart-valves and, as has been discussed, dairy cow cubicle mattresses and mats. This is mainly because they can be easily formed, for example by compression moulding, into monolithic components that exhibit sophisticated force-deformation behaviours. The force-deformation response of a synthetic polymer dairy cow cubicle bed is dominated by the cushioning property of the absorbent layer, such as the rubber crumbs in a Pasture Mat mattress and the EVA in a Maxibed 'cushion'. In contrast to structural metals, their stress-strain response is non-linear, even at small strains, but it is proposed, given this domination by the absorbent layer, that such a product can be modelled as a homogenous continuum, even though it has a heterogeneous microstructure.

Hyperelastic materials need not be nonlinear, although most are, but they are essentially path-independent and do not admit hysteresis losses. A path-dependent response, such as viscoelasticity, can be inserted but hysteresis losses are usually small compared to the other energies involved in an impact and hyperelasticity is a useful approximation to the constitutive response of many materials.

Other essential features of a hyperelastic material are that it is a material that maintains its elastic response even when the deformation to which it is subjected is large and so, being path independent, there is a natural reference state and a bijective function $\sigma(\varepsilon)$. Therefore, there is a strain energy function $U(\varepsilon)$ from which the stresses may be derived using

$$\sigma_{ij} = (\partial U)/\partial\varepsilon_{ij} \qquad (3.33)$$

σ and ε must be energy-conjugate generalised stresses and strains.

Linear elastic materials can be described using constitutive equations based on the strain energy function

$$U = {}^{1}\!/_{2} \times E \times \varepsilon^{2} \qquad (3.34)$$

$$\Rightarrow \qquad \sigma = (\partial U)/\partial \varepsilon \tag{3.35}$$

$$= E\varepsilon \tag{3.36}$$

A hypothetical non-linear elastic material might have an energy function of the form

$$U = {}^{1}/_{3}E\varepsilon^{3} \tag{3.37}$$

$$\Rightarrow \qquad \sigma = (\partial U)/\partial \varepsilon \tag{3.38}$$

$$= E\varepsilon^{2} \tag{3.39}$$

which is quadratic hyperelasticity, with tension stiffening, such as that observed in the force-deformation relationship for EVA foam mats and rubber-crumb mattresses in Chapter 5. A more general expression would be,

$$U = {}^{1}/_{\beta}E\varepsilon^{\beta} \tag{3.40}$$

where β allows a range of observed values for non-linear materials to be matched.

However, following Ogden (1984), it is currently preferable to express the strain energy as a function of the stretch ratio λ, thus

$$U = \mu_o/\alpha\times(\lambda^{\alpha}{}_{1}+\lambda^{\alpha}{}_{2}+\lambda^{\alpha}{}_{3}-3) \tag{3.41}$$

where μ_o is the initial shear modulus.

The -3 is required to ensure that $U = 0$ when the three stretch ratios λ_i have values =

1, i.e. in the un-deformed state. The shear modulus μ sets the overall resistance to deformation of the material, while the index α is a dimensionless elastic constant that controls the curvature of the material under load and so has been termed the 'hyperelastic stiffening index' in the current work. $\lambda = 1$ when a material is un-deformed and, in compression, $\lambda < 1$ and, predictably, material destruction is represented by $\lambda = 0$. Generalising further, U may involve more than one value for both α and μ. Such as in the Ogden strain energy function (Ogden, 1984):

$$U = \sum_{i=1}^{3} 2\mu_i / \alpha i \times [\lambda^{\alpha i}{}_1 + \lambda^{\alpha i}{}_2 + \lambda^{\alpha i}{}_3 - 3] \quad (3.42)$$

where

$$\mu_0 = \sum_{i=1}^{N} \mu_i \quad (3.43)$$

Rubber-like materials are also almost incompressible, having a very high bulk modulus or, equivalently, a Poisson's ratio $\nu \cong 0.5$ but hyperelastic theory has been extended to admit compressibility, giving what is known as a hyperfoam. Storakers (1986) thus developed the strain-energy functional U shown as Eqn (3.44).

$$U = \sum_{i=1}^{N} 2\mu_i/\alpha_i^2[\lambda_1^{\alpha i}+\lambda_2^{\alpha i}+\lambda_3^{\alpha i}-3+1/\beta_i(j_{el}^{-\alpha i\beta i}-1)] \qquad (3.44)$$

Where β_i is related to Poisson's ratio by $\nu_i/(1-2\nu_i)$ and is a dimensionless elastic constant that sets the curvature of the material under load along with α_i and, J is the product of $\lambda_1\lambda_2\lambda_3$, a measure of the relative volume.

The essential feature of the constitutive model of a hyperelastic material is a sufficiently continuous strain-energy functional that acts as a potential from which stresses may be derived by differentiation with respect to a kinematic quantity, such as the stretch ratio (Ogden, 1984).

Chapter 4.0 Laboratory quasi-static load testing of dairy cow cubicle bed materials

4.1 Force-deflection curves as a measure of cubicle bed cushioning

Nilsson (1988) described cubicle bed compliance or cushioning in terms of its uniaxial force-deflection relationship and set maximum and minimum limits of acceptability (*Fig. 4.1*). The maximum level of compliance, or minimum level of stiffness, was determined by the need for stability when the animal is standing and was equated to the force-deflection characteristic of a 15 cm thick layer of sawdust bedding. The minimum level of cushioning was set by the need to attenuate the large compressive force generated when a cow lies down or gets up. This concurred with Irps' (1983) view of the differing lying and standing needs of a cow in a cubicle. The Nilsson (1988) limiting curves were established using a knee-simulating indenter of 100 mm in diameter. Dumelow (1995) adapted this technique and conducted cushioning tests on beds using a 120 mm diameter indenter after measurements in a herd showed this to be the average knee-joint size.

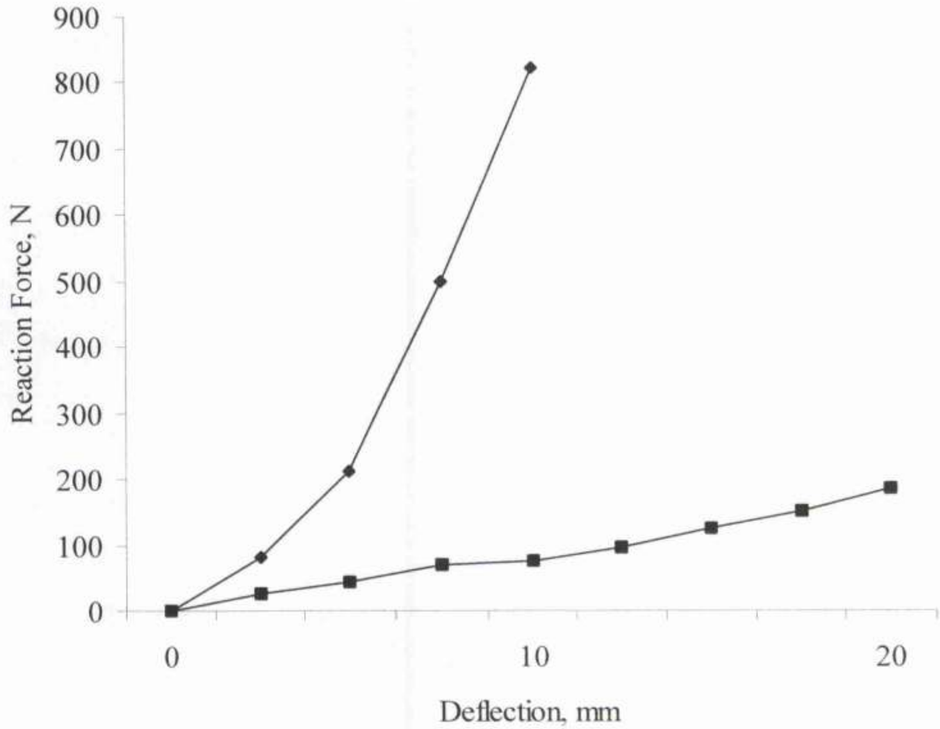


Fig. 4.1 Nilsson (1988) upper and lower curve limits for cubicle bed compliance for a 45 mm diameter indenter

4.2 Equipment and procedures for quasi-static load testing of dairy cow cubicle beds

Quasi-static compression tests were conducted using a Lloyd Instruments LR 30K machine (*Fig. 4.2*) fitted with a 30 kN load cell. A 45 mm diameter round-edged flat steel indenter applied the compression force at a constant rate of 8 mms^{-1} to the rubber-crumb mattress and EVA mat samples and force-deflection curves for each bed type were produced via proprietary software running on an on-line PC (*Fig. 4.3*). The indenter used was smaller than the 120 mm average dairy cow knee joint diameter recorded by Dumelow (1995) but Nilsson (1988) and Dumelow (1995) showed that the results from any size of indenter could be correlated to any other by the scaling relationship:

$$F_2 = F_1 \times [(3R_2 - d)/(3R_1-d)] \qquad \text{(Dumelow, 1995)}$$

Where: F1 = the impact force for a given deflection with indenter size 1;

F2 = the impact force for a given deflection with indenter size 2;

R1 = indenter 1 radius;

R2 = indenter 2 radius;

d = deflection.

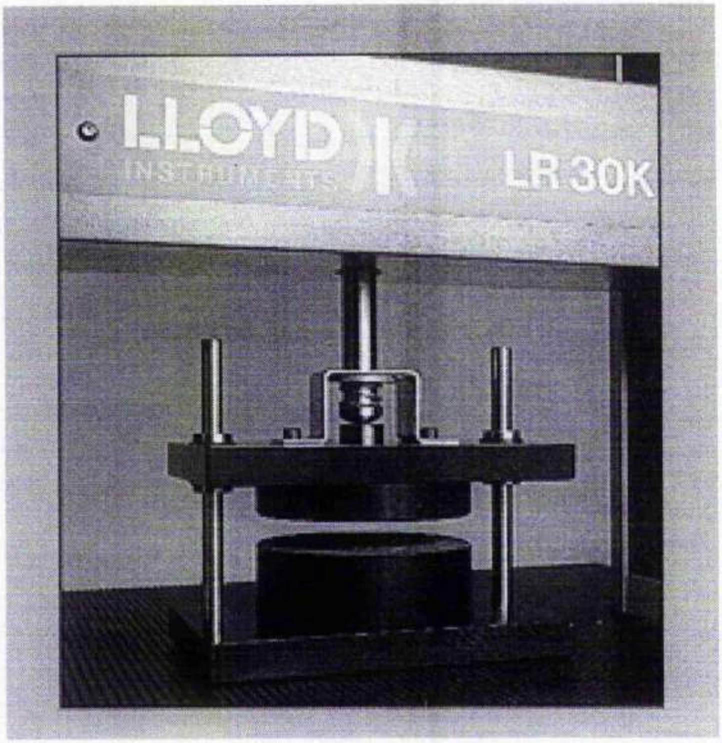


Fig. 4.2 Lloyd Instruments LR 30K

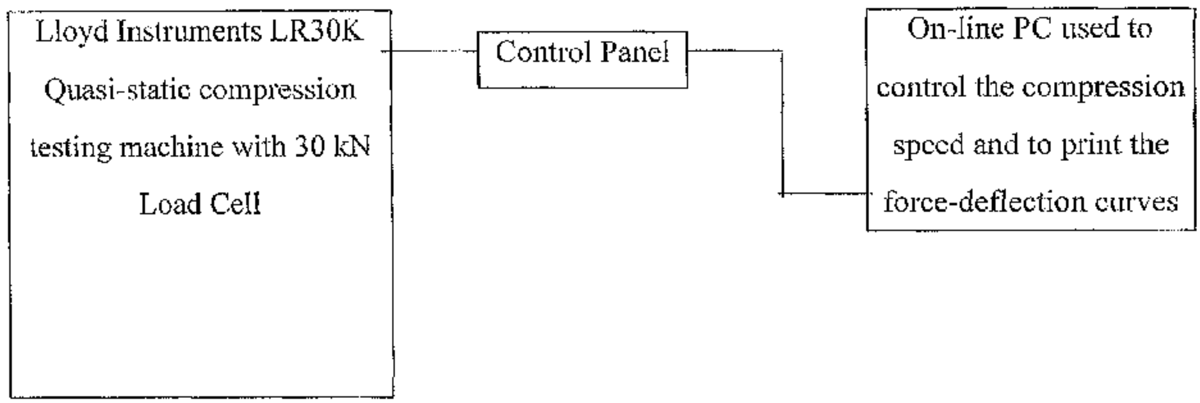


Fig. 4.3 Line diagram of quasi-static testing and control arrangement

4.3 Quasi-static compression test results and discussion

The compliance of the rubber-crumb mattress was shown to be greater than that of the EVA mat by consistently generating a lower reaction force throughout the deflection range (*Fig. 4.4*). This increased cushioning is suggested as reason why there were fewer overall injuries recorded in the two-farm study for the cows on the rubber-crumb beds but it does not explain the similar incidence of major injuries found in the two types of bed (Chapter 2.0). However, both of the products tested meet Nilsson (1988) compliance criteria and sell at the 'better quality' end of the market so they might be expected to be capable of preventing major injuries. The difference in cushioning between the bed types shows up in the longer-term variation in minor injury scores in Chapter 2.0.

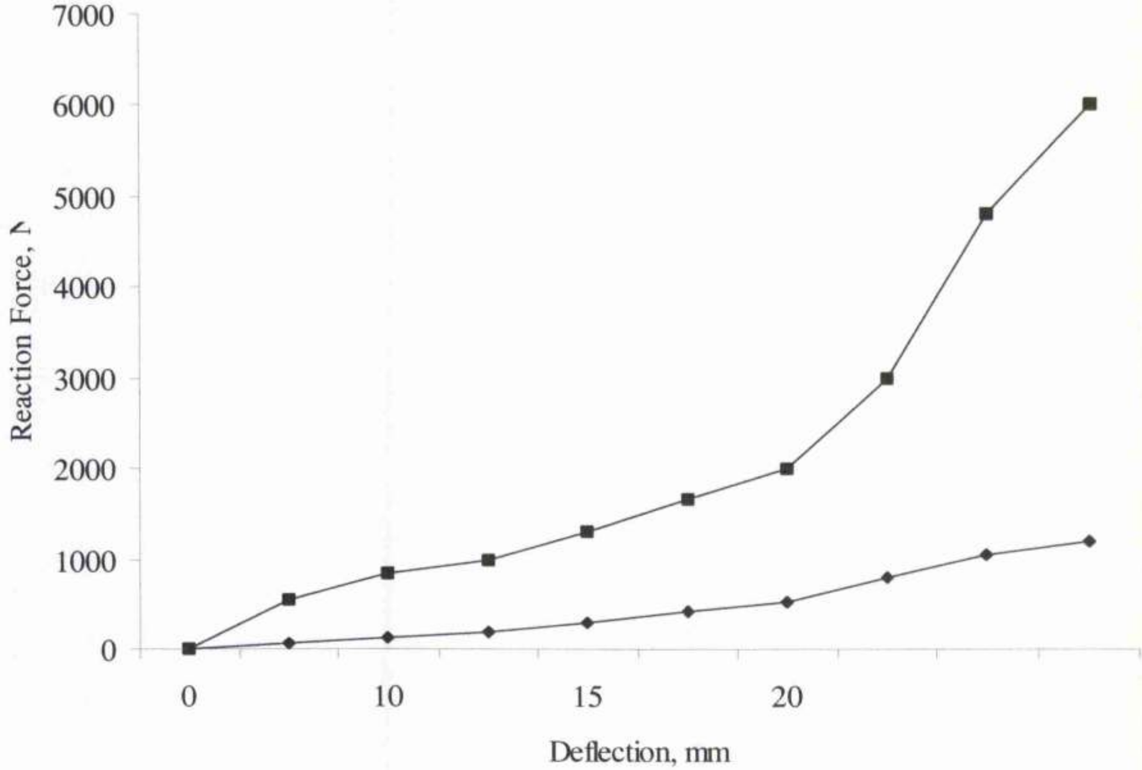


Fig. 4.4 Laboratory uniaxial quasi-static compression test force-deflection curves for samples of the rubber-crumb ◆ and the ethylene vinyl acetate (EVA) ■ cubicle bed types

Dumelow (1995) showed that a number of synthetic beds are not within the comfort range set out by Nilsson (1988). They were essentially too stiff. For the current work, comfort limits have been adapted for a 45 mm indenter and the rubber-crumb mattress and EVA mat force-deflection curves produced were compared to the Nilsson upper and lower limit (Nilsson, 1988) in *Fig. 4.5*.

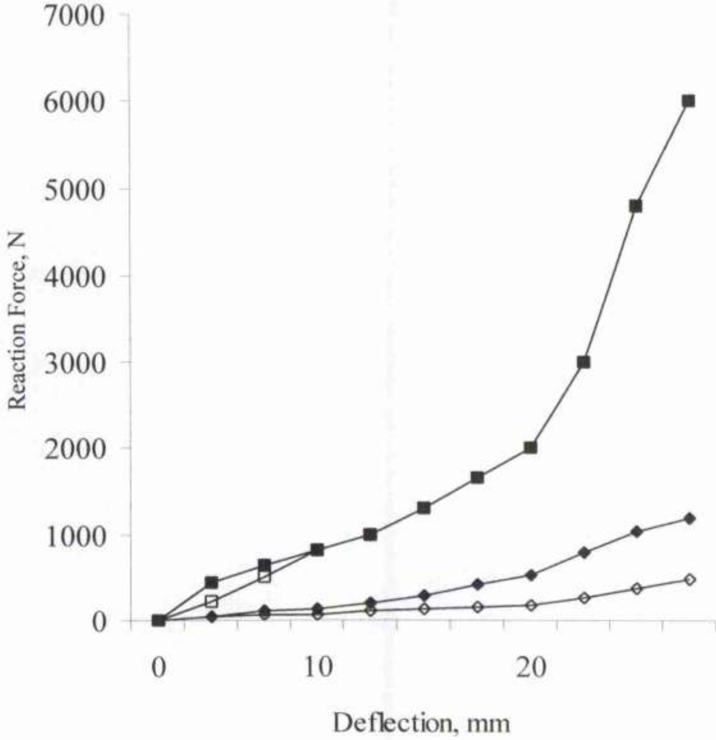


Fig. 4.5 Rubber-crumb mattress ◆ and EVA mat ■ force-deflection curves compared to Nilsson (1988) maximum ◇ and minimum □ compliance limits adapted for a 45 mm diameter indenter

The curve for minimum compliance from Nilsson (1988) has deflection values up to, but not greater than, 10 mm. The EVA mat curve (*Fig. 4.5*) shows it to be close to the minimum compliance limit (Nilsson 1988). That is, any stiffer would be too stiff for the lying down comfort of a cow. The rubber-crumb mattress curve shows that, according to the Nilsson (1988) parameters, it is close to the compliance maximum. That is, any more compliant and it would be too much so for the stability of a standing cow.

To illustrate the importance of having a compliant surface on a cubicle bed, a reinforced concrete approximate force-deflection relationship is shown in *Fig. 4.6*. Concrete is well outside the comfort range.

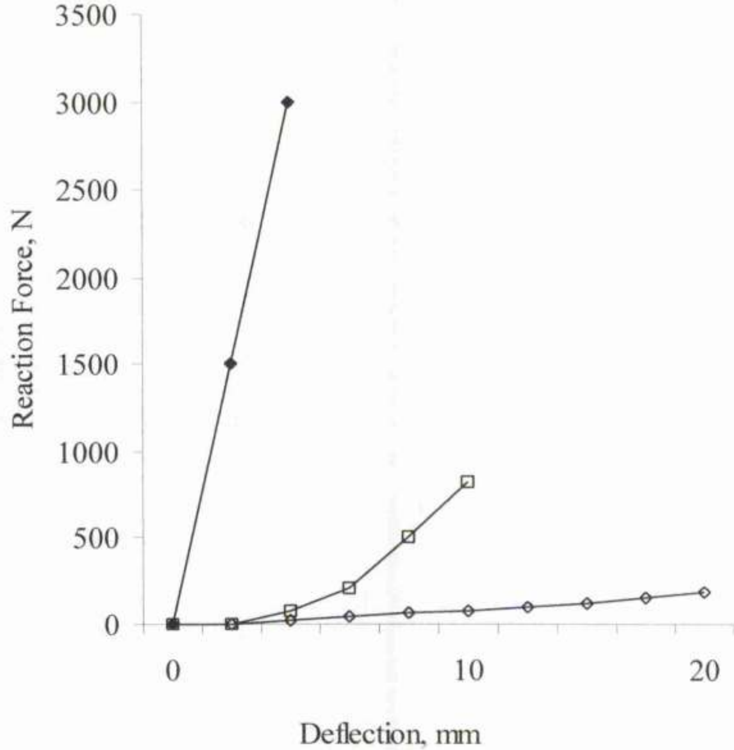


Fig. 4.6 Concrete bed ♦ approximate compliance compared to Nilsson (1988) maximum ◇ and minimum □ compliance limits adapted for a 45 mm diameter indenter

A quasi-static compression 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 should be correlated to Nilsson (1988) by the mathematical method shown in Sub-chapter 4.2.

A limitation to the quasi-static compression test method, as a measure of whether or not a cubicle bed is comfortable enough for lying and standing, is that the equipment is not useable for tests *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 dynamic impact test, that has been used to evaluate new and aged mats and mattresses *in situ*, is described in Chapter 6.

Chapter 5.0 Computational modelling of cubicle beds as hyperfoams

5.1 Introduction

Chapter 5 combines the hyperelastic theory of Chapter 3 and the uniaxial quasi-static compression tests of Chapter 4 to create computational models of cubicle beds using nonlinear finite element analysis (NL FEA).

5.2 Finite element analysis

Impact and abrasion damage results from the application of mechanical forces and has often been studied using computer-aided engineering tools. FEA is a tool that was initially developed for the stress analysis of standard engineering materials and structures but following recent developments it is now possible to analyse more complex materials such as biological tissue and polymer foams. It thus offers the potential for an improved method of predicting the cushioning performance of cubicle bed materials at reduced cost and with minimum disruption to animals when compared with farm-based studies.

In Chapter 5 FEA will be used to model rubber crumb mattresses and ethylene vinyl acetate (EVA) foam mats. These materials show long-term, time-dependent behaviours but, over the short duration of a knee impact, they are elastic and return to their initial state when the load is removed. However, their response is not linear and they cannot be assigned a single elastic modulus that is valid at all loads.[1] They are then more correctly classed as hyperelastic.

5.3 Hyperelastic theory applied to cubicle bed computational modelling

The α_i, μ_i and β_i in the Storakers (1986) strain energy function, (Chapter 3, Eqn 3. 44) are material elastic constants that can be chosen to agree with experimental data from quasi-static compression testing. The λ_i are the principal deviatoric stretches. The individual values for μ_i in N>1 hyperelasticity vary considerably but their summation equates to the initial shear modulus μ_o, which in practical terms set the initial slope of the stress-strain curves. As noted earlier, the α_i control the curvature of the deformation by acting as a 'power-stiffening index', which determined the rate of compression-stiffening. The β_i are related to Poisson's ratio and also to the initial bulk modulus k_o which is $\Sigma^N_{i=1} \times 2\mu_I[(^1/_3)+\beta_I]$. j_{el} is the total volumetric strain.

Mills and Gilchrist (2000) discuss values required for these hyperelastic constants for polyurethane foams to match curves using data from uniaxial compression tests and from the Ogden strain energy function as described in the Abaqus problem manual (HKS, 1998). The Mills and Gilchrist (2000) curves were determined from the strain energy function by partial differentiation with respect to the appropriate strain measure. For uniaxial deflection the principal stresses were given as

$$\sigma_L = \frac{\partial U}{\partial \lambda_L} = \frac{2}{\lambda_L}\sum_{i=1}^{n}\frac{\mu_i}{\alpha_i}\left(\lambda_L^{\alpha_i} - J^{-\alpha_i\beta_i}\right) \quad (5.1)$$

Under uniaxial compression Poisson's ratio ν approximates to 0 and as a consequence of this $\beta = 0$. This reduces the calculation for uniaxial stress from Eqn

5.1 to

$$\sigma_1 = \frac{2}{\lambda_1}\sum_{i=1}^{n}\frac{\mu_i}{\alpha_i}\left(\lambda_L^{\alpha_i} - 1\right) \tag{5.2}$$

Mills and Gilchrist (2000) made three-way comparisons for a polyurethane foam for uniaxial compression testing, predictions of N = 1 variants of the Ogden strain energy function using

α = -2, 2 and 8 for a μ = 10 kPa and α = 20 for a μ = 20 kPa

Comparisons were also made, for PU38 foam (foam density 38 kg m^{-3}), of uniaxial compression stress strain data and Ogden strain energy function predictions for N = 1, applying μ = 10 kPa and α = 8, and for N = 2, α_1 = 20, μ_1 = 20 kPa, α_2 = -2, μ_2 = 0.20 kPa.

Both hyperelasticity and hyperfoam behaviour have recently been encoded into several non-linear finite element analysis codes, including Abaqus/Explicit (HKS, 1998), which has been used in the current work. The value of N can be chosen by the analyst, who must compromise between the improved fit to experimental data that is achieved by a higher-order polynomial and the reduced stability of the numerical routines. Typically, $1 \leq N \leq 3$. In comparisons of quasi-static uniaxial compression tests of cubicle bed materials, described in detail in Chapter 5, N=1 worked well in the EVA foam cow mat model, but N=3 hyperelasticity was required in the modelling for the rubber-crumb mattress. As stated in Chapter 1.0, using hyperelastic theory to model rubber-crumb mattresses and EVA foam mats is a new approach and finalising material property data that allows successful modelling for all cubicle bed types is a topic for continuing research.

5.4 EVA foam and rubber-crumb cubicle bed computational models

Given the experimental force-deflection curves for each of the two materials tested (Chapter 4), it was necessary to extract the material constants needed to define the hyperelastic strain-energy functional. Software utilities are available to do this but there is no guarantee that the resulting functional will be numerically stable at the range of deformations to be expected. To ensure this it was necessary to run full finite element analyses with the material model derived.

A finite element mesh was generated for each of the bed types using the I-DEAS computer-aided engineering package (SDRC Inc., Ohio, USA), which has limited finite element analysis facilities (*Fig 5.3* and Fig. *5.4*). This simple mesh of axisymmetric elements is not intended to represent exactly an actual animal joint in contact with a cubicle bed surface but rather to model the materials laboratory tests and so determine the hyperelastic material properties that are required for bed compression simulations. The mesh was analysed by the more sophisticated Abaqus Explicit (HKS, 1998) nonlinear finite element analysis code that is specifically profiled for contact and impact problems. The results, such as the progressively deforming shape of the hyperfoam beds under a compressive load, shown as Fig. *5.5* and Fig. *5.6*, were presented on a graphical post-processor.

Preliminary analyses to simulate the EVA foam were carried out with best estimates of the material constants based on values found by Thomson *et al.*, (1999). Force-deflection simulations under quasi-static loading were run and the results compared with the physical tests. The material constants in Chapter 3 (Eqn 3.44) were then adjusted, incrementally, in a series of computational experiments, until the computed response matched the measured, compression-stiffening response of the real material (Fig. *5.8*). The computational experiments showed that EVA could be modelled with first-order (N = 1) Ogden hyperelasticity.

In contrast, the rubber-crumb material was not well represented by first-order hyperelasticity and higher-order polynomials were tried. An N=3 hyperfoam model was established. This required the adjustment of more free constants in the functional, which was not a practical undertaking. The procedure for determining the properties of the rubber-crumb mattress was to make use of a facility in the finite element code by which ordered pairs of uniaxial stress-strain datapoints were specified. The code itself then extracted the best-fit material constants. These best-fit values were inserted as a starting point and the pairs were adjusted incrementally until the desired material response was obtained (Fig. *5.10*).

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).

5.4.1 Input files

The input file is used to create the mesh of elements that represent, in model form, the material to be analysed. Fig. *5.1* shows the input file for the EVA mat. 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. Quadrilateral elements were created in the model by co-ordinated corner nodes (Fig. *5.3* and Fig. *5.4)*. By creating a series of continuous elements and evaluating the extent of their individual displacement under load, the total displacement of a mat or mattress was determined.

Fig. *5.1* Ideas pre-processor input file for the EVA mat model

```
*HEADING
EVA mat
*NODE, NSET=SOLEN
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 2, 0.0000000E-03,-4.0000000E-03, 0.0000000E-03
 3, 0.0000000E-03,-8.0000000E-03, 0.0000000E-03
 4, 0.0000000E-03,-1.2000000E-02, 0.0000000E-03
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 6, 0.0000000E-03,-2.0000000E-02, 0.0000000E-03
 7, 0.0000000E-03,-2.4000000E-02, 0.0000000E-03
 8, 0.0000000E-03,-2.8000000E-02, 0.0000000E-03
 9, 0.0000000E-03,-3.2000000E-02, 0.0000000E-03
 10, 0.0000000E-03,-3.6000000E-02, 0.0000000E-03
 11, 0.0000000E-03,-4.0000000E-02, 0.0000000E-03
 12, 3.0000000E-03, 0.0000000E-03, 0.0000000E-03
 13, 3.0000000E-03,-4.0000000E-03, 0.0000000E-03
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 99, 2.4000000E-02,-4.0000000E-02, 0.0000000E-03
 100, 2.7000000E-02, 0.0000000E-03, 0.0000000E-03
 101, 2.7000000E-02,-4.0000000E-03, 0.0000000E-03
 102, 2.7000000E-02,-8.0000000E-03, 0.0000000E-03
 103, 2.7000000E-02,-1.2000000E-02, 0.0000000E-03
 104, 2.7000000E-02,-1.6000000E-02, 0.0000000E-03
 105, 2.7000000E-02,-2.0000000E-02, 0.0000000E-03
 106, 2.7000000E-02,-2.4000000E-02, 0.0000000E-03
 107, 2.7000000E-02,-2.8000000E-02, 0.0000000E-03
 108, 2.7000000E-02,-3.2000000E-02, 0.0000000E-03
 109, 2.7000000E-02,-3.6000000E-02, 0.0000000E-03
 110, 2.7000000E-02,-4.0000000E-02, 0.0000000E-03
 111, 3.0000000E-02, 0.0000000E-03, 0.0000000E-03
 112, 3.0000000E-02,-4.0000000E-03, 0.0000000E-03
 113, 3.0000000E-02,-8.0000000E-03, 0.0000000E-03
 114, 3.0000000E-02,-1.2000000E-02, 0.0000000E-03
 115, 3.0000000E-02,-1.6000000E-02, 0.0000000E-03
 116, 3.0000000E-02,-2.0000000E-02, 0.0000000E-03
 117, 3.0000000E-02,-2.4000000E-02, 0.0000000E-03
 118, 3.0000000E-02,-2.8000000E-02, 0.0000000E-03
 119, 3.0000000E-02,-3.2000000E-02, 0.0000000E-03
 120, 3.0000000E-02,-3.6000000E-02, 0.0000000E-03
 121, 3.0000000E-02,-4.0000000E-02, 0.0000000E-03
*NODE
1000, 0., 0.081
*RIGID BODY, REF NODE=1000
*ELEMENT,TYPE=CAX4R,ELSET=SOLEX
 1, 1, 2, 13, 12
 2, 2, 3, 14, 13
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 21, 23, 24, 35, 34
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 23, 25, 26, 37, 36
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 29, 31, 32, 43, 42
** 30, 32, 33, 44, 43
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 33, 36, 37, 48, 47
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 85, 93, 94, 105, 104
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 89, 97, 98, 109, 108
** 90, 98, 99, 110, 109
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 95, 104, 105, 116, 115
 96, 105, 106, 117, 116
 97, 106, 107, 118, 117
 98, 107, 108, 119, 118
 99, 108, 109, 120, 119
** 100, 109, 110, 121, 120
*SOLID SECTION, ELSET=SOLEX, MATERIAL=EVA
**************************************************************
*MATERIAL, NAME=EVA
**
** Only current test material active - others commented out
**
*HYPERFOAM, N=1
 0.48E6, 0.4, 0.2
*DENSITY
 1000.
**
*******************************************************
**
*NSET, NSET=YAXIS, GEN
 1, 10
*NSET, NSET=YAXIS
 1000
*NSET, NSET=SBASE, GEN
 10, 120, 11
*NSET, NSET=SEDGE, GEN
 111, 119
*BOUNDARY
 YAXIS, XSYMM
 SBASE, ENCASTRE
 SEDGE, 1
*AMPLITUDE, NAME=RAMP
 0.0, 0.0, 1.0, 1.0
**************************************************
*STEP
*DYNAMIC, EXPLICIT
 , 1.0
*RIGID SURFACE, NAME=HEEL, REF NODE=1000, TYPE=SEGMENTS, FILLET R=0.005
START, 0.025, 0.025
 LINE, 0.025, 0.0001
 LINE, 0.000, 0.0001
*BOUNDARY, AMP=RAMP
 1000, 2, 2, -0.026
*ELSET, ELSET=SOLTE, GEN
 1, 91, 10
*ADAPTIVE MESH, ELSET=SOLEX
*SURFACE DEFINITION, NAME=SOLES
 SOLTE, S4
*CONTACT PAIR
 HEEL, SOLES
*RESTART, WRITE, NUMBER INTERVAL=25
*END STEP
**********************************************
```

Fig. *5.2* Ideas pre-processor input file for the rubber-crumb mattress model

```
*HEADING
Rubber-crumb Mattress
*NODE, NSET=SOLEN
 1, 0.0000000E-03,-6.5000000E-02, 0.0000000E-03
 2, 5.9090909E-03,-6.5000000E-02, 0.0000000E-03
 3, 1.1818182E-02,-6.5000000E-02, 0.0000000E-03
 4, 1.7727273E-02,-6.5000000E-02, 0.0000000E-03
 5, 2.3636364E-02,-6.5000000E-02, 0.0000000E-03
 6, 2.9545455E-02,-6.5000000E-02, 0.0000000E-03
 7, 3.5454545E-02,-6.5000000E-02, 0.0000000E-03
 8, 4.1363636E-02,-6.5000000E-02, 0.0000000E-03
 9, 4.7272727E-02,-6.5000000E-02, 0.0000000E-03
 10, 5.3181818E-02,-6.5000000E-02, 0.0000000E-03
 11, 5.9090909E-02,-6.5000000E-02, 0.0000000E-03
 12, 6.5000000E-02,-6.5000000E-02, 0.0000000E-03
 13, 0.0000000E-03,-5.9090909E-02, 0.0000000E-03
 14, 5.9090909E-03,-5.9090909E-02, 0.0000000E-03
 15, 1.1818182E-02,-5.9090909E-02, 0.0000000E-03
 16, 1.7727273E-02,-5.9090909E-02, 0.0000000E-03
 17, 2.3636364E-02,-5.9090909E-02, 0.0000000E-03
 18, 2.9545455E-02,-5.9090909E-02, 0.0000000E-03
 19, 3.5454545E-02,-5.9090909E-02, 0.0000000E-03
 20, 4.1363636E-02,-5.9090909E-02, 0.0000000E-03
 21, 4.7272727E-02,-5.9090909E-02, 0.0000000E-03
 22, 5.3181818E-02,-5.9090909E-02, 0.0000000E-03
 23, 5.9090909E-02,-5.9090909E-02, 0.0000000E-03
 24, 6.5000000E-02,-5.9090909E-02, 0.0000000E-03
 25, 0.0000000E-03,-5.3181818E-02, 0.0000000E-03
 26, 5.9090909E-03,-5.3181818E-02, 0.0000000E-03
 27, 1.1818182E-02,-5.3181818E-02, 0.0000000E-03
 28, 1.7727273E-02,-5.3181818E-02, 0.0000000E-03
 29, 2.3636364E-02,-5.3181818E-02, 0.0000000E-03
 30, 2.9545455E-02,-5.3181818E-02, 0.0000000E-03
 31, 3.5454545E-02,-5.3181818E-02, 0.0000000E-03
 32, 4.1363636E-02,-5.3181818E-02, 0.0000000E-03
 33, 4.7272727E-02,-5.3181818E-02, 0.0000000E-03
 34, 5.3181818E-02,-5.3181818E-02, 0.0000000E-03
 35, 5.9090909E-02,-5.3181818E-02, 0.0000000E-03
 36, 6.5000000E-02,-5.3181818E-02, 0.0000000E-03
 37, 0.0000000E-03,-4.7272727E-02, 0.0000000E-03
 38, 5.9090909E-03,-4.7272727E-02, 0.0000000E-03
 39, 1.1818182E-02,-4.7272727E-02, 0.0000000E-03
 40, 1.7727273E-02,-4.7272727E-02, 0.0000000E-03
 41, 2.3636364E-02,-4.7272727E-02, 0.0000000E-03
 42, 2.9545455E-02,-4.7272727E-02, 0.0000000E-03
 43, 3.5454545E-02,-4.7272727E-02, 0.0000000E-03
 44, 4.1363636E-02,-4.7272727E-02, 0.0000000E-03
 45, 4.7272727E-02,-4.7272727E-02, 0.0000000E-03
 46, 5.3181818E-02,-4.7272727E-02, 0.0000000E-03
 47, 5.9090909E-02,-4.7272727E-02, 0.0000000E-03
 48, 6.5000000E-02,-4.7272727E-02, 0.0000000E-03
 49, 0.0000000E-03,-4.1363636E-02, 0.0000000E-03
 50, 5.9090909E-03,-4.1363636E-02, 0.0000000E-03
 51, 1.1818182E-02,-4.1363636E-02, 0.0000000E-03
 52, 1.7727273E-02,-4.1363636E-02, 0.0000000E-03
 53, 2.3636364E-02,-4.1363636E-02, 0.0000000E-03
 54, 2.9545455E-02,-4.1363636E-02, 0.0000000E-03
 55, 3.5454545E-02,-4.1363636E-02, 0.0000000E-03
 56, 4.1363636E-02,-4.1363636E-02, 0.0000000E-03
 57, 4.7272727E-02,-4.1363636E-02, 0.0000000E-03
 58, 5.3181818E-02,-4.1363636E-02, 0.0000000E-03
 59, 5.9090909E-02,-4.1363636E-02, 0.0000000E-03
 60, 6.5000000E-02,-4.1363636E-02, 0.0000000E-03
 61, 0.0000000E-03,-3.5454545E-02, 0.0000000E-03
 62, 5.9090909E-03,-3.5454545E-02, 0.0000000E-03
 63, 1.1818182E-02,-3.5454545E-02, 0.0000000E-03
 64, 1.7727273E-02,-3.5454545E-02, 0.0000000E-03
 65, 2.3636364E-02,-3.5454545E-02, 0.0000000E-03
 66, 2.9545455E-02,-3.5454545E-02, 0.0000000E-03
 67, 3.5454545E-02,-3.5454545E-02, 0.0000000E-03
 68, 4.1363636E-02,-3.5454545E-02, 0.0000000E-03
 69, 4.7272727E-02,-3.5454545E-02, 0.0000000E-03
 70, 5.3181818E-02,-3.5454545E-02, 0.0000000E-03
 71, 5.9090909E-02,-3.5454545E-02, 0.0000000E-03
 72, 6.5000000E-02,-3.5454545E-02, 0.0000000E-03
 73, 0.0000000E-03,-2.9545455E-02, 0.0000000E-03
 74, 5.9090909E-03,-2.9545455E-02, 0.0000000E-03
 75, 1.1818182E-02,-2.9545455E-02, 0.0000000E-03
 76, 1.7727273E-02,-2.9545455E-02, 0.0000000E-03
 77, 2.3636364E-02,-2.9545455E-02, 0.0000000E-03
 78, 2.9545455E-02,-2.9545455E-02, 0.0000000E-03
 79, 3.5454545E-02,-2.9545455E-02, 0.0000000E-03
 80, 4.1363636E-02,-2.9545455E-02, 0.0000000E-03
 81, 4.7272727E-02,-2.9545455E-02, 0.0000000E-03
 82, 5.3181818E-02,-2.9545455E-02, 0.0000000E-03
 83, 5.9090909E-02,-2.9545455E-02, 0.0000000E-03
 84, 6.5000000E-02,-2.9545455E-02, 0.0000000E-03
 85, 0.0000000E-03,-2.3636364E-02, 0.0000000E-03
 86, 5.9090909E-03,-2.3636364E-02, 0.0000000E-03
 87, 1.1818182E-02,-2.3636364E-02, 0.0000000E-03
 88, 1.7727273E-02,-2.3636364E-02, 0.0000000E-03
 89, 2.3636364E-02,-2.3636364E-02, 0.0000000E-03
 90, 2.9545455E-02,-2.3636364E-02, 0.0000000E-03
 91, 3.5454545E-02,-2.3636364E-02, 0.0000000E-03
 92, 4.1363636E-02,-2.3636364E-02, 0.0000000E-03
 93, 4.7272727E-02,-2.3636364E-02, 0.0000000E-03
 94, 5.3181818E-02,-2.3636364E-02, 0.0000000E-03
 95, 5.9090909E-02,-2.3636364E-02, 0.0000000E-03
 96, 6.5000000E-02,-2.3636364E-02, 0.0000000E-03
 97, 0.0000000E-03,-1.7727273E-02, 0.0000000E-03
 98, 5.9090909E-03,-1.7727273E-02, 0.0000000E-03
 99, 1.1818182E-02,-1.7727273E-02, 0.0000000E-03
 100, 1.7727273E-02,-1.7727273E-02, 0.0000000E-03
 101, 2.3636364E-02,-1.7727273E-02, 0.0000000E-03
 102, 2.9545455E-02,-1.7727273E-02, 0.0000000E-03
 103, 3.5454545E-02,-1.7727273E-02, 0.0000000E-03
 104, 4.1363636E-02,-1.7727273E-02, 0.0000000E-03
 105, 4.7272727E-02,-1.7727273E-02, 0.0000000E-03
 106, 5.3181818E-02,-1.7727273E-02, 0.0000000E-03
 107, 5.9090909E-02,-1.7727273E-02, 0.0000000E-03
 108, 6.5000000E-02,-1.7727273E-02, 0.0000000E-03
 109, 0.0000000E-03,-1.1818182E-02, 0.0000000E-03
 110, 5.9090909E-03,-1.1818182E-02, 0.0000000E-03
 111, 1.1818182E-02,-1.1818182E-02, 0.0000000E-03
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 113, 2.3636364E-02,-1.1818182E-02, 0.0000000E-03
 114, 2.9545455E-02,-1.1818182E-02, 0.0000000E-03
 115, 3.5454545E-02,-1.1818182E-02, 0.0000000E-03
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 119, 5.9090909E-02,-1.1818182E-02, 0.0000000E-03
 120, 6.5000000E-02,-1.1818182E-02, 0.0000000E-03
 121, 0.0000000E-03,-5.9090909E-03, 0.0000000E-03
 122, 5.9090909E-03,-5.9090909E-03, 0.0000000E-03
 123, 1.1818182E-02,-5.9090909E-03, 0.0000000E-03
 124, 1.7727273E-02,-5.9090909E-03, 0.0000000E-03
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 126, 2.9545455E-02,-5.9090909E-03, 0.0000000E-03
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 129, 4.7272727E-02,-5.9090909E-03, 0.0000000E-03
 130, 5.3181818E-02,-5.9090909E-03, 0.0000000E-03
 131, 5.9090909E-02,-5.9090909E-03, 0.0000000E-03
 132, 6.5000000E-02,-5.9090909E-03, 0.0000000E-03
 133, 0.0000000E-03, 0.0000000E-03, 0.0000000E-03
 134, 5.9090909E-03, 0.0000000E-03, 0.0000000E-03
 135, 1.1818182E-02, 0.0000000E-03, 0.0000000E-03
 136, 1.7727273E-02, 0.0000000E-03, 0.0000000E-03
 137, 2.3636364E-02, 0.0000000E-03, 0.0000000E-03
 138, 2.9545455E-02, 0.0000000E-03, 0.0000000E-03
 139, 3.5454545E-02, 0.0000000E-03, 0.0000000E-03
 140, 4.1363636E-02, 0.0000000E-03, 0.0000000E-03
 141, 4.7272727E-02, 0.0000000E-03, 0.0000000E-03
 142, 5.3181818E-02, 0.0000000E-03, 0.0000000E-03
 143, 5.9090909E-02, 0.0000000E-03, 0.0000000E-03
 144, 6.5000000E-02, 0.0000000E-03, 0.0000000E-03
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*RIGID BODY, REF NODE=1000
*ELEMENT,TYPE=CAX4R,ELSET=SOLEX
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 119, 129, 130, 142, 141
 120, 130, 131, 143, 142
 121, 131, 132, 144, 143
*SOLID SECTION, ELSET=SOLEX, MATERIAL=RUB
*******************************************************
*MATERIAL, NAME=RUB
**
** Only current test material active - others commented out
**
*HYPERFOAM, N=3
**HYPERFOAM, N=3, TEST DATA INPUT, POISSON=0.2
-512617,3.55501,298262,7.39213,272532,-1.7729,0.20,0.20
0.2
*UNIAXIAL TEST DATA
** nominal stress, nominal strain
**- 0E6, -0
**-0.01E6, -0.05
**-0.02E6, -0.10
**-0.04E6, -0.15
**-0.08E6, -0.20
**-0.13E6, -0.25
**-0.21E6, -0.30
**-0.33E6, -0.35
**-0.50E6, -0.40
**-0.80E6, -0.45
**-1.24E6, -0.50
**-1.40E6, -0.515
**-1.50E6, -0.52
**-1.60E6, -0.53
**-1.70E6, -0.55
**-2.50E6, -0.60
*DENSITY
 300.
**
*******************************************************
**
*NSET, NSET=YAXIS, GEN
 1, 133, 12
*NSET, NSET=YAXIS
 1000
*NSET, NSET=SBASE, GEN
 1, 12
*NSET, NSET=SEDGE, GEN
 12, 144, 12
*BOUNDARY
 YAXIS, XSYMM
 SBASE, ENCASTRE
 SEDGE, 1
*AMPLITUDE, NAME=RAMP
 0.0, 0.0, 1.0, 1.0
*******************************************
*STEP
*DYNAMIC, EXPLICIT, ELEMENT BY ELEMENT
 , 1.0,,1.E-5
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 LINE, 0.000, 0.0001
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*ELSET, ELSET=SOLTE, GEN
 111, 121
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*CONTACT PAIR
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*RESTART, WRITE, NUMBER INTERVAL=25
*END STEP
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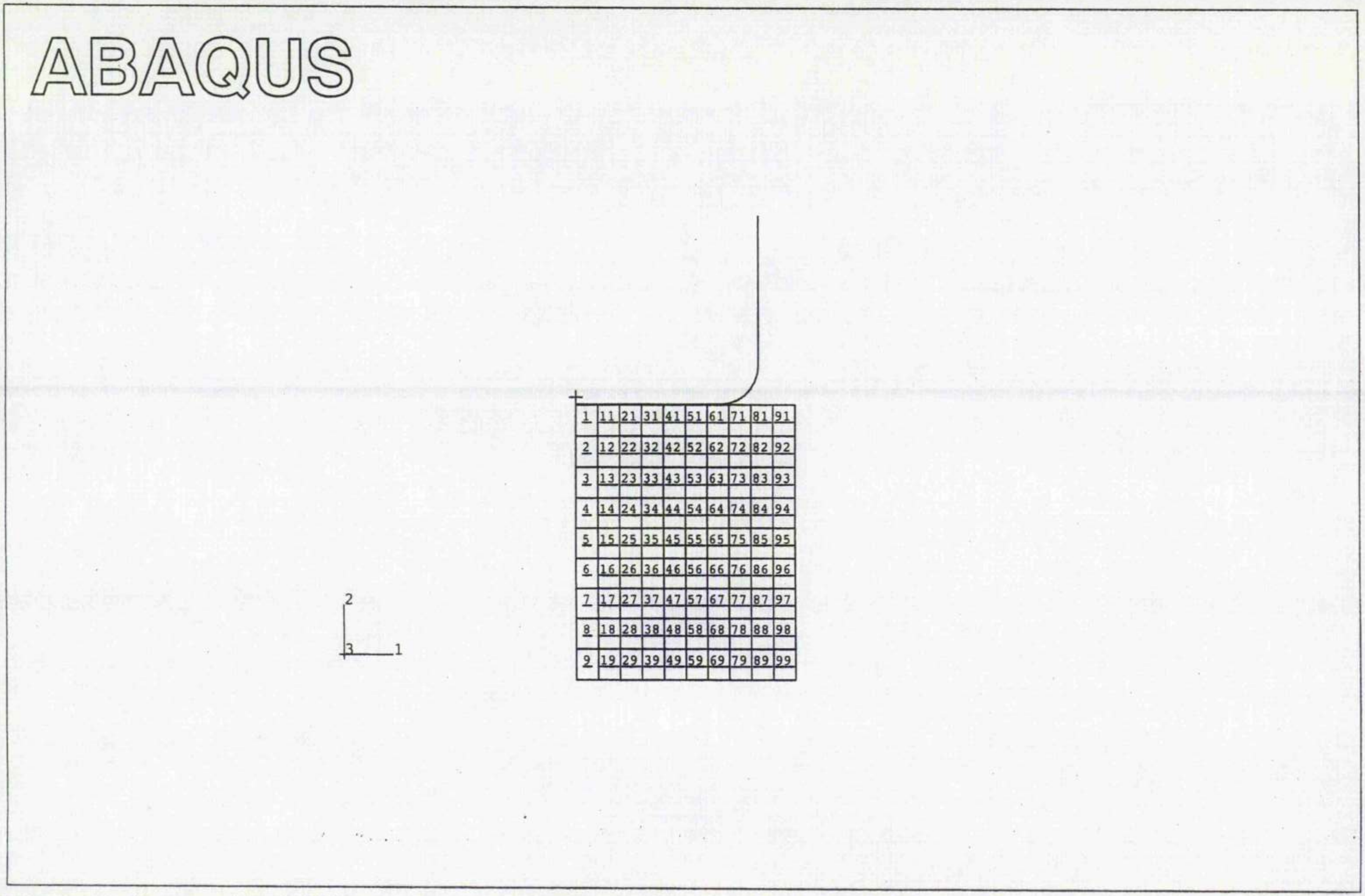
Fig. *5.3* Finite element mesh for the EVA mat model


ABAQUS
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6 16 26 36 46 56 66 76 86 96
7 17 27 37 47 57 67 77 87 97
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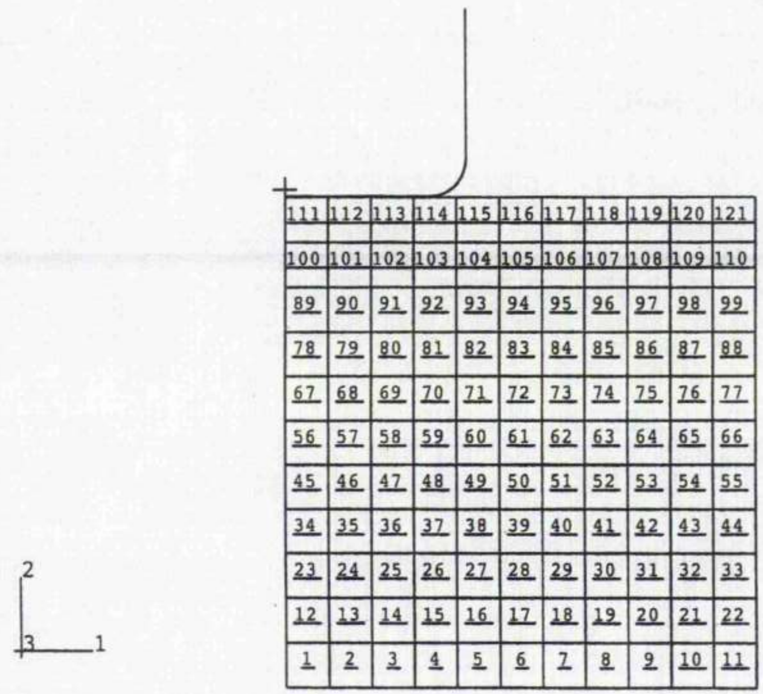
9 19 29 39 49 59 69 79 89 99
2
3
1

Fig. *5.4* Finite element mesh for the rubber-crumb mattress model

ABAQUS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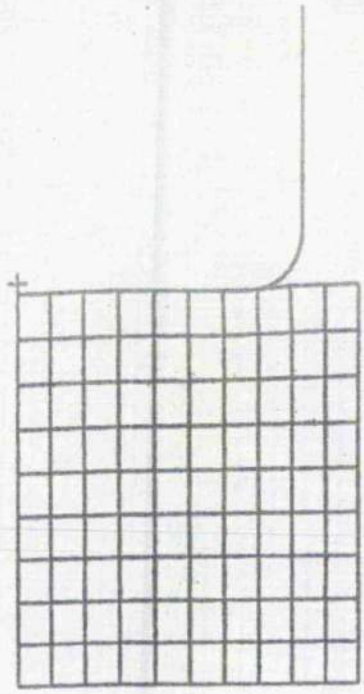
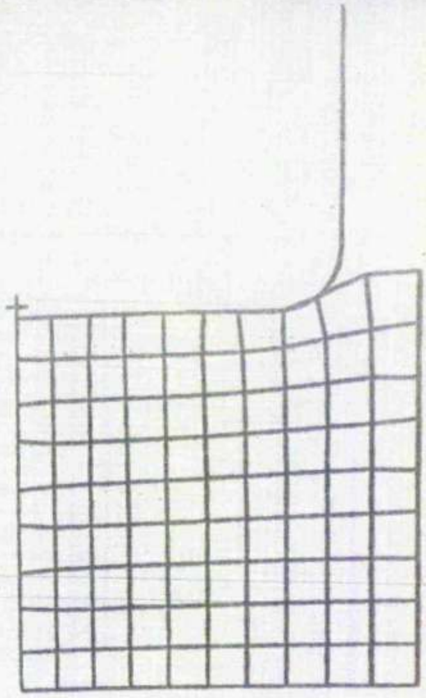
56 57 58 59 60 61 62 63 64 65 66
45 46 47 48 49 50 51 52 53 54 55
34 35 36 37 38 39 40 41 42 43 44
23 24 25 26 27 28 29 30 31 32 33
12 13 14 15 16 17 18 19 20 21 22
1 2 3 4 5 6 7 8 9 10 11
2
3
1

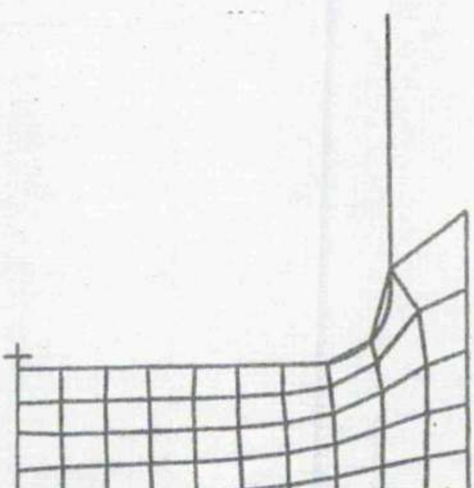
Fig. *5.5* Abaqus/Post images of the progressively deforming shape of an EVA mat sample under a compressive load



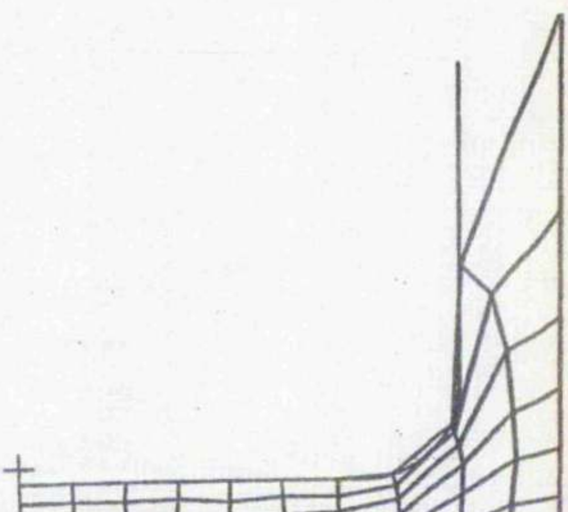
(a)



(b)

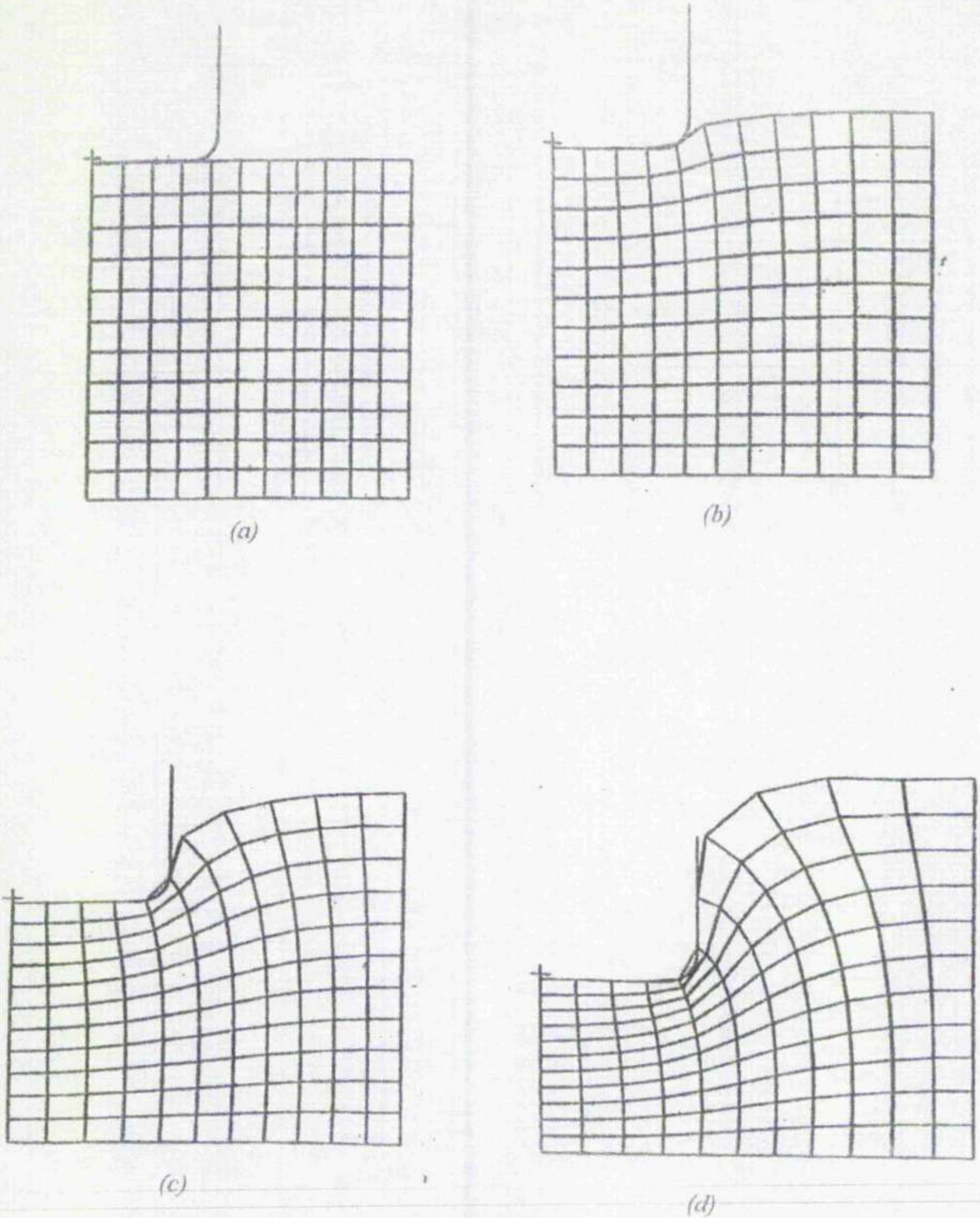


(c)



(d)

Fig. *5.6* Abaqus/Post images of the progressively deforming shape of the rubber-crumb mattress model under a compressive load


(a)
(b)
(c)
(d)

5.4.2 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, described in Chapter 4, 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.

The uni-axial compression tests 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 (Fig. *5.5*; Fig. *5.6*) to bring the knee onto the cubicle bed model and compress the elements. 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.

5.4.3 The EVA 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 $0.2x10^6$, $0.4x10^6$, $0.6x10^6$ and $0.8x10^6$. 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.

Fig. 5.7 shows that the value of μ found to correlate to a reaction force of 1000 N at 12 mm deflection was 480,000.

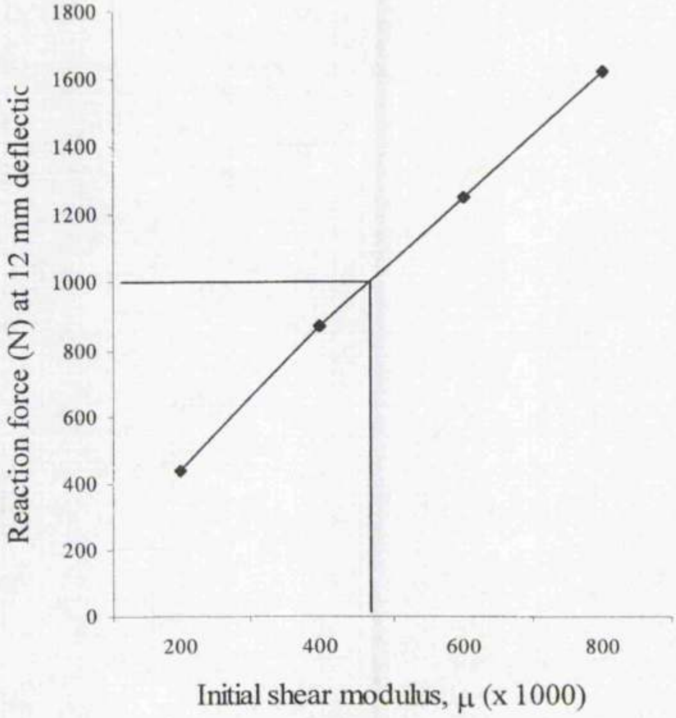


Fig. 5.7 Curve of reaction force at 12 mm deflection for four EVA mat computer models with four values for initial shear modulus, μ

The laboratory force-deflection curve for the EVA 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 $0.48\text{x}10^6$ 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 and Fig. *5.8* shows the result of the matching process for the EVA mat. Fig. *5.9* shows the contour plot of the 22-components of the Cauchy stress in the EVA mat model at maximum compression.

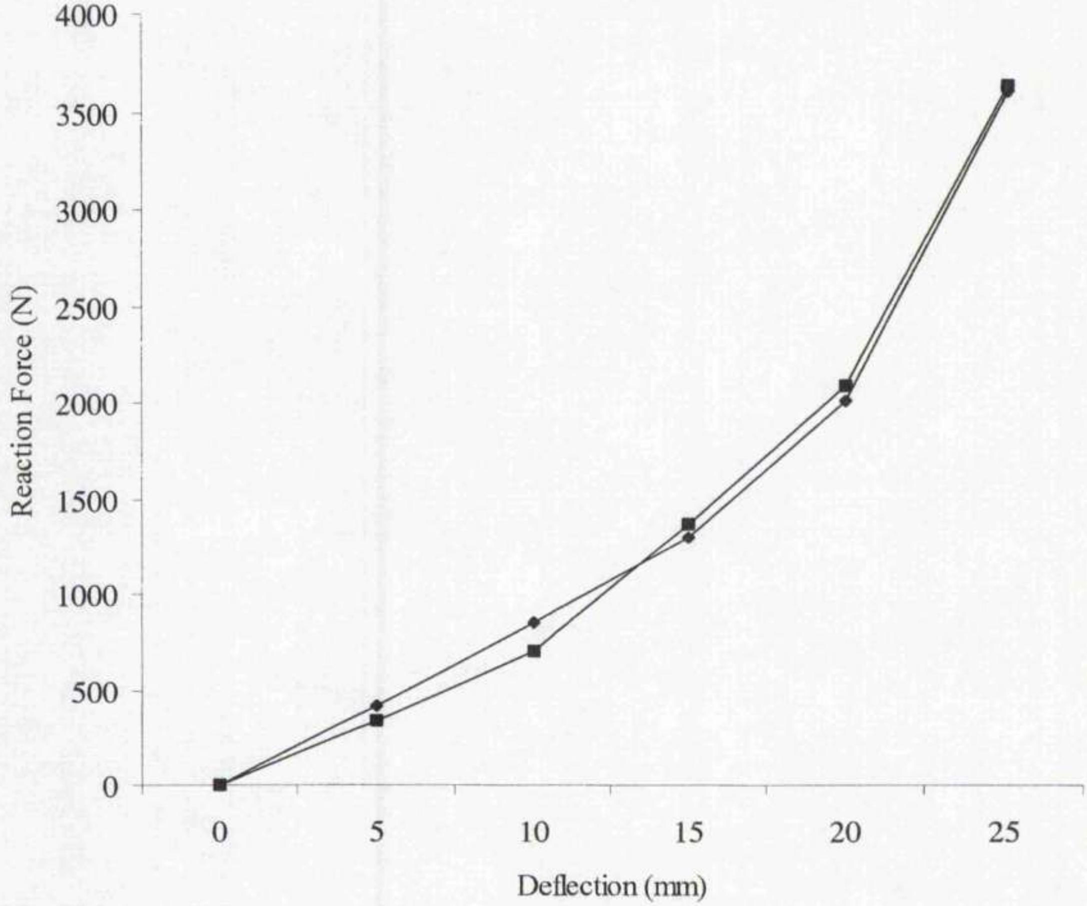
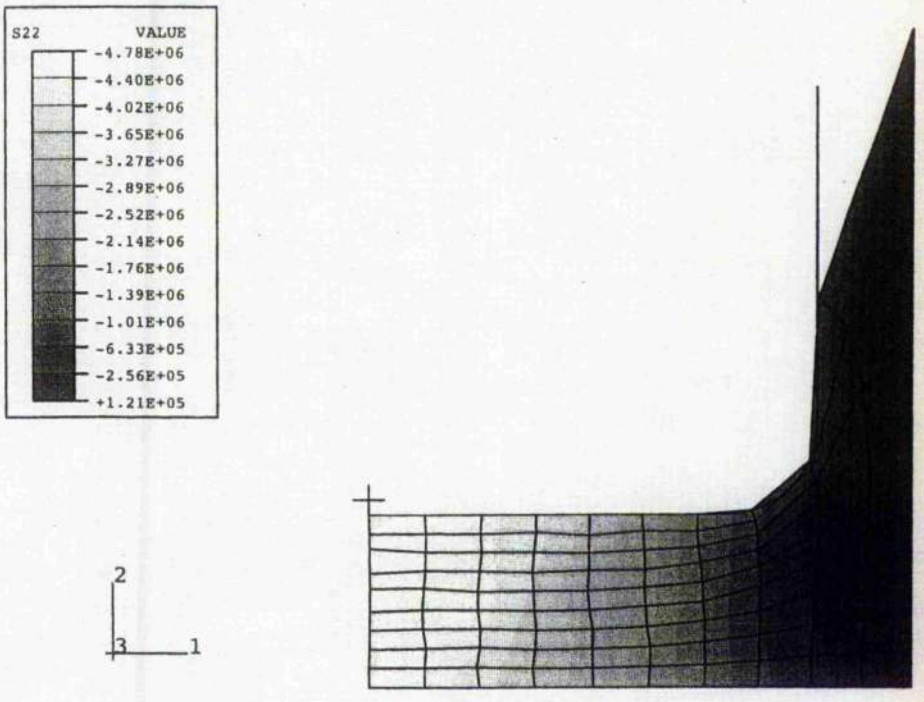


Fig. 5.8 Ethylene vinyl acetate (EVA) mat force-deflection curve comparison using a laboratory uniaxial quasi-static compression test ◆ and Abaqus explicit finite element analysis ■

Fig. 5.9 Contour plot of the 22-components of the Cauchy stress in the EVA mat model at maximum compression

ABAQUS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-3.27E+06
-2.89E+06
-2.52E+06
-2.14E+06
-1.76E+06
-1.39E+06
-1.01E+06
-6.33E+05
-2.56E+05
+1.21E+05
2
3
1

5.4.4 The rubber-crumb mattress model

The above process was repeated for the rubber-crumb mattress model. The behaviour under load of the mattress was different and the corresponding values for μ and α were different. That is, the Abaqus values of μ and α that produced a match of the laboratory curve for the rubber-crumb mattress 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 EVA mat model, the Abaqus program capability showed its worth when it was used 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. This successful matching was seen as a major benefit of the work and the skills developed can be applied to further modelling work to help farmers with product purchase information. The matching values of α and μ for the rubber-crumb mattress were produced by Abaqus in three estimates for three programme runs (N=3 hyperfoam). These values are shown in Fig. *5.2* and are reproduced here for convenience:

	μ	α	ν
1.	-512617	3.55501	0.20
2.	298262	7.39213	0.20
3.	272532	-1.7729	0.20

Fig. *5.10* shows the closely matching curves from the quasi-static compression tests and from the computational simulation of the rubber-crumb mattress compression. Fig. *5.11* shows the contour plot of the 22-components of the Cauchy stress in the rubber-crumb mattress at maximum compression.

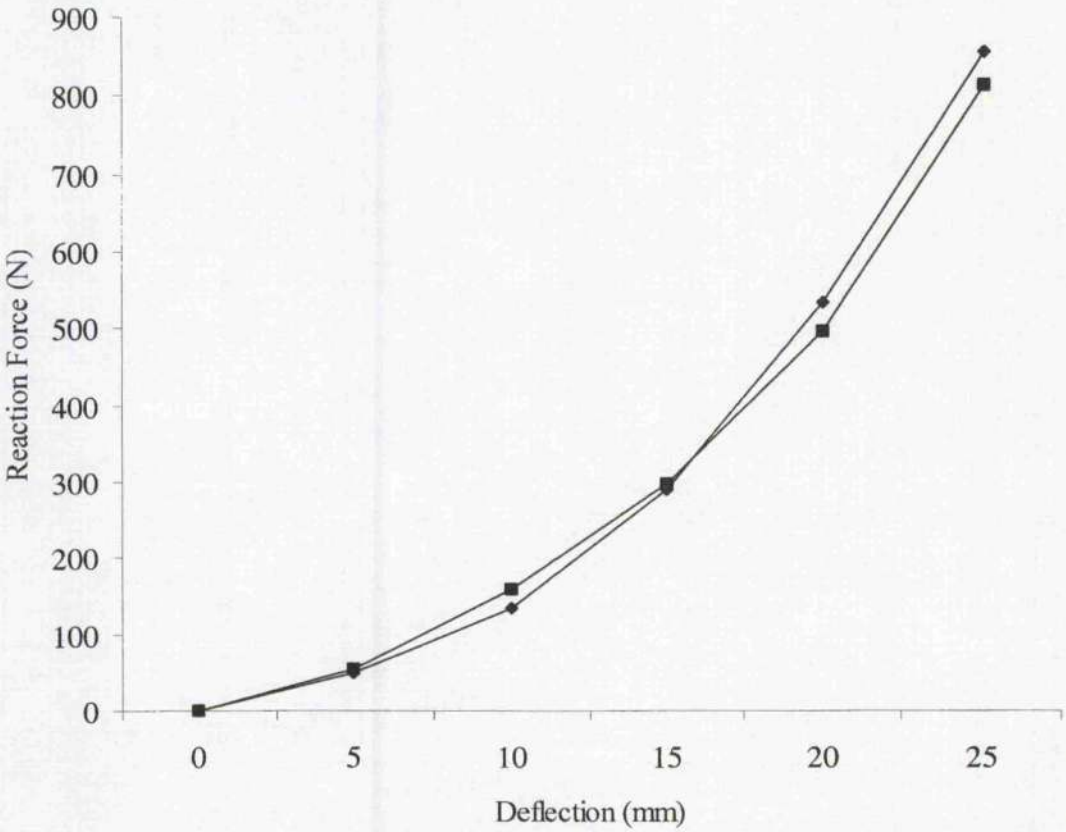
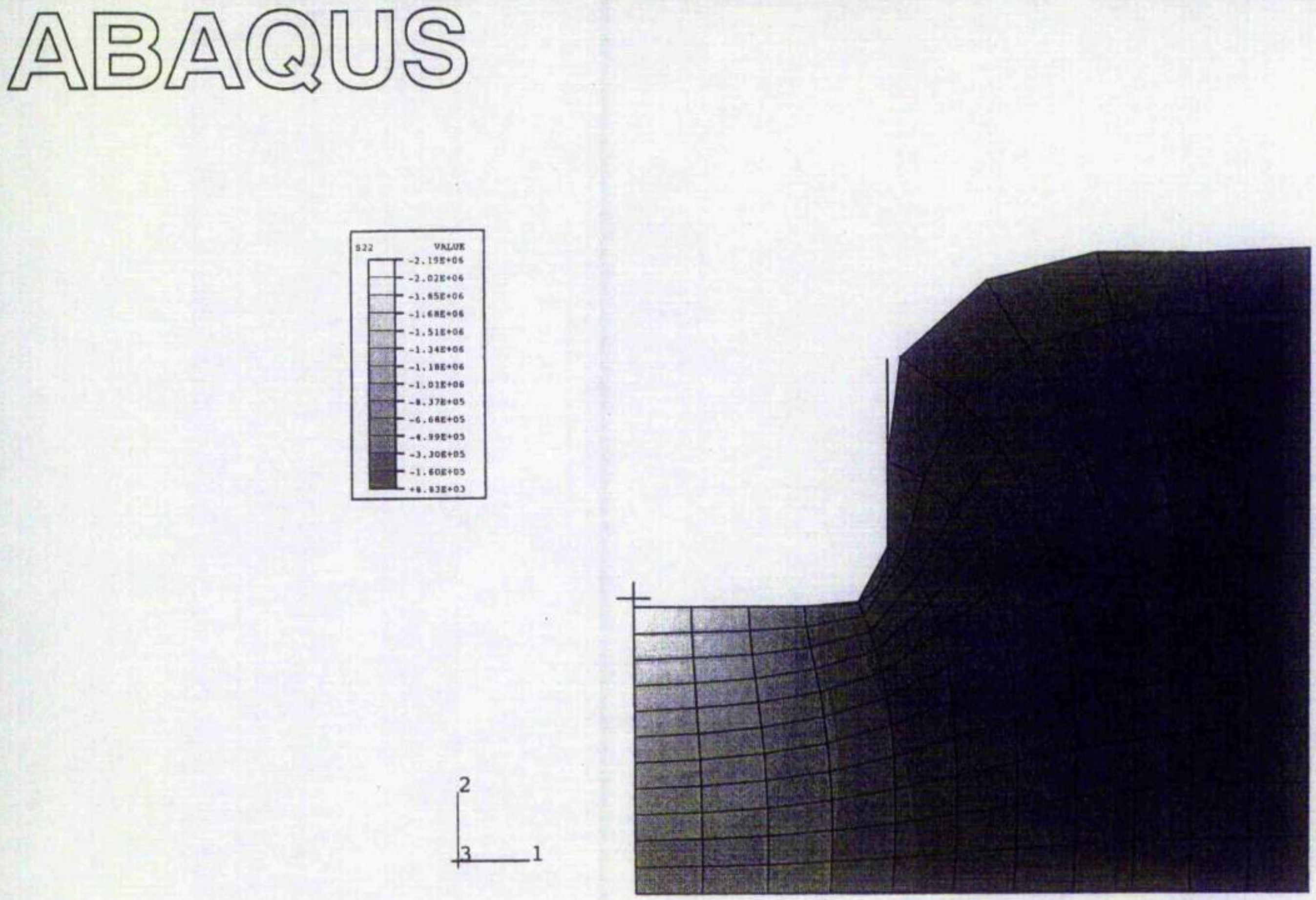


Fig. *5.10* Rubber-crumb mattress force-deflection curve comparison using a laboratory uniaxial quasi-static compression test ◆ and Abaqus explicit finite element analysis ■

Fig. *5.11* Contour plot of the 22-components of the Cauchy stress in the rubber-crumb mattress at maximum compression


ABAQUS
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-8.37E+05
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-4.99E+05
-3.30E+05
-1.60E+05
+8.83E+03
2
3
1

5.5 Cubicle bed modelling summary

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.

Fig. *5.5* and Fig. *5.6* show the progressive deformation of the EVA mat and the rubber-crumb mattress in finite element simulations. Both the rubber-crumb and the EVA material show qualitatively similar responses but their force-deflection responses are different. Fig. *5.8* shows the best-fit of the FEA force-deflection curve compared to the laboratory materials test for the EVA mat sample. Fig. *5.10* shows the best fit of the FEA curve to the materials laboratory tests for the rubber-crumb material.

Matching the laboratory and computer-simulated curves suggests that the computer model version could be manipulated in order to answer questions about cubicle bed performance. For example, FEA was used to show quickly and cost-effectively that reducing the thickness of the rubber-crumb mattress model to 30 mm from its original thickness of 65 mm, by re-setting the position of the base elements in the mesh input file (Fig. *5.12*) caused a reduction in cushioning performance (Fig. *5.14*). The progressive deformation of the compacted rubber-crumb mattress is shown as Fig. *5.13*. Alternatively, the required thickness of an EVA mat to improve its cushioning performance to one that is equal to or beyond that of a standard thickness rubber-crumb mattress may be determined. Determining an optimum specification for a synthetic cubicle bed, in terms of performance and cost, is a target for future FEA. Further work is required to show to cubicle bed manufacturers the full value of FEA of cubicle bed models at various thicknesses and densities of rubber, foam or any hyperelastic material.

Fig. *5.12* Ideas pre-processor input file for the half-thickness rubber-crumb mattress model

```
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** Only current test material active - others commented out
**
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**HYPERFOAM, N=3, TEST DATA INPUT, POISSON=0.2
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0.2
*UNIAXIAL TEST DATA
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 85, 133, 12
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*NSET, NSET=SBASE, GEN
 73, 84
**1, 12
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 LINE, 0.000, 0.0001
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 111, 121
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*SURFACE DEFINITION, NAME=SOLES
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*CONTACT PAIR
 HEEL, SOLES
*RESTART, WRITE, NUMBER INTERVAL=25
*END STEP
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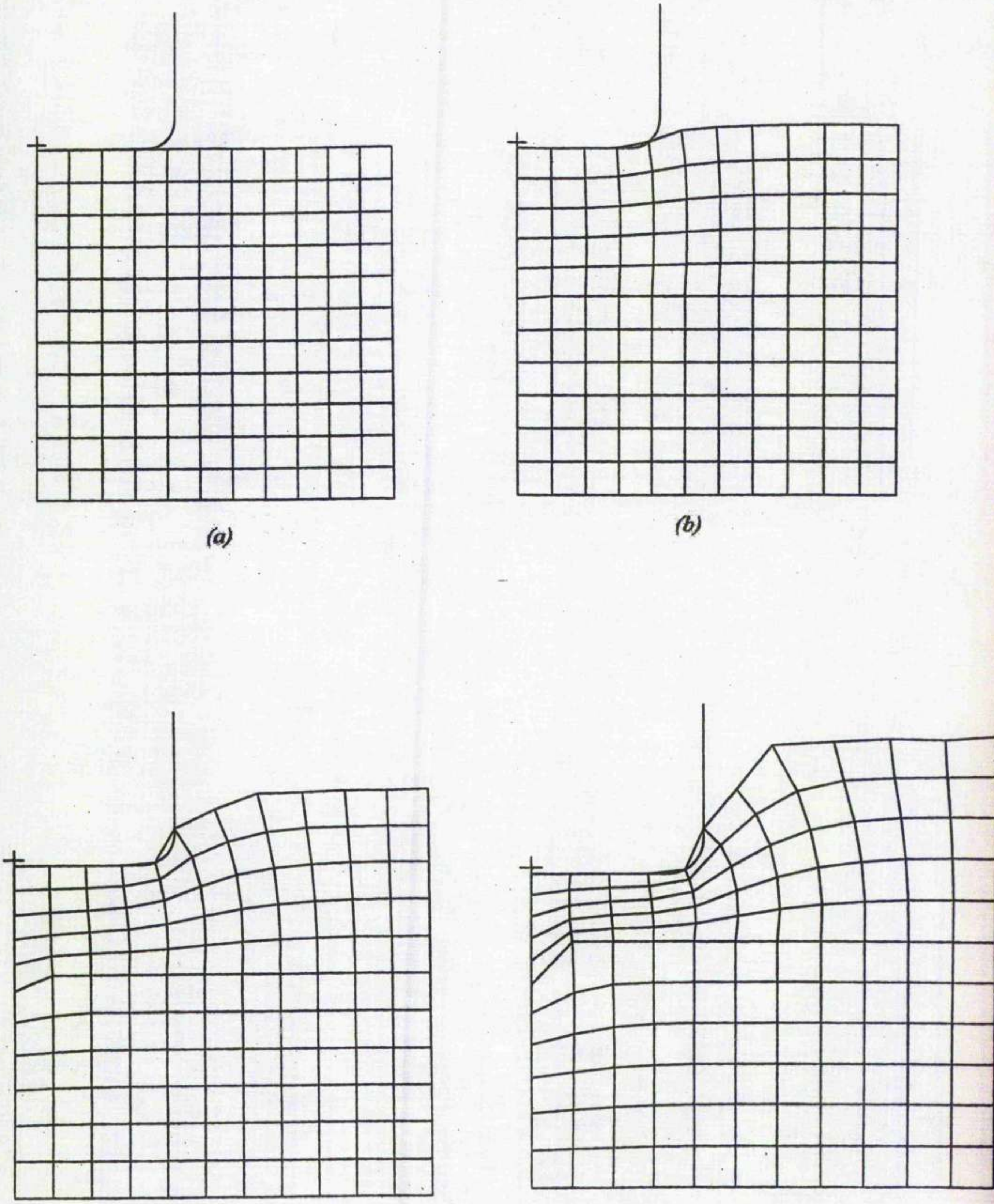
18

Fig. *5.13* Abaqus/Post images of the progressively deforming shape of the half-thickness rubber-crumb mattress model under a compressive load



(a) (b)

(c) (d)

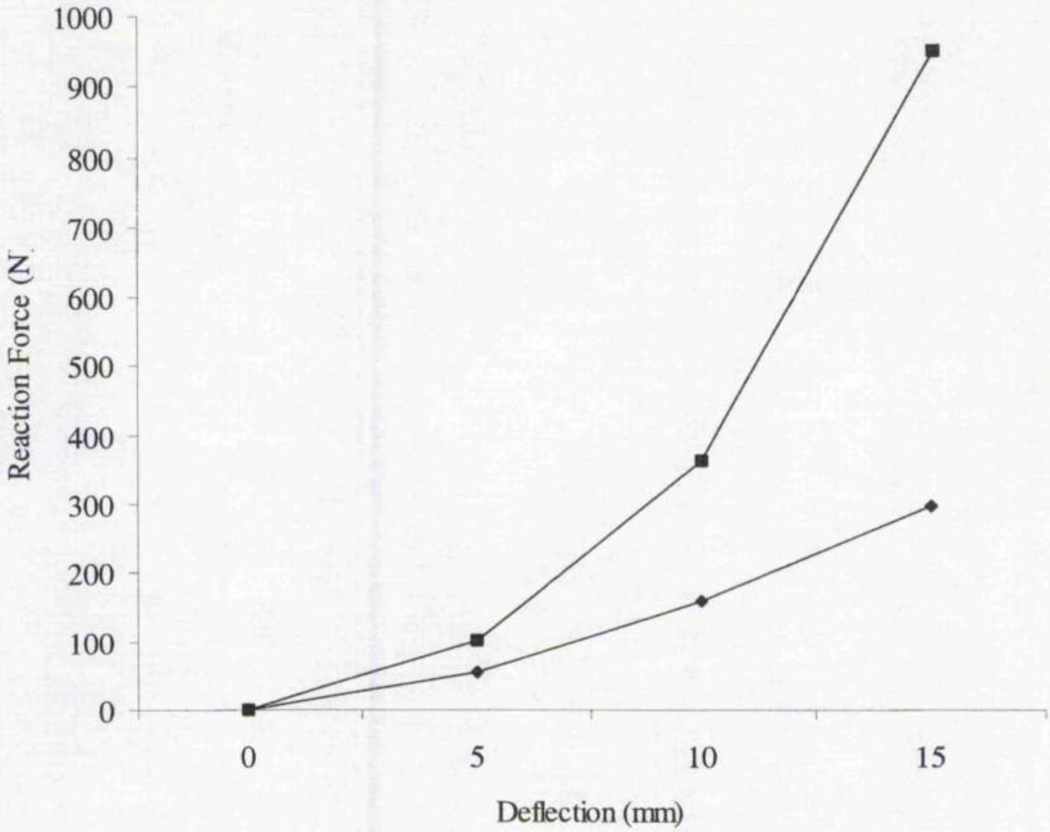
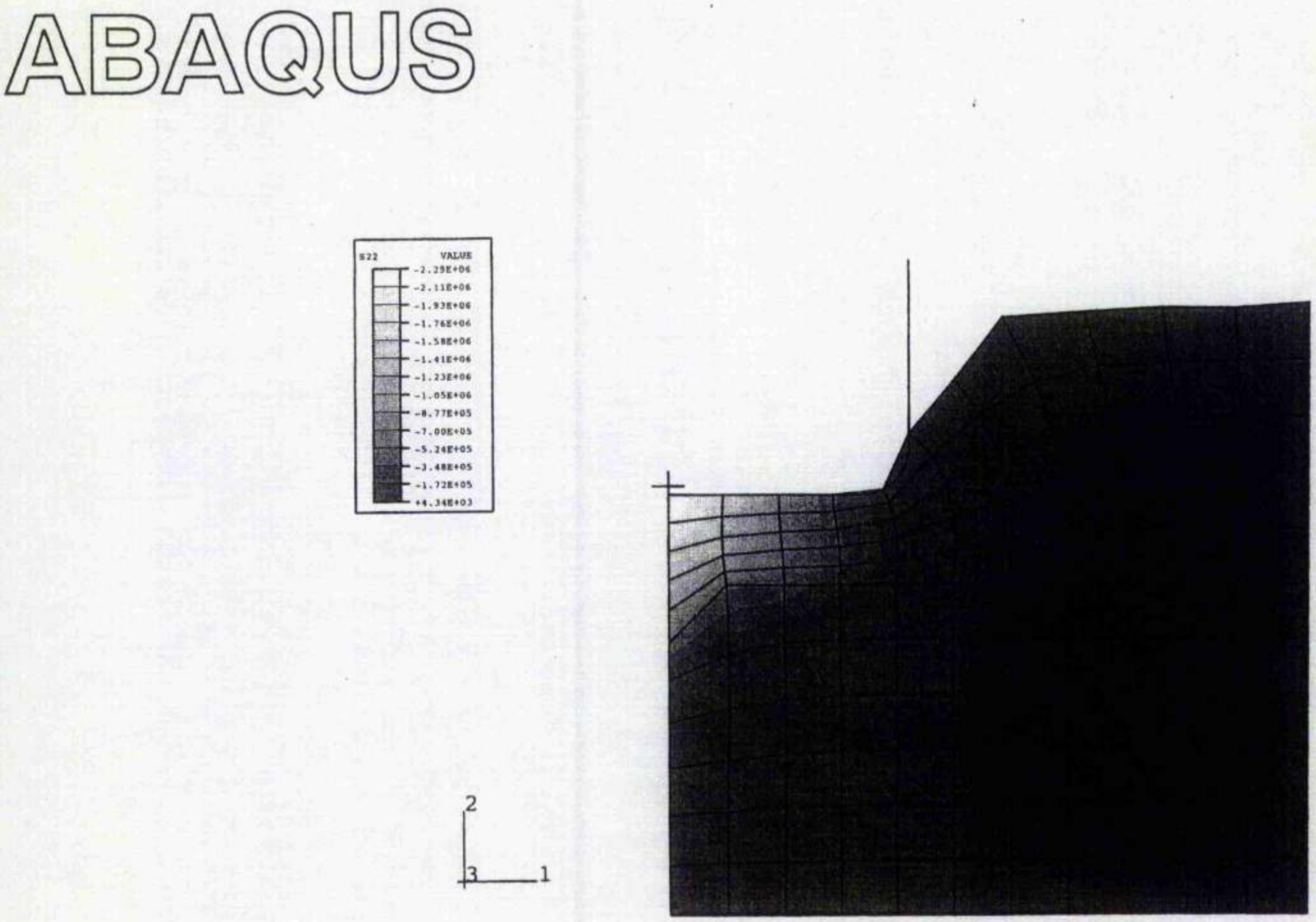


Fig. *5.14* Abaqus computer model force-deflection simulations for a full-thickness rubber-crumb mattress ◆ compared to one compressed to half-thickness ■

Fig. *5.14* is the computer model illustration of the hardening of the rubber-crumb mattress in time and shows the potential value of the FEA applications. Fig. 5.15 shows the contour plot of the 22-components of the Cauchy stress in the simulated half-thickness rubber-crumb mattress at maximum compression. The actual full-thickness rubber-crumb bed was tested in a mechanical engineering laboratory. An actual reduced thickness (because it had compacted with use) rubber-crumb bed was tested in place in a dairy house cubicle (Chapter 6). The full-thickness rubber-crumb bed was found to be more compliant.

Fig. *5.15* Contour plot of the 22- components of the Cauchy stress in the half-thickness rubber-crumb mattress at maximum compression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-5.24E+05
-3.48E+05
-1.72E+05
+4.34E+03
2
3
1

Chapter 6.0 Dynamic impact load testing of dairy cow cubicle beds

6.1 NF P90-104 (AFNOR, 1992)

To determine a force measurement for a cow dropping onto cubicle beds and to determine any change in cushioning performance after a number of years in use, dynamic impact tests were carried out using the NF P90-104 accelerometric method for synthetic sports surfaces from L'Association Française de Normalisation (AFNOR, 1992).

The principle of NF P90-104 (AFNOR, 1992) is to apply an impact load by means of a free-falling mass fitted with an accelerometer. If the peak acceleration to zero velocity (deceleration) of a moving mass on impacting a surface is rapid, the force developed is high and, clearly, potentially damaging to the mass.

NF P90-104 (AFNOR, 1992) yields various parameters that describe cubicle bed cushioning. By double integration of the record of acceleration with respect to time, the force-deflection characteristic of the surface under test can be obtained. The first integration with respect to time yields a value for the peak velocity of the mass and the second integration with respect to time gives the maximum deformation of the surface caused by the impact. Measurement of the maximum acceleration (ms^{-2}) multiplied by the mass (kg) gives the maximum force sustained by a surface for a given drop height. A high value for peak acceleration indicates 'hardness' or greater surface stiffness. A lower maximum acceleration indicates 'softness' or more surface compliance. Contact time is also a useful descriptor of the mechanical response of a surface to an impact mass. A long contact time, on an elastic surface, is associated with a low peak acceleration and, by inference, greater cushioning.

6.2 Dynamic impact tests of cubicle beds using NF P90-104 (AFNOR, 1992)

The tests were carried out on used beds in June 2000 at a dairy farm in Hampshire, England, where the cubicle beds had been occupied by a herd all year round since 1997 and on new bed samples in a laboratory setting (Table 6.1).

The NF P90-104 (AFNOR, 1992) test apparatus was as follows:

- accelerometer with a 60 mm diameter cylindrical flat steel indenter attached to an eight kilogrammes drop-mass (Fig. *6.1*);
- signal conditioning amplifier matched to the accelerometer;
- pre-filter to match the recorded signal to the discrete sampling recording system
- tripod with an adjustable height (Fig. *6.2*); a battery-operated electromagnet to hold and subsequently release the eight kilogrammes mass (Fig. *6.2*);
- software and data processing hardware to control the sampling system and to carry out the required analysis of the recorded data.

The whole system including the impact mass, the accelerometer and its mounting system had an upper cut-off frequency of no less than 10 kHz, a lower limiting frequency no greater than 0.2 Hz and a sampling frequency not less than 50 kHz.

The tripod was to set up to give a drop height of 174 mm, established by trial-and-error as that required to produce an impact force of 2 kN, the force generated by the knee joint of a 600 kg descending cow, (Dumelow, 1995). The magnet was engaged to hold the eight-kilogram mass above the impact point then released to allow the drop-mass to drop onto the cubicle bed. The accelerometer signal was passed to the computer for calculation of the maximum acceleration and, by double-integration, the deflection. The procedure was repeated for three test drops on the bed surface (Fig. *6.3*). The drop points 1, 2 and 3 shown in Fig. *6.3* were in the area of the cubicle mat or mattress that normally received the dynamic impact of a knee force when a cow lay down. 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 were used in this test to give an indication of 'un-used' or short-term impact resistance performance.

Table 6.1 Cubicle beds used in dynamic impact tests

		Year installed	Intensity of use
Used EVA mat	tested in place	1997	Zero grazing
Used rubber-crumb mattress	tested in place	1997	Zero grazing
New EVA mat sample	tested in laboratory	-	-
New rubber-crumb mattress sample	tested in laboratory	-	-

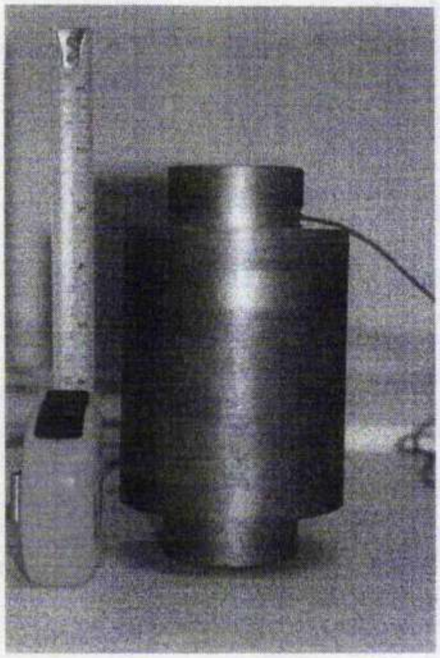

Fig. 6.1 Eight kilogram drop-mass used to simulate impacting knee of a dairy cow

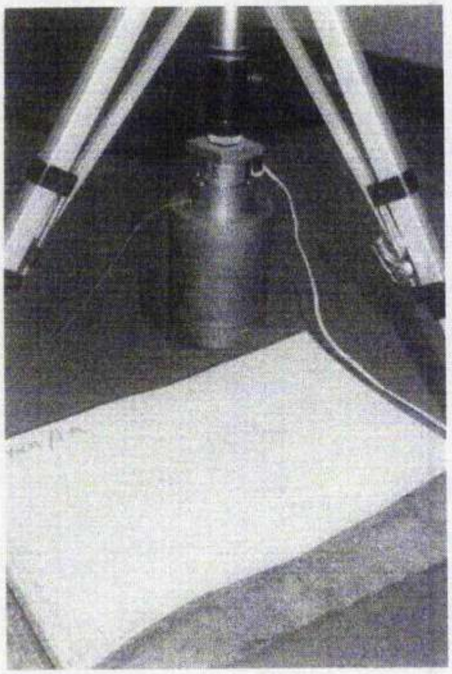

Fig. 6.2 Tripod, eight kilogram mass and accelerometer above a rubber-crumb mattress sample

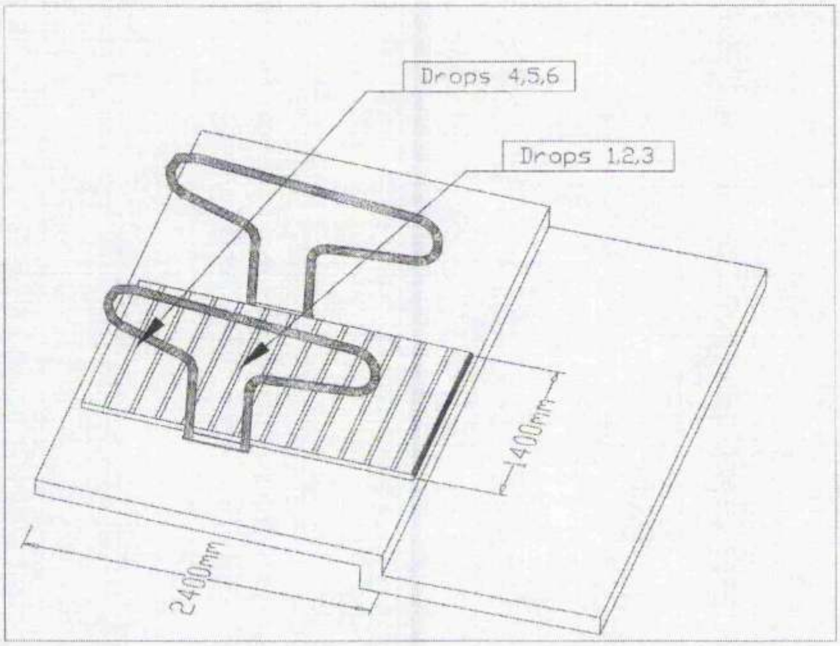

Fig. 6.3 Dynamic impact test drop points

6.3 Dynamic impact test results and discussion

The most compliant bed was the new rubber-crumb bed where the average peak acceleration from three drops was 224.7 ms^{-2} (Table 6.3). But there was an increase, compared to the new version *($p<0.001$)*, for the average peak acceleration to 552.9 ms^{-2} in the test for the fourth year rubber-crumb mattress. Surface penetration was down from 23.9 mm in the new bed to 10.4 mm in the fourth year bed *($p=0.003$)*. These results implied that a reduction in rubber-crumb bed compliance had occurred with use. The results for the EVA bed (Table 6.2) also implied a reduced cushioning performance in time, although the data showed a less stark change than that for the rubber-crumb beds. The EVA bed average peak acceleration values were 241.9 ms^{-2} (new bed) and 257.5 ms^{-2} (fourth year bed) *($p=0.007$)*. The EVA bed averaged value for maximum surface deflection actually showed an increase with use from 11.7 mm to 13.0 mm *($p=0.026$)*, but this 1.3 mm difference, although statistically different, was not considered to be as important as the peak acceleration measurement. An inference may be made that the EVA bed results showed a more stable long-term performance, based upon the much larger changes in cushioning performance in the rubber-crumb beds tested.

Further evidence of the better time-stable behaviour of the EVA mat was inferred from the contact time results (Table 6.2) and from the results of the tests done at impact points 4, 5 and 6 (*Fig. 6.3*). The new EVA bed had an average contact time of 21.1 ms and the used EVA bed had an average contact time of 21.8 ms *($p=0.057$)*. In contrast, again, the rubber-crumb bed performance (Table 6.3) was seen to have changed in time with the new bed average contact time recorded as 33.2 ms and the used bed average contact time being 14.8 ms (*p=0.002*). Impact points 4, 5 and 6 were inferred as 'as-new' surfacing since this general area would rarely, if ever, receive a knee impact. The average peak acceleration for the used EVA bed was 255.7 ms^{-2} (Table 6.4), which was similar to the average peak acceleration for the area that would have received repeated knee impacts in the years that the bed had been used. Likewise, contact time and maximum penetration results for the used EVA bed for drop points 4,5 and 6 were similar to those for points 1,2 and 3, which implied a stable long-term performance. The front edge results for the used rubber-crumb mattress (Table 6.5) showed a poor cushioning performance, average peak acceleration was 498.5 ms^{-2}, average contact time was 16 ms and the average maximum penetration was 11.7 mm. This was not an area of the bed that would have received knee impact loads in the years of use and would not, therefore, have compacted in the same manner as did the centre part of the bed. One explanation for the high average peak acceleration is that the rubber crumbs migrated from the centre part of the bed to the front and settled there as a more solid mass.

Farmers considering a cubicle bed choice may wish to know the impact injury potential of a particular mat or mattress type throughout the life of the product. This information can be gained from NF P90-104 (AFNOR, 1992) and could be offered by manufacturers in the form of a standard test certificate for impact absorption of a bed in the new condition and at 1-year intervals thereafter.

The current thesis proposes that the test procedure in NF P90-104 (AFNOR, 1992) could be used by dairy cow bed manufacturers to test their products. The protocol of NF P90-104 (AFNOR, 1992) requires sports surfaces to be re-tested every year and such an approach in cubicle bed certification may be valuable to farmers as the purchase of synthetic beds is a five to ten year investment.

As a starting point for finding a suitable performance standard, the new condition rubber-crumb mattress bed was found to be effective in minimising systematic injury in cows (Chapter 2) and is proposed as having a potential benchmark level for cushioning performance. The maximum acceleration recorded on the rubber-crumb mattress, for the set cow knee drop height, was 224.7 ms^{-2} (Table 6.3) and is proposed as the indicator of minimum cushioning performance. Comparisons of other new and aged products could be made against this benchmark maximum acceleration using the same test procedure. Fall height of the test mass (8 kg) was fixed according to the cow knee fall height that resulted in the expected maximum force exerted upon a single knee during the descending process, 2 kN. The test fall height for a 8 kg mass that corresponded to a peak force of 2 kN (174 mm) on a new rubber-crumb mattress was used. Maximum acceleration was variable according to the surface compliance or stiffness. Surfaces could be tested for peak acceleration from the cow knee fall height and those that are within a close range, perhaps ± 10%, of the peak acceleration that equates to the 224.7 ms^{-2} of the benchmark cubicle bed may be deemed to satisfy. A result that shows a cubicle bed to be more than 10% softer than the benchmark should still be deemed to be unsatisfactory because there is a minimum requirement for stiffness for when the animal is standing in the cubicle (Nilsson, 1988). That is, she needs some stability underfoot at that time.

The animal observation work carried out for Chapter 2 revealed that cows housed in cubicles with new rubber-crumb mattresses had better lying times and fewer injuries than those in cubicles with new EVA mats. Quasi-static tests were carried out in the current work on new rubber-crumb and EVA samples that showed the rubber-crumb to be the softer of the two types (Chapter 4). Nilsson (1988) set standard softness and hardness limits for cubicle beds and in the current work the new rubber-crumb sample was shown to be well within these limits and the new EVA sample was on the borderline of 'too hard'. Dumelow (1995) tested a number of synthetic cubicle bed types and found them to be outwith the cushioning minimum set by Nilsson (1988).

These findings from various research sources suggest that a new condition rubber-crumb mattress is a satisfactory cubicle bed product and its cushioning performance in terms of peak acceleration (224.7 ms^{-2}) may be an acceptable performance datum. Using this datum the new rubber-crumb bed type (224.7 ms^{-2}), the new EVA type (241.9 ms^{-2}) and the fourth year EVA type (257.5 ms^{-2}) could all be deemed to satisfy. However, the fourth year rubber-crumb bed (552.9 ms^{-2}) would be considered unsatisfactory. This procedure could be of assistance to cubicle bed manufacturers as an easily repeatable, on-farm cushioning performance test methodology.

Table 6.2 EVA bed impact test comparison of new and fourth year condition

	Drop height (mm)	Test number	New condition EVA bed	Fourth year condition EVA bed	
Peak acceleration (ms^{-2})	174	1	237.9	255.1	
	174	2	244.0	258.7	
	174	3	243.9	258.6	
		average	241.9	257.5	*p=0.007*
Maximum deflection (mm)	174	1	11.3	13.1	
	174	2	11.9	13.0	
	174	3	12.0	13.1	
		average	11.7	13.1	*p=0.026*
Contact time (s)	174	1	0.0206	0.0218	
	174	2	0.0212	0.0218	
	174	3	0.0215	0.0218	
		average	0.0211	0.0218	*p=0.057*

The data in Table 6.2 was analyzed by a one-way ANOVA using a two-sample t-test of significance assuming unequal variances.

Table 6.3 Rubber-crumb bed impact test comparison of new and fourth year condition

	Drop height (mm)	Test number	New condition rubber-crumb bed	Fourth year condition rubber-crumb bed	
Peak acceleration (ms^{-2})	174	1	204.5	542.0	
	174	2	228.8	556.5	
	174	3	240.8	560.1	
		average	224.7	552.9	$p<0.001$
Maximum deflection (mm)	174	1	25.2	10.3	
	174	2	23.8	10.4	
	174	3	22.7	10.5	
		average	23.9	10.4	$p=0.003$
Contact time (s)	174	1	0.0345	0.0148	
	174	2	0.0332	0.0148	
	174	3	0.0320	0.0147	
		average	0.0332	0.0148	$p=0.002$

The data in Table 6.3 was analyzed by a one-way ANOVA using a two-sample t-test of significance assuming unequal variances.

Table 6.4 EVA bed impact test results for drop points 4, 5 and 6 (the front of the fourth year condition bed)

	Drop height (mm)	Test number	Fourth year condition EVA bed
Peak acceleration (ms^{-2})	174	4	252.2
	174	5	256.7
	174	6	258.3
		average	255.7
Maximum deflection (mm)	174	4	13.3
	174	5	13.4
	174	6	13.7
		average	13.5
Contact time (s)	174	4	0.0221
	174	5	0.0223
	174	6	0.0226
		average	0.0223

Table 6.5 Rubber-crumb bed impact test results for drop points 4, 5 and 6 (the front of the fourth year condition bed)

	Drop height (mm)	Test number	Fourth year condition rubber-crumb bed
Peak acceleration (ms^{-2})	174	4	489.1
	174	5	499.0
	174	6	507.5
		average	498.5
Maximum deflection (mm)	174	4	11.7
	174	5	11.5
	174	6	11.9
		average	11.7
Contact time (s)	174	4	0.016
	174	5	0.016
	174	6	0.017
		average	0.016

Chapter 7.0 Conclusions

7.1 Dairy cow observation study

The literature review revealed that the cubicle housing environment offered to dairy cows in winter can be enhanced by the addition of a synthetic bed. The dairy cow observation study (Chapter 2) found that there was a good response from the cows to both of the products evaluated in terms of health and welfare, with reference to published data from cow studies on various bed types.

Chapter 2 set out to establish, in a one-winter trial period, if the rubber-crumb mattress cubicle bed was worth the extra cost to a farmer in terms of better health and welfare for a dairy herd and higher production levels. In terms of a direct comparison of the mattress and the mat in the areas of lying behaviour, hock and knee injuries the mattress was the better product. In the matter of cow cleanliness the mat was better for the udder. There was no clear difference in terms of feed eaten, milk production, locomotion, clinical lameness or sawdust bedding bacteria levels.

Therefore, if the purchasing decision is based on health and welfare the results of this trial point to a Pasture Mat (Mattress) purchase. If, however, the decision to buy is based upon milk yield and composition then the EVA Mat would be chosen because of its lower cost. Simplifying the purchasing decision to a matter of price paid per bed, the higher the price differential between mattresses and mats, the less attractive the mattress purchase becomes. Conversely, the lower the price differential, the more attractive the mattress becomes.

7.1.1 Summary of results from the dairy cow observations

Rubber-crumb mattress cows spent more time lying down and less time standing doing nothing. Rubber-crumb mattress cows generally had fewer hock and knee injuries at both farms in the study. However, at Myerscough the EVA mat cows had equally healthy looking knees, and in terms of the worst type of hock and knee injury there were no differences between the groups. Examination of total body dirtiness results showed no significant difference between bed groups but the EVA mat cows had cleaner udders.

Rubber-crumb mattress cows ate more than EVA mat cows at both sites but weight changes and body condition scores were not significantly different between groups. Milk yield and milk composition results (butterfat and protein percentage levels and somatic cell count) showed that there was no difference in cow performance. There were no differences in cow locomotion or clinical lameness results.

7.2 Measurement methods for cubicle bed cushioning performance

It was clear from the literature review and the observation study of Chapter 2 that that the getting-up and lying down actions of cows are bio-mechanically different. This led to a major objective of this thesis being to develop test methodologies for the quasi-static compression push of a cow getting up and the dynamic impact of a cow lying down. In addition, it was evident from discussions with dairy farmers in the observation study (Chapter 2) that a synthetic cubicle bed purchase is a medium to long term investment and consequently a method to measure longer-term cushioning performance was also sought. Current dairy building design practice includes reference to BS 5502 Part 40 (BSi, 1990) guidelines on cubicle length and width, but there is no stated performance standard for cubicle bed cushioning. A manufacturer of a rubber-crumb mattress showcased a new specification at the Royal Ulster Agricultural Society annual show in Belfast, Northern Ireland in 2002. Their cubicle bed has changed from a loose-fill rubber-crumb product to a bonded foam base covered with a flat topcover as a reaction to fears of long-term cushioning performance loss due to compaction.

7.2.1 Correlating injury score findings to mechanical response of hyperfoams

The cubicle bed materials were described as hyperfoams and their characteristics were discussed in Chapter 3 in terms of strain energy potential, $U(\varepsilon)$. A suitable form of $U(\varepsilon)$ afforded analysis of the hyperelastic material constants, α, μ and ν in nonlinear FEA material modelling. Correlating knee injury score analysis (Chapter 2) to force-deflection curves from laboratory quasi-static compression tests (Chapter 4) and finite element analysis (Chapter 5) for the two cubicle bed types led to a point where injury-reduction potential could be inferred from computer modelling.

7.2.2 The quasi-static compression push of a cow getting up

Both cubicle bed types studied were shown by the quasi-static compression tests (Chapter 4) to be compliant enough to minimise incidences of severe knee injury scores. It was also shown by the compression tests that the rubber-crumb mattress was the more compliant of the two bed types and as such should have been the cause of fewer injuries in the cows. This inference was substantiated by injury score analysis from Chapter 2.

The proposed dual use of nonlinear FEA in conjunction with laboratory quasi-static testing of cubicle beds are, firstly, measuring the compression force exerted when a cow gets up from the lying position and, secondly, as a tool for quickly and cost-effectively predicting what performance change may occur in simulated time.

7.2.3 The dynamic impact force of a cow lying down

Accelerometric testing was used to determine the cushioning effect of a cubicle bed when a dynamic impact force is applied. The peak 'a' measurement results in Chapter 6 showed the new condition rubber-crumb mattress to be more compliant than the new condition EVA mat. But, the cushioning performance of the aged rubber-crumb mattress was much reduced compared to the new rubber-crumb mattress and the new and old EVA mats.

The dual uses of the accelerometric test method of cushioning performance (Chapter 6) of cubicle beds are firstly, as a measurement of the impact force from a cow's knee on dropping to the bed surface and secondly, as an in-situ assessment of long-term cushioning performance in real time.

7.3 Recommendations for future work

7.3.1 Computational modelling

The current work established computational models for rubber-crumb mattresses and EVA foam mats for dairy cow cubicle beds. Further work on the detail of the characteristic hyperelastic constants of hyperfoams is proposed in order to be able to take a template input file and refine it for any variation of cubicle bed material and thickness. Having done this it is hoped that it would be possible to show new condition and long-term cushioning performance for an animal's getting up movement, i.e. what is essentially a quasi-static compressive loading condition, for such a range of bed specifications. Further, it is proposed that work is done using the established models on simulating a dynamic impact load to measure the forces exerted by a cow knee on dropping to a bed cushioning surface.

7.3.2 Accelerometric testing

The dual uses of the accelerometric test method of cushioning performance of cubicle beds are firstly, as a measurement of the impact force from a cow's knee on dropping to the bed surface and secondly, as an on-site assessment of long-term cushioning performance in real time. The latter of these two applications is offered as an important new contribution to agricultural engineering in response to a call in the literature for an on-site test of cubicle bed softness. It is suggested in the current work that this test method could be incorporated into a revision of or a supplement to BS 5502: 1990: Part 40 (BSi, 1990) in order to encourage agricultural engineers and building designers to make an objective-based judgement of what synthetic cubicle beds are best for farmers to install. Conclusions are made in the current work based upon the results achieved in Chapter 6 from tests done on rubber-crumb mattresses and EVA mats, but there are other dairy cow bed options available. It is the accelerometric test procedure of NF P90-104 that is potentially valuable to agricultural engineers and a follow-up study should be carried out with many more bed specifications involved to improve the value of the statistical analysis and to offer farmers comprehensive information on cubicle bed cushioning performance.

Glossary/abbreviations/definitions

Animal classification

Primiparous	Refers to a cow in first lactation
Multiparous	Refers to multiple lactations

Clinical lameness

N.LAME	the number of cows which went lame at least once
WEEKS LAME	total number of weeks lame per cow
N.EVENTS	the number of lameness events per cow

Behaviour

L-scan	lying, recorded by scan sampling
LR/L	proportion of lying time spent ruminating
SO	idling (standing, doing nothing)
logSO	log transformed idling
SO(C)/SO	proportion of idling time spent in cubicles
S½	standing half-in cubicles with back feet in passageway
logS½	log transformed S½
L-TOTAL	total lying time, recorded by event sampling
L-BOUTS	number of lying bouts over 24h
L-MAX	maximum bout length
L-MIN	minimum bout length
L-AV	average bout length

Lunging	Forward movement of an animal to get up from lying position

Cubicle bed materials and properties

EVA	Ethylene vinyl acetate
NL FEA	Non-linear finite element analysis
α	Hyperelastic stiffening index
μ	Initial shear modulus (Pa)
ν	Poisson's ratio
λ	Stretch ratio

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Appendices

1. Injury assessment in cow foreknees

2. Lying behaviour data collection sheets

Appendix 1 Injury assessment in cow foreknees

Cow	1=core, 2=filler, 3=new	Group	Pre-trial	wk1	wk3	wk5	wk7	wk8	wk9	wk11	wk13	wk15	wk17	wk19	wk21	wk23	wk25	wk27	wk29	Max	Min	Ave
167	1	rubber-crumb	0	5	1	0	1													5	0	1.4
282	1	rubber-crumb	0	0	0	0	2		0	2	2	1	2	0	0	1	0	1	0	2	0	0.7
357	1	rubber-crumb	0	0	0	0	0		0	0	1	0	2	2	0	1	1	0	0	2	0	0.4
359	1	rubber-crumb	0	0	0	0	0		0	0	0	4	2	1	2	1	2	2	1	4	0	0.9
409	1	rubber-crumb		0	0	0	0		0	0	1	0	1	5	0	5	6	5	5	6	0	1.9
425	1	rubber-crumb	0	0	0	0	0		1	0	2	1	2	0	1	1	2	1	6	6	0	1.1
498	1	rubber-crumb	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0	0	1	0	0.1
502	1	rubber-crumb	0	0	0	0	2													2	0	0.4
538	1	rubber-crumb	0	0	0	0	1		0	0	2	0	1	0	1	0	2	1	2	2	0	0.6
555	1	rubber-crumb	0	0	0	0	0		0	0	0	0	0	0	0	0	2	0	0	2	0	0.1
574	1	rubber-crumb		1	0	0	0		5	1	0	5	1	4	1	1	6	2	2	6	0	1.9
587	1	rubber-crumb	0	0	0	0	0		0	0	0	0	0	0	0	0	1	0	0	1	0	0.1
594	1	rubber-crumb	0	0	0	0	0		1	1	1	2	2	0	2	1	5	3	3	5	0	1.3
599	1	rubber-crumb	0	0	0	0	0		0	0	0	0	2	0	0	5	5	0	10	10	0	1.4
613	1	rubber-crumb	0	0	0	0	1		5	0	2	1	1	0	0	1	0	1	0	5	0	0.8
10	2	rubber-crumb		0	0	0	1													1	0	0.3
110	2	rubber-crumb	0	0	0	0	0													0	0	0.0
299	2	rubber-crumb	0	5	0	2	1													5	0	1.6
355	2	rubber-crumb	0	0	0	1	0													1	0	0.2
386	2	rubber-crumb		0	0	0	0													0	0	0.0
404	2	rubber-crumb		0	0	0	1													1	0	0.3
415	2	rubber-crumb		0	0	1	1													1	0	0.5
435	2	rubber-crumb	0	0	0	0	1													1	0	0.2
437	2	rubber-crumb	0	0	0	0	1													1	0	0.2
482	2	rubber-crumb	5	0	0	0	0													5	0	1.0
488	2	rubber-crumb	0	0	0	0	0													0	0	0.0
508	2	rubber-crumb	0	0	0	0	0													0	0	0.0

Injury assessment in cow foreknees at SAC Ayr

540	2	rubber-crumb	0	0	0	0	0													0	0	0.0
581	2	rubber-crumb	0	5	0	0	0													5	0	1.0
408	3	rubber-crumb						0	0	0	1	0	1	0	0	0	0	0	0	1	0	0.2
463	3	rubber-crumb						0	2	0	2	2	2	0	0	0	2	6	2	6	0	1.5
483	3	rubber-crumb						2	2	2	6	4	1	4	0	2	2	3	1	6	0	2.4
507	3	rubber-crumb						2	4	1	1	2	1	1	1	1	1			4	1	1.5
530	3	rubber-crumb						4	3	2	1	2	1	1	0	2	0	0	0	4	0	1.3
533	3	rubber-crumb						2	1	1	2	1	2	0	1	0	1	2	1	2	0	1.2
541	3	rubber-crumb						0	1	2	0	1	1	0	2	1	1	1	2	2	0	1.0
546	3	rubber-crumb						0	1	1	0	2	1	0	2	0	1	1	0	2	0	0.8
552	3	rubber-crumb						0	0	0	1	0	5	0	0	0	0	0	1	5	0	0.6
558	3	rubber-crumb						1	0	2	1	0	2	0	1	0	0	0	0	2	0	0.6
567	3	rubber-crumb						1	1	0	0	1	1	0	0	0	1	0	1	1	0	0.5
577	3	rubber-crumb						4	2	2	2	2	2	0	1	0	0	0	1	4	0	1.3
588	3	rubber-crumb						1	0	1	0	0	2	1	0	1	1	5	0	5	0	1.0
597	3	rubber-crumb						0	0	0	0	3	0	0	0	0	1	1	2	3	0	0.6
603	3	rubber-crumb						0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
612	3	rubber-crumb						0	0	0	0	0	0	0	1	0	0	2	1	2	0	0.3
127	1	EVA foam	0	0	0	1	2													2	0	0.6
272	1	EVA foam	0	0	1	2	1		1	1	3	6	1	0	2	0	2	10	10	10	0	2.5
293	1	EVA foam	0	0	0	2	1		0	0	0	2	2	1	1	2	2	2	3	3	0	1.1
358	1	EVA foam	0	0	0	2	2		0	0	2	2	1	2	1	1	2	1	1	2	0	1.1
387	1	EVA foam	0	0	0	2	1		1	0	2	1	2	2	2	0	1	2	0	2	0	1.0
432	1	EVA foam	0	0	0	2	2		0	0	0	2	2	2	1	1	2	2	2	2	0	1.1
455	1	EVA foam	0	0	0	2	2		1	1	0	2	0	1	0	1	2	2	1	2	0	0.9
520	1	EVA foam	0	0	2		1													2	0	0.8
539	1	EVA foam	0	0	1	2	2		1	2	2	2	2	1	2	2	2	2	2	2	0	1.6
563	1	EVA foam	0	0	1	2	0		1	0	0	1	1	1	1	1	1	0	0	2	0	0.6
591	1	EVA foam	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	1	0	0.1

Injury assessment in cow foreknees at SAC Ayr

592	1	EVA foam	0	0	0	1	0		2	2	2	2	2	1	0	0	1	0	0	2	0	0.8
595	1	EVA foam	0	0	0	2	1		2	2	2	6	2	2	1	2	2	2	2	6	0	1.8
604	1	EVA foam	0	0	0	1	1		5	5	6	5	5	5	6	6	6	10	5	10	0	4.1
620	1	EVA foam		0	0	2	2		1	1	0	2	2	0	0	1	1	0	0	2	0	0.8
78	2	EVA foam	0	0	0	2	1													2	0	0.6
202	2	EVA foam			0	0	1													1	0	0.3
233	2	EVA foam		0	0	2	2													2	0	1.0
309	2	EVA foam		0	1	2	2													2	0	1.3
377	2	EVA foam		0	0	2	0													2	0	0.5
390	2	EVA foam	0	0	0	1	2													2	0	0.6
426	2	EVA foam		0	0	1	1													1	0	0.5
443	2	EVA foam		0	1	1	1													1	0	0.8
462	2	EVA foam		0	0	2	2													2	0	1.0
477	2	EVA foam		0	0	0	0													0	0	0.0
480	2	EVA foam		0	0	2	0													2	0	0.5
486	2	EVA foam	0	0	0	2	1													2	0	0.6
494	2	EVA foam	0	0	0	2	1													2	0	0.6
565	2	EVA foam	0	0	1	2	4													4	0	1.4
430	3	EVA foam						0	1	1	3	2	2	2	2	2	2	1	1	3	0	1.6
448	3	EVA foam						2	2	0	0	1	1	1	2	2	2	0	0	2	0	1.1
499	3	EVA foam						1	0	1	1	2	2	1	0	1	2	0	2	2	0	1.1
515	3	EVA foam						0	0	0	0	4	0	0	0	0	.0	0	0	4	0	0.3
531	3	EVA foam						2	2	1	2	1	1	1	1	1	0	0	0	2	0	1.0
534	3	EVA foam						0	0	0	0	0	0	0	1	1	0	1	0	1	0	0.3
536	3	EVA foam						0	1	2	2	0	0	0	1	1				2	0	0.8
557	3	EVA foam						0	0	1	0	2	2	2	2	2	2	1	2	2	0	1.3
564	3	EVA foam						0	2	2	2	2	2	0	2	0	0	1	0	2	0	1.1
607	3	EVA foam						2	2	2	2	2	2	1	0	2	2	0	1	2	0	1.5
611	3	EVA foam						4	2	2	4	2	2	2	2	2	1	2	2	4	1	2.3

Injury assessment in cow foreknees at SAC Ayr

619	3	EVA foam						0	2	2	2	1	2	2	2	2	2	1	2	2	0	1.7
626	3	EVA foam						4	2	1	2	4	0	2	2	4	2	1	3	4	0	2.3
629	3	EVA foam						0	1	0	1	1	0	0	0	0	0	0	0	1	0	0.3
630	3	EVA foam						0	0	0	0	1	0	2	2	1	1	1	1	2	0	0.8
634	3	EVA foam						2	1	0	0	2	2	3	1	1	1	0	0	3	0	1.1

Cow	core/ fller	group	Pre-trial	wk 1	wk 3	wk 5	wk 7	wk 8	wk 9	wk 11	wk 13	wk 15	wk 17	wk 19	wk 21	wk 23	wk 25	wk 27	Max	Min	Ave
67	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	5	5.0	0.0	0.4
238	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
244	1	rubber-crumb	0	0	5	1	0	0	0	5	10	5	1	5	5	10	10	0	10.0	0.0	3.6
297	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
300	1	rubber-crumb	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5.0	0.0	0.3
301	1	rubber-crumb		0	0	10	10	0	0	0	0	0	0	0	0	0	0	0	10.0	0.0	1.3
324	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
325	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0						0.0	0.0	0.0
331	1	rubber-crumb	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0.0	0.1
333	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
615	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
688	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
969	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
989	1	rubber-crumb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5.0	0.0	0.3
176	2	rubber-crumb	0	0	5	0	0												5.0	0.0	1.0
182	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
186	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
259	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
274	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
283	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
286	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
314	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
322	2	rubber-crumb	0	0	0	5	5												5.0	0.0	2.0
612	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
901	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
932	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
954	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
976	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
1099	2	rubber-crumb	0	0	0	0	0												0.0	0.0	0.0
24	3	rubber-crumb						0	0	0	0	0	0	0	5	0	0	0	5.0	0.0	0.5
36	3	rubber-crumb						0	0	2	4	0	0	0	0	0	0	0	4.0	0.0	0.5
91	3	rubber-crumb						0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0

Injury assessment in cow foreknees at Myerscough

120	3	rubber-crumb						0	0	0	0	0	0	0	5	0	0	0	5.0	0.0	0.5
154	3	rubber-crumb						0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
201	3	rubber-crumb						0	0	0	0	0	0	0	0	0	2	0	2.0	0.0	0.2
220	3	rubber-crumb						0	1	0	0	0	0	0	0	0	0	0	1.0	0.0	0.1
228	3	rubber-crumb						0	5	0	0	0	0	0	0	0	0	0	5.0	0.0	0.5
236	3	rubber-crumb						0	0	0	5	0	0	0	0	0	0	0	5.0	0.0	0.5
251	3	rubber-crumb						0	0	0	5	0	0	0	0	5	0	0	5.0	0.0	0.9
273	3	rubber-crumb						0	0	0	1	0	0	1	5	0	0	0	5.0	0.0	0.6
340	3	rubber-crumb						0	0	0	0	0	0	0	5	0	0	0	5.0	0.0	0.5
703	3	rubber-crumb						0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
912	3	rubber-crumb						0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
927	3	rubber-crumb						0	0	1	0	0	0	0	0	0	0	0	1.0	0.0	0.1
66	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	1	EVA foam	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5.0	0.0	0.3
214	1	EVA foam	0	0	0	0	0												0.0	0.0	0.0
239	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
248	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	10.0	0.0	0.6
255	1	EVA foam	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5.0	0.0	0.3
290	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
302	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
315	1	EVA foam	0	1	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5.0	0.0	0.4
318	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0						0.0	0.0	0.0
330	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
334	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
609	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
960	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
994	1	EVA foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
79	2	EVA foam	0	0	5	0	0												5.0	0.0	1.0
93	2	EVA foam	1	0	0	0	0												1.0	0.0	0.2
94	2	EVA foam	0	0	0	0	0												0.0	0.0	0.0
123	2	EVA foam	0	0	0	5	5												5.0	0.0	2.0
184	2	EVA foam	0	0	0	0	0												0.0	0.0	0.0
193	2	EVA foam	0	0	0	0	0												0.0	0.0	0.0

Injury assessment in cow foreknees at Myerscough

253	2	EVA foam	0	0	0	0	0												0.0	0.0	0.0
270	2	EVA foam	0	0	0	0	0												0.0	0.0	0.0
282	2	EVA foam	0	0	0	0	0												0.0	0.0	0.0
307	2	EVA foam	0	0	0	0	0												0.0	0.0	0.0
323	2	EVA foam	0	0	0	0	0												0.0	0.0	0.0
601	2	EVA foam	0	0	5	5	0												5.0	0.0	2.0
633	2	EVA foam	0	0	0	0	0												0.0	0.0	0.0
935	2	EVA foam	0	0	0	5	5												5.0	0.0	2.0
44	3	EVA foam						0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
138	3	EVA foam						0	1	0	5	0	0	0	0	0	5	5	5.0	0.0	1.5
153	3	EVA foam						0	0	0	5	0	0	0	0	0	0	0	5.0	0.0	0.5
205	3	EVA foam						0	0	2	5	0	0	0	0	0	0	5	5.0	0.0	1.1
221	3	EVA foam						0	1	5	0	0	0	0	0	0	0	0	5.0	0.0	0.5
235	3	EVA foam						0	0	5	5	0	0	5	0	5	5	0	5.0	0.0	2.3
257	3	EVA foam						0	5	2	4	0	0	0	1	0	0	0	5.0	0.0	1.1
261	3	EVA foam						0	1	2	0	0	0	0	0	0	0	0	2.0	0.0	0.3
264	3	EVA foam						0	0	0	5	0	0	0	0	0	0	0	5.0	0.0	0.5
275	3	EVA foam						0	0	0	0	0	0	0	1	0	0	0	1.0	0.0	0.1
319	3	EVA foam						0	0	2	0	0	0	0	0	0	0	0	2.0	0.0	0.2
338	3	EVA foam						0	1	0	0	0	0	0	0	0	5	5	5.0	0.0	1.0
626	3	EVA foam						0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
630	3	EVA foam						0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
967	3	EVA foam						0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0

Injury assessment in cow foreknees at Myerscough

Appendix 2 Lying behaviour data collection sheets

Date: Time:	L / S / $S^1/_2$	C (No.) / P / F	F / R / D / O
Cow			

Date:

Time:

Cow	Cubicle No.	Time of lying down	Time of rising	Other events noted e.g. tractor, people intervention