HEAD PROTECTION, THE APPLICATION OF MATHEMATICAL MODELLING.

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***Abstract** - U.K. military helmets consist of a fibre reinforced polymer shell combined with a high density foam liner. Such a design provides the wearer with protection against fragmenting munitions and low speed impacts. This paper describes the use of computer models to simulate the response of military helmets to impact conditions. The models have been used to study the influence of helmet design parameters such as; type and thickness of foam liner, shell thickness and head/helmet conformity.*

Introduction.

Military helmets are designed for a number of applications. In addition to a specified ballistic and impact performance, they must meet additional requirements of long-term wear, comfort, stability and maximum coverage with an optimised weight. **Figure 1** lists some of the requirements for current in-service helmets. Whilst these factors are not listed in any particular order, it should be noted that all situations demand impact protection.

Helmets may be used in environmental conditions ranging from the tropics to the Arctic circle. Reliability of helmets is ensured by testing to investigate the effect on mechanical properties of these extremes of temperature and humidity **(Figure 2)**.

Development of Computer Models.

The models were developed under an extra-mural research contract in such a manner as to minimise the materials input data required. The authors of this paper do not presume to take credit for the work carried out nor to embark on a detailed explanation of the mathematics involved. A brief description of the literature on which they were based and the models themselves is, however, pertinent.

Relevant Literature.

The models were developed after the completion of a thorough literature review. Foams are classified by the way that they deform, that is, flexible or rigid. In addition they may act in an elastic, plastic or brittle manner. Generally, flexible foams are elastic and rigid foams fail by the plastic collapse or brittle crushing of the cells. The foam may contain open or closed cells.

Foam morphology has been well discussed in the literature (**Patel and Finnie, 1970**, **Chan and Nakamura, 1969**, **Dawson and Shortall, 1982** and **Menges and Knipschild, 1975**). Foam cells are nucleated as spherical bubbles which expand with increasing pressure. At a gas volume of 76% these bubbles impinge to form irregular polyhedron cells. Low density foams contain angular cells, whilst high density foams contain spherical cells.

The models utilised in this paper are largely based on the work of Ashby which has been published in numerous papers (**Gibson *et al.*, 1980** and **1982**, **Gibson and Ashby, 1982** and **Maiti *et al.*, 1984**). This work is based on a dimensional analysis and has shown that the ration of the cell wall thickness to the length of cell determines the foam mechanical properties. The dominant mechanism for foam linear elastic deformation is the elastic bending of the thick cell walls. In the plateau phase of deformation which dictates energy absorption:

(i) elastic cell wall buckling leads to non-linear elastic behaviour
(ii) plastic collapse is due to the stress exceeding the polymer yield stress value
(iii) brittle crushing occurs when the surface stress exceeds the failure stress

During the densification process, the modulus of the foam is equivalent to that of the base polymer when the voids have been compressed (**Rusch, 1969**). Ashby confirmed that this occurred when the relative density was approximately 0.33.

The compression of a closed cell foam leads to gas compression resulting in a contribution to the total foam stress and may assist in helmet liner recovery (**Rusch, 1970**). The significance of pneumatic damping in energy absorption mechanisms is unclear and it is thought (**Patel and Finnie, 1970**) that at high strain rates viscoelasticity would dominate.

The viscoelastic response of the foam is described using the work of **Rusch** (**1969**, **1970a** and **1970b**) for rate independent response and that of **Meinecke and Schwaber** (**1970** and **1971**) and **Meinecke *et al.*, 1971** for rate dependent responses.

Description of the Models.
The first model, Genfoam, can be used to describe the behaviour of a flat foam specimen under both quasi-static and dynamic impact conditions. The deformation process was considered as a combination of different mechanisms. These were represented analytically as a series of parallel elements **(Figure 3)**. Some of the mechanisms were mutually exclusive whilst others had prescribed limits of applicability. Materials properties required as input data to the Genfoam model are:

(i) the Young's modulus of the solid polymer.
(ii) the relative density of the foam, that is, the ratio between the density of the foam and that of the solid polymer.

These were obtained from foam manufacturer's as confidential information. The behaviour of the complete helmet (shell plus liner) under impact was originally modelled using a finite element process **(Figure 4)**. This detailed representation was designed to investigate the stress-strain behaviour of the helmet components and both the deformed and rigid body motions. Prediction of the influence of design parameters on the impact response proved to be difficult with the finite element model. In particular, mesh collapse was observed when the foam liner was constructed of a soft material. The finite element model was, therefore, used to validate a simpler, more flexible lumped parameter model.

The lumped parameter model (Genhel) incorporates the Genfoam model discussed previously. The following assumptions are made in the Genhel model:

(i) the head and helmet are axisymmetrical, that is, they are defined by a single radius o curvature
(ii) the impactor and the head are stiffer than the helmet

(iii) the foam has uniform thickness
(iv) the liner extends beyond the impact area
(v) the strain distribution in the liner is independent of the amount of loading

The components of the model are shown in **Figure 5** and include:

(i) the impactor mass.
(ii) the helmet shell mass.
(iii) a spring representing the compression stiffness of the foam liner.
(iv) a rigid head form.

Variations on Genhel allow for the vertical impaction of:

(i) a helmet containing a headform onto a flat surface.
(ii) an impactor dropping onto a resiliently mounted headform to represent the interaction of the helmet and skull. It is a gross simplification.

The only material property required as input data to the Genhel model is the Young's modulus of the helmet shell which may be determined using standard techniques.

The Genfoam computer programme stores results as strain, strain rate, total stress and energy absorbed (per unit volume) at each chosen time increment. Parameters investigated by Genhel are; duration and speed of impact, liner type and thickness, and shell thickness, curvature, Young's modulus and mass. Results are presented as; force, acceleration, displacement, deflection and velocity versus time plots.

Validation of Models.

The Genfoam model was validated by comparison of predicted impact responses to those experimentally determined at SCRDE.

Figures 6a and **6b** illustrates such a comparison for a 37J impact on two different foam materials. Good agreement is observed between the simulated and experimental maximum deceleration and duration of response for both materials. Such data justifies the use of the Genfoam model to predict foam response under dynamic loading conditions. Foam A is seen to exhibit both increased deceleration and duration of response compared to Foam B and could, therefore, be rejected from a materials selection procedure. Such plots can, therefore, be used for the screening of possible candidate materials for use as helmet liners.

Genhel was validated by two comparisons. Firstly, a comparison between the response to impact as predicted by the finite element model and Genhel. This was conducted using a relatively stiff liner to prevent the finite element grid from collapsing. Secondly, the Genhel model was compared to experimental data.

Figure 7 compares typical experimental data from a 122.5J impact on a combat helmet to that predicted using the Genhel model. The data is in the form of an impactor acceleration/time curve. All major features of the experimental curve are seen to be reproduced by the Genhel prediction. Excellent agreement is observed between the experimental and predicted maximum accelerations and duration of response. Confidence in both the Genfoam and Genhel models has, therefore, been established.

Mechanism of Loading During Impact.

Initially, Genhel was used to consider one geometry of helmet shell and two different foam materials. This research clarified the mechanisms associated with impacts of 122.5J onto (military) helmets and demonstrated that local bending and rigid body motion occurred. This later feature led to compression of the liner, whilst the interaction of impactor and shell produced the characteristic shape of the measured impacts.

Genhel allows for the prediction of the forces in the helmet and liner and the acceleration, displacement and velocity of the impactor and helmet. **Figures 8-11** illustrate these factors and may be used to describe the sequence of events during impact.

When the impactor hits the shell, displacement of the helmet occurs resulting in impactor deceleration (time period 0.50ms-1.00ms). The light weight helmet accelerates rapidly and it's velocity first equals and then exceeds that of the impactor. The first peak in the force/time curve occurs at the point of equal velocity (1.25ms). The helmet crown begins to flatten and this downward movement is resisted by compression forces generated in the foam liner. This results in retardation of the helmet. The impactor is now travelling at an equal velocity compared to the helmet and this corresponds to the first trough in the force/time curve (2.3ms).

Local shell deformation is caused by the increased velocity of the impactor and the elastic recovery of the foam liner, which pushes the shell upwards. This later mechanism causes the impactor to decelerate. The second peak in the force/time curve occurs when the impactor and shell experience equal velocity (4ms).

The impactor and helmet are now moving away from the headform. If the helmet remains in contact with the headform and more elastic foam recovery occurs, a third peak may be observed. The rebound speed of the impactor is greater than that of the helmet due to the relaxation of residual shell bending.

Influence of Design Parameters.

From the above discussion it is seen that the Genhel model provides a convenient means for examining both design parameters and materials utilised for military helmets. Parameters of particular interest are:

(i) liner material.
(ii) liner thickness.
(iii) headform radius.
(iv) shell thickness.

Each of these factors is discussed for the current combat helmet undergoing a impact of 5kg at 7m/s, that is 122.5J.

Liner material.

Three different foam materials were chosen for assessment. These were designated:

X - high density polyethylene

Y - polypropylene
Z - low density polyethylene

The force/time curves predicted by Genfoam are presented in **Figure 12**. Material X is seen to transmit the minimum peak force to the headform. The remaining materials are all seen to exhibit large impact peak forces due to the densification of the foams. The duration of the forces transmitted by foams Y and Z are similar to half the natural frequency of the period of vibration of the human skull and are undesirable. In addition, the duration of the complete response is longer than observed with foam X. Foam Z is seen to exhibit the worst impact protection of the three foams examined and the impact results in foam collapse. Foam X appears to be the most suitable for use as a (military) helmet liner.

Liner thickness.
Figure 13 illustrates the effect of reducing the thickness of a liner manufactured of material X by approximately 30%. Whilst the average force acting on the headform is not seen to vary significantly, several peaks are observed. The duration of these peaks is similar to half the natural frequency of the skull and are undesirable. At a time period of approximately 6ms, sharp peaks are observed due to the formation of large strains and foam densification. A relatively thick liner is therefore required for adequate impact protection in a typical military helmet.

Head radius.
Altering the headform radius may be used to assess the influence of closeness of helmet fit. **Figure 14** illustrates the effect of a 122.5J impact onto a helmet mounted on a 80mm and a 85mm headform. The increased radius of 85mm has led to an increased peak force and reduced deflection compared to the 80mm headform. The larger contact area would, however, compensate for the increased force and the foam liner will experience a reduced level of stress. This would suggest a reduction in contact pressure on the headform and lead to the conclusion that conformal contact does offer an advantage in impact protection.

Shell thickness.
The Genhel simulated response to an impact for combat helmets of average thickness 5mm, 7mm and 9mm are presented in **Figure 15**. Minimum variation in peak force experienced by the helmet is observed on decreasing the helmet thickness from 9mm to 7mm. However, a reduction of approximately 18.75% in the peak force is observed when the shell thickness is reduced from 7mm to 5mm. Whilst the reduction in the maximum force is desirable, confliction with ballistic protection requirements may occur.

Conclusions.

1. It has been demonstrated that the flat foam model, Genfoam, simulates impact behaviour. The predicted decelerations and duration of response show good correlation to experimental data.

2. The lumped parameter model, Genhel, has been used to successfully predict the response to impact of a combat helmet. All features of the impacts were reproduced. The model was used to predict the variation of force, acceleration, displacement and velocity /time response of the helmet and the impactor.

3. Genfoam has been successfully used to survey available foam materials. The material which displayed the required characteristics of minimum peak force transmitted was a high density polyethylene foam.

4. Genhel was used to identify the influence of design parameters. Prediction suggested that good impact protection requires close fitting shells, relatively thick liners and a reduced shell thickness. However, this later factor may conflict with ballistic protection requirements.

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FIGURE 1. REQUIREMENTS FOR MILITARY HELMETS.

COMBAT	RIOT	PARACHUTIST	TANK CREW	BOMB DISPOSAL
Fragment protective	**Impact protective**	**Impact protective**	**Impact protective**	Fragment protective
Impact protective	Area protected	Fragment protective	Fragment protective	Blast resistant
Compatible	Visor	Weight	Headset compatible	**Impact protective**
Weight	Fire resistant	Compatible	Comfortable	Area protected
Comfortable	Comfortable	Comfortable	Close fit	Visor
Stable	Compatible	Secure fit		Communications
Long life	Cost	Stable		
Cost	Long life	Long life		

FIGURE 2. IN-SERVICE HELMETS.

HELMET	ENERGY (J)	Conditions (+2°C)			Impactor	Positions.
Combat	122	-20°C	+20°C, wet	+50°C	Flat	Crown
Parachutists	163	-20°C	+20°C, wet	+50°C	Flat	Rear + front
Tank crew	122	-31°C	+15°C, dry	+44°C	Flat	Crown
	30	-30°C	5 at +25°C	+44°C	Flat	Crown + front
Bomb disposal	122	-	+20°C, dry	-	Flat	Crown

FIGURE 3. ELEMENTS IN THE GENFOAM MODEL.

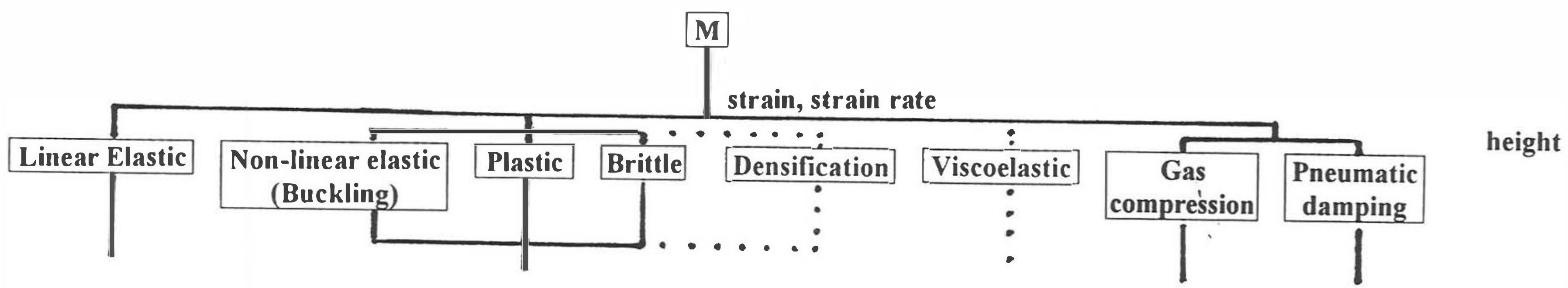


FIGURE 4. FINITE ELEMENT MODEL.

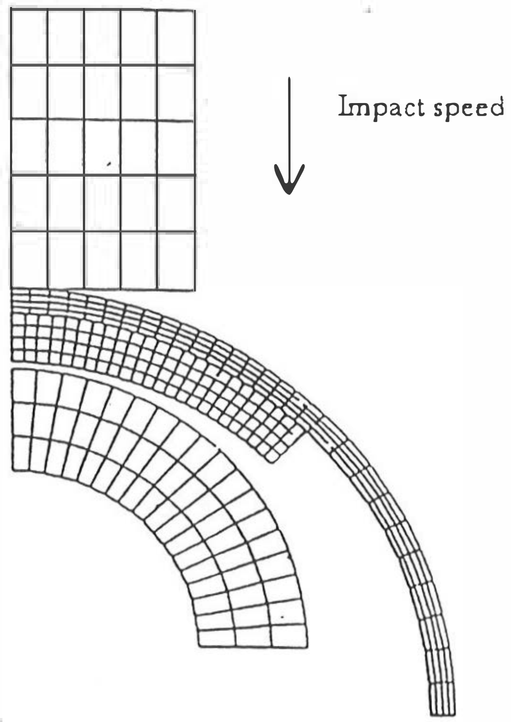


FIGURE 5. LUMPED PARAMETER MODEL.

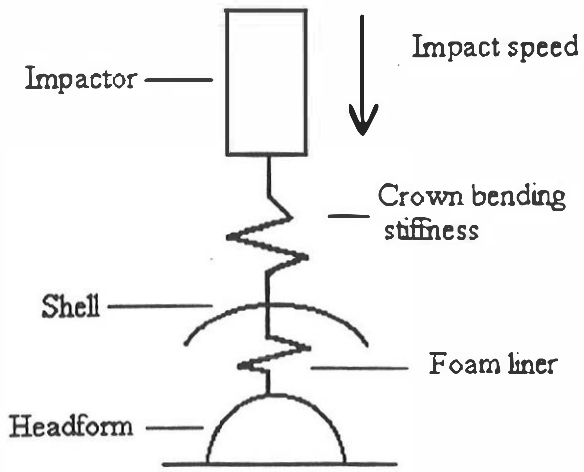


FIGURE 6A. COMPARISON OF PREDICTED AND EXPERIMENTAL DECELERATION FOR FOAM A.

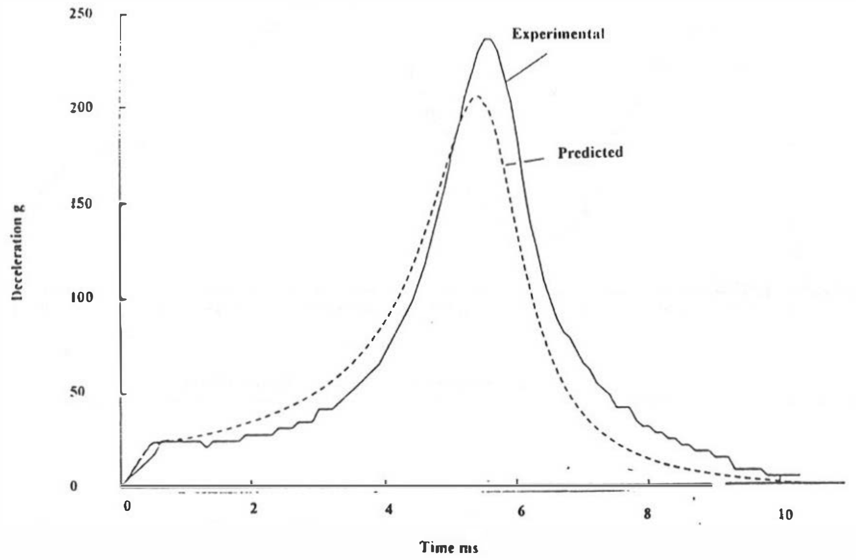


FIGURE 6B. COMPARISON OF PREDICTED AND EXPERIMENTAL DECELERATION FOR FOAM B.

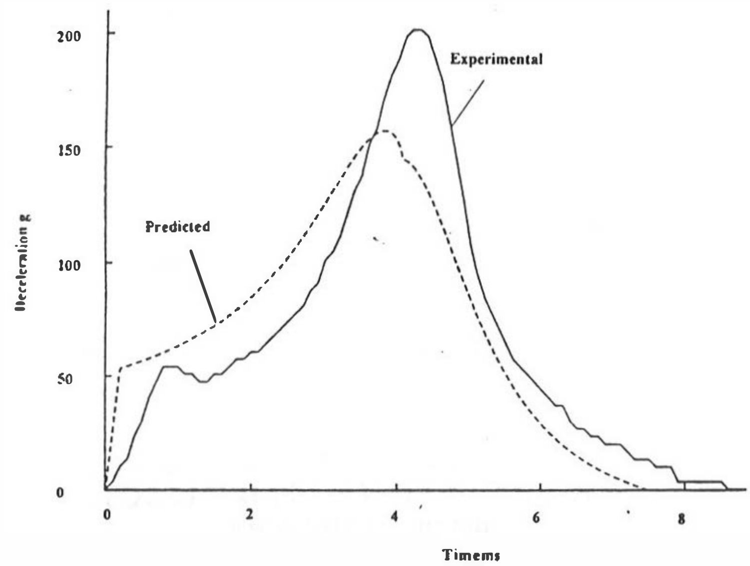
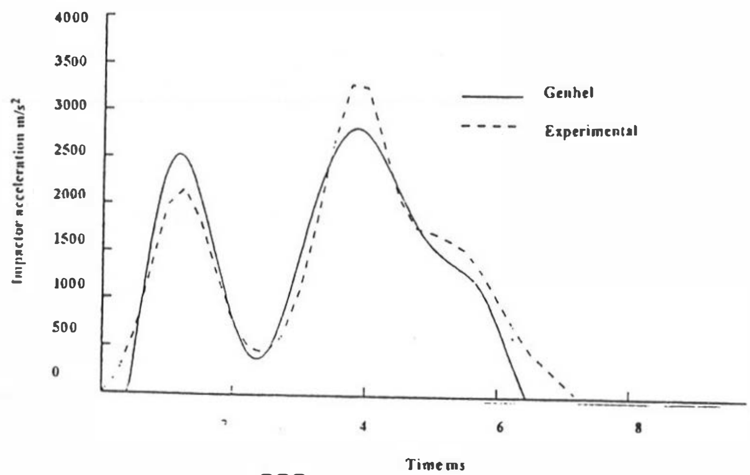


FIGURE 7. 122.5J SIMULATED IMPACT ON COMBAT HELMET.



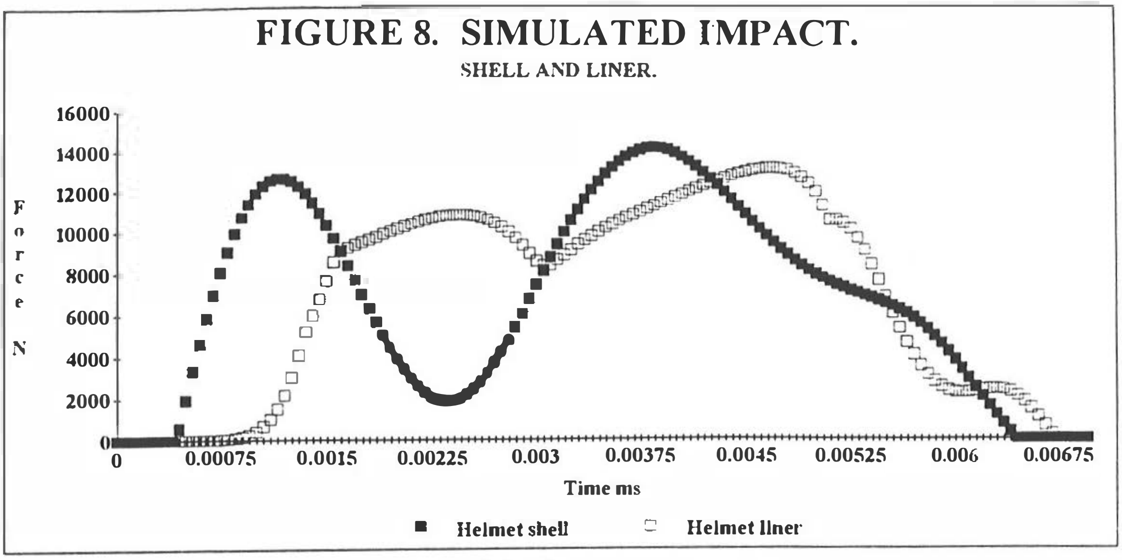


FIGURE 8. SIMULATED IMPACT.
SHELL AND LINER.
16000
14000
12000
10000
8000
6000
4000
2000
0
Force N
0
0.00075
0.0015
0.00225
0.003
0.00375
0.0045
0.00525
0.006
0.00675
Time ms
Helmet shell
Helmet liner

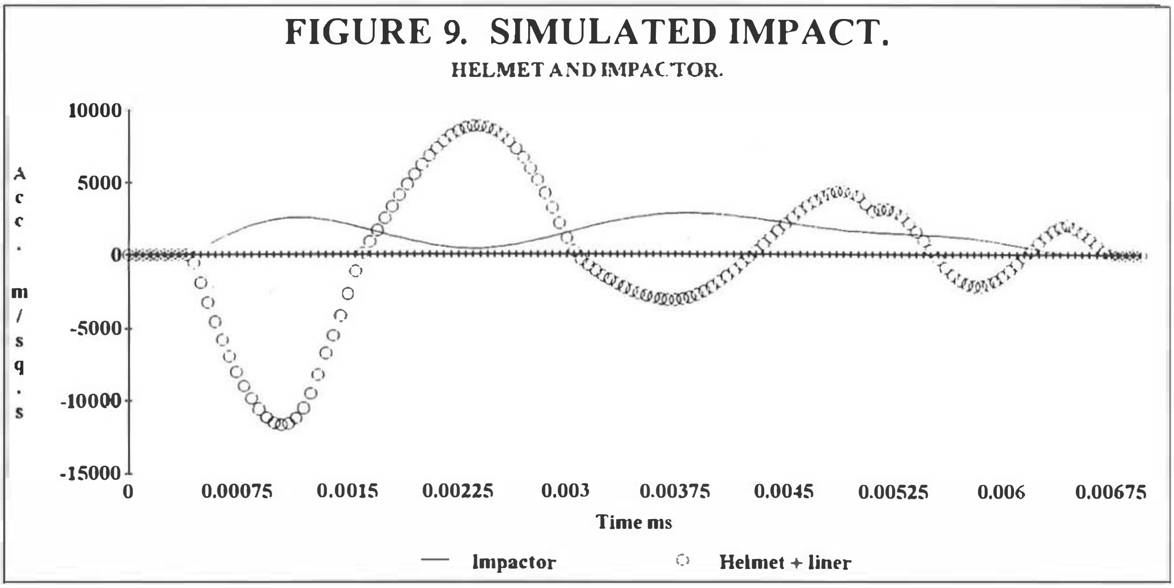


FIGURE 9. SIMULATED IMPACT.
HELMET AND IMPACTOR.
10000
5000
0
-5000
-10000
-15000
Acc. m/sq.s
0
0.00075
0.0015
0.00225
0.003
0.00375
0.0045
0.00525
0.006
0.00675
Time ms
Impactor
Helmet + liner

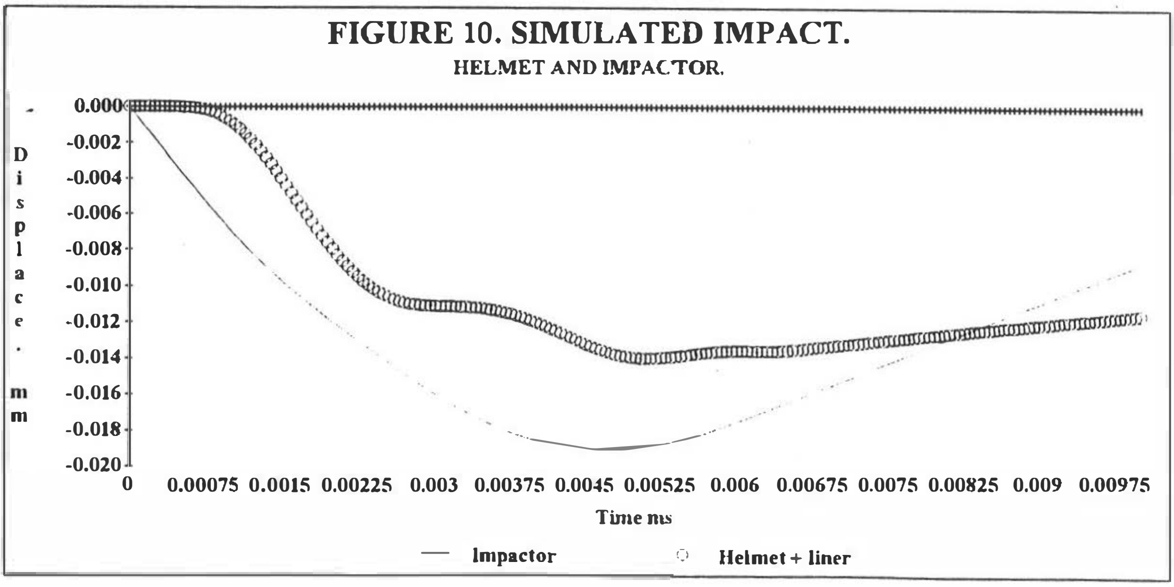


FIGURE 10. SIMULATED IMPACT.
HELMET AND IMPACTOR.
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
-0.014
-0.016
-0.018
-0.020
Displace. mm
0
0.00075
0.0015
0.00225
0.003
0.00375
0.0045
0.00525
0.006
0.00675
0.0075
0.00825
0.009
0.00975
Time ms
Impactor
Helmet + liner

FIGURE 11. SIMULATED IMPACT.

HELMET AND IMPACTOR.

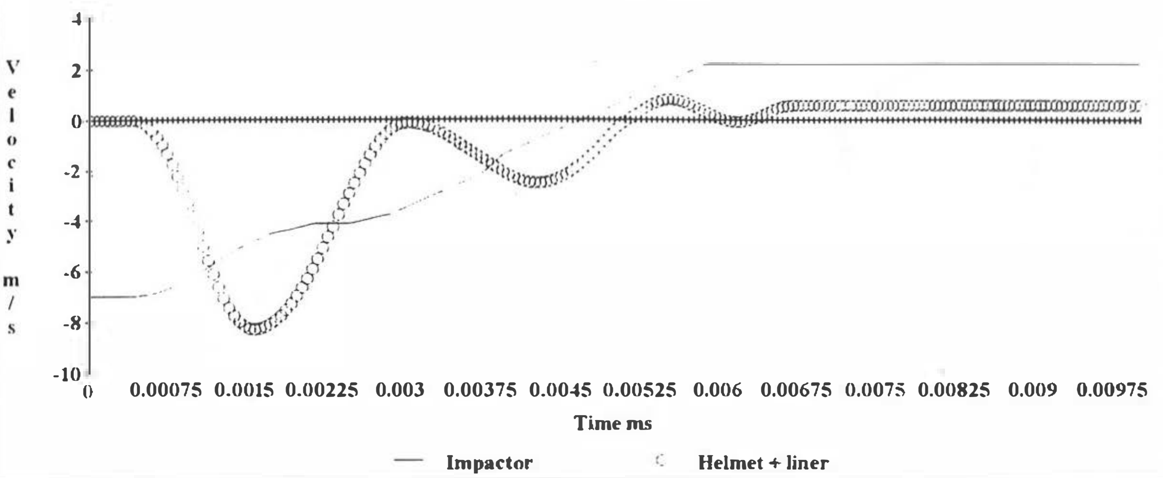


FIGURE 12. SIMULATED IMPACT.

COMPARISON OF FOAMS.

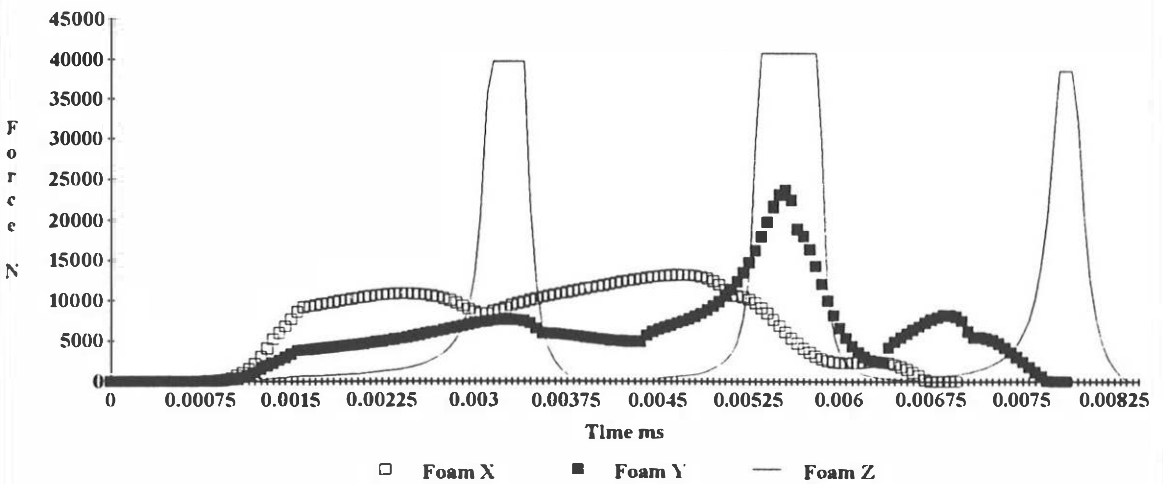


FIGURE 13. SIMULATED IMPACT.

EFFECT OF LINER THICKNESS.

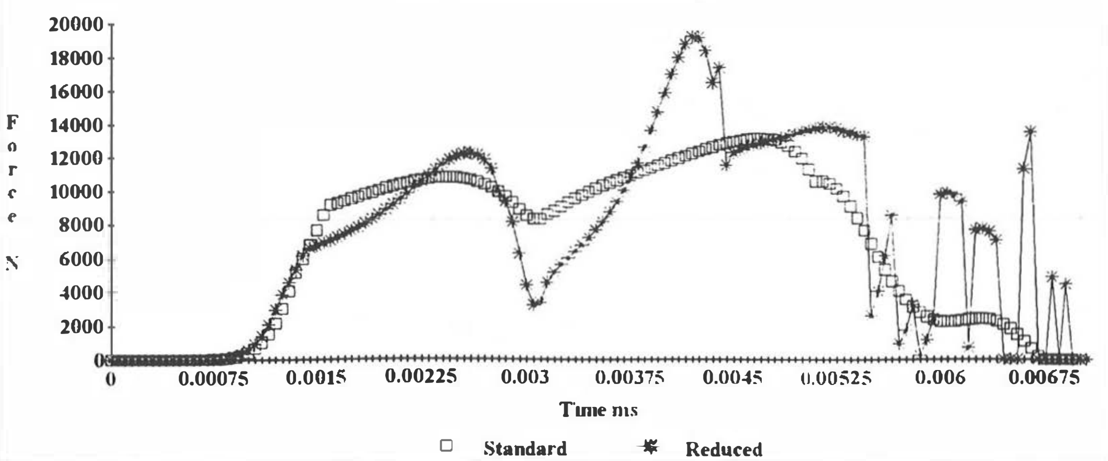
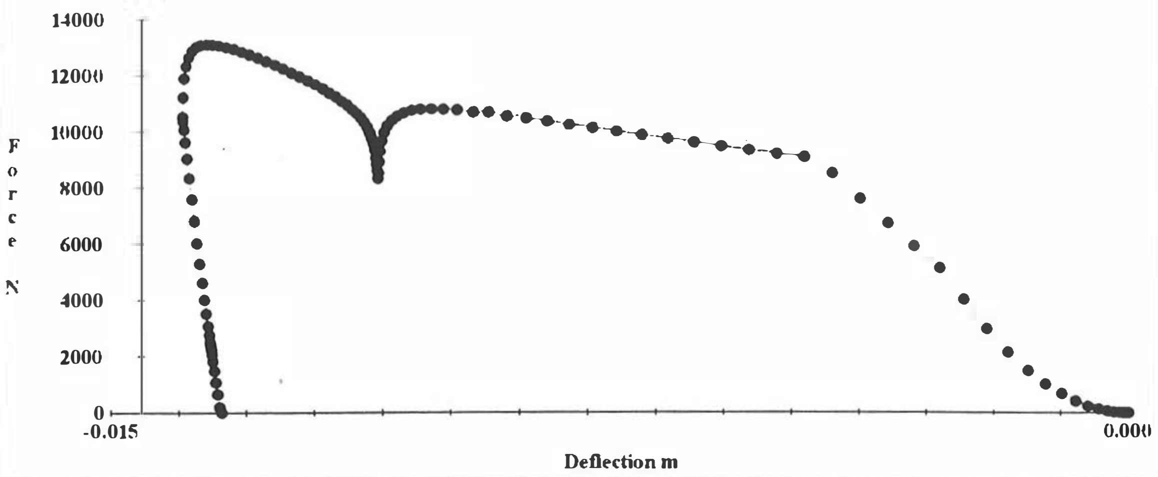


FIGURE 14. SIMULATED IMPACT.

80MM HEAD RADIUS



85MM HEAD RADIUS

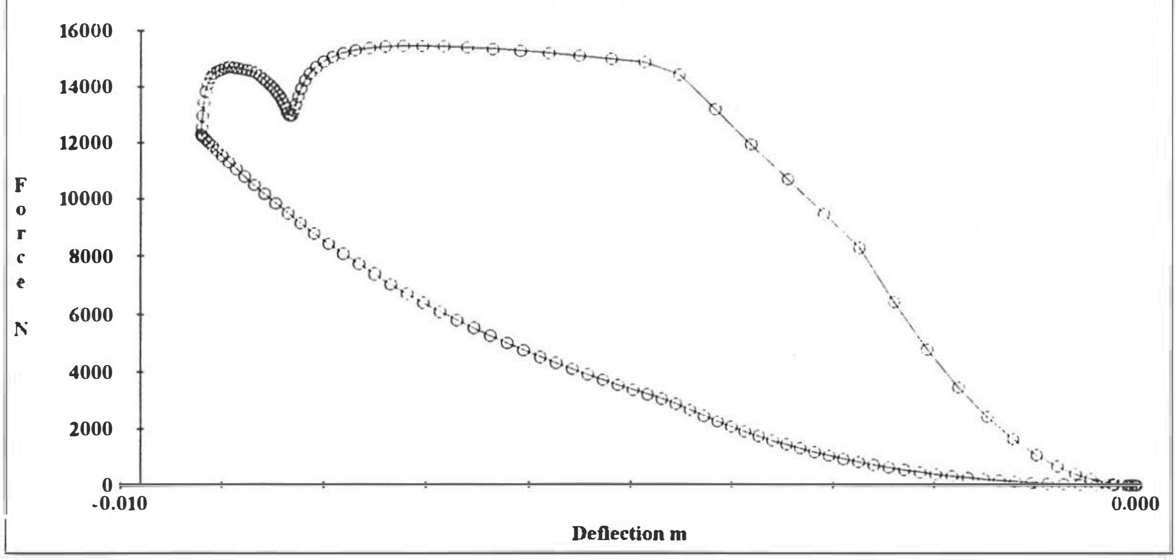


FIGURE 15. SIMULATED IMPACT.

EFFECT OF SHELL THICKNESS, FOAM X