Motorcycle helmet load spreading performance for impacts into rigid and deformable objects

S Chandler, A Gilchrist and N J Mills
School of Metallurgy and Materials
University of Birmingham, U K.

ABSTRACT

There is accident evidence that when a helmetted motorcyclist impacts a deformable steel panel on a car, there may not be any measureable crushing of the polystyrene foam helmet liner. This is especially the case if the helmet shell material is fibreglass(GRP), and if there is double curvature of the helmet shell at the impact site. To investigate this, laboratory impact tests were made in which the headform accelerations, the pressure distributions on both sides of the helmet liner, and the strain distribution in the crushed foam were measured. The helmet construction was varied from the standard thermoplastic shell plus polystyrene foam liner to experimental helmets with a much larger ratio of shell stiffness to foam yield stress. Results show that for the standard helmets the load spreading capacity of the shell is limited and in consequence the liner is crushed over a limited area when the helmet impacts a rigid anvil. For the experimental helmet the area of crushed foam is large, and the pressure distribution is uniform across the projected area of the headform, except for high energy impacts when the foam bottoms out. The optimum foam yield stress for impacts on deformable panels is significantly lower than that currently used, particularly when the foam is inside a relatively rigid GRP shell. The consequence of this for European Standards is discussed.

INTRODUCTION

During 1990 two cases of fatal motorcycle accidents were examined where, despite there being high forces applied to the shell of fibreglass helmets, the polystyrene foam liners were uncrushed. In both cases the main cause of death was fracture of the base of the skull. In one case the rear of the helmet had impacted some part of the door structure of a car, the motorcyclist being stationary when the car struck him from the rear at approximately 60 mph. In the other the fibreglass chinbar of the helmet hit a concrete post at the side of the road. The chinbar remained intact and high forces were transmitted through the rider's jawbone to the base of the skull. His skull was forced back into the rear of the helmet but the liner remained uncrushed. These crashes lead the authors to consider whether the foam chosen for use in motorcycle helmets was ideal for all types of accidents.

Helmet designers empirically select the density and thickness of the polystyrene foam to meet the impact tests in the test standard, which are at one velocity (5 to 8 ms^{-1} depending on the standard) onto rigid flat and hemispherical anvils. Other researchers have shown that liners of motorcycle helmets are not optimised for impacts on to rigid flat surfaces; Grandel & Schaper(1987) showed that for side impacts at 8.9 ms^{-1} the peak acceleration could be reduced by replacing the polystyrene liner in a helmet by polyurethane foam or by 'Hexcel' honeycomb. Kostner & Stocker (1988) used a ring element computer model to predict that, for a crown impact at energies up to 150 J, a helmet with a low polystyrene density of 32 kg m^{-3} and a thin 3 mm shell would give lower peak acceleration values than current designs with a 60 kg m^{-3} foam density and 4 mm shell thickness. We have considered the deformation mechanisms in the helmet shell and polystyrene liner(Mills and Gilchrist 1991) and concluded that it is impossible to optimise the foam for all types of objects hit.

The aim of this research was to provide experimental evidence of the pressure distributions across the inside of the helmet liner in impact tests on to different classes of objects. By doing this for different shell materials and foam liner characteristics it is possible to verify the theoretical models of load spreading in helmet impacts.

HELMETS USED

The selection of helmets was made to cover the range of possible design charactaristics. The factors that increase the spreading of the impact load across the headform are many; they include

a the impact site - the double curvature of the crown of a helmet makes the shell stiffer and more able to spread load. When a force is applied near the rim of the helmet the proximity of the unconstrained edge makes the shell more flexible.

b the relative stiffness of the shell and foam materials - the bending stiffness of the shell is related to the stiffness of a beam made from the same material, in that it depends on the product of the in-plane Youngs modulus and the cube of the shell thickness. The compressive yield stress of polymer foams depends on both the nature of the polymer and the foam density raised to a power between 1.5 and 2.

c the shape and stiffness of the object impacted - in terms of national helmet tests the rigid steel anvil of 50 mm radius is the most likely to concentrate the impact forces on the headform.

Two extremes of helmet construction were selected initially to mark out the limits of behaviour.

The first is representative of current motorcycle helmets having thermoplastic shells. The full face shell had been injection moulded from 4 to 5 mm thick ABS. In the latest BS 6658 helmets the foam liner is often modified in the crown region by cutting out some of the foam and sometimes using an insert of a softer foam. To avoid this complexity the earlier BS 2495 helmets were used as they had a uniform foam construction. This helmet by virtue of its relatively soft shell and rigid foam liner should tend to concentrate the impact forces. The 56 kg m^{-3} density polystyrene foam has an initial yield stress of 0.7 MNm^{-2}.

The second is an experimental construction in which a very stiff Kevlar / epoxy composite shell is combined with a lower yield stress low-density polyethylene foam. The shell uses 0^o / 90^o woven prepreg and has a thickness of 2.2 + 0.2 mm. The 70 kg m^{-3} density foam has an initial yield stress of 0.29 MNm^{-2}. As the shell has 4 times the bending stiffness of the ABS thermoplastic shell and the foam yield stress is half that of the polystyrene foam, the ratio of shell bending stiffness to foam yield stress is 8 times the standard value.

PRESSURE VARIATION OVER THE HELMET SURFACE

Attempts to measure the pressures continuously using piezoelectric PVDF film transducers were unsuccessful because there were spurious signals which swamped the pressure response if the film was bent. Consequently the pressure sensitive film made by Fuji Photo Co Ltd under the name Super Low Pressure Prescale film was used. This consists of two coated films, placed in contact, that develop an increasing degree of redness as higher surface pressures are applied. It was necessary to calibrate the film dynamically with the foam under test, as the texture of the foam affects the appearance of the Prescale film after impact. Polystyrene foam is moulded from expanded beads. The outline of the bead boundaries were visible after the foam was calibrated by a falling flat steel anvil impacting a sandwich of the polystyrene foam, the Prescale film, and an ABS sheet supported on a flat steel table. For the LDPE foam which is made by the BXL process of expanding extruded LDPE sheet there is no bead structure but the Prescale film shows a pointilliste response. Calibrated samples of film were used for visual comparison with the films from helmet tests. It had been hoped that a scanning densitometer would provide graphical output of pressure against position, but there were problems of spurious marks(creases in the film or rubbing of the two layers when inserting the liners into the helmets) and the fine scale texture of the pattern (fig 1) being recorded by the densitometer.

For the helmet impacts the Prescale film was mounted on the inside of the foam liner and, for the stiffer polystyrene foam, between the helmet shell and the liner. This enables the contribution of the liner in spreading the load to be investigated. As the polystyrene liner consisted of two pieces joined along the median plane, it was possible to inscribe a 5 mm grid of lines on the joint surface. This could then be examined after the impact (fig 2) to identify the region of permanent plastic deformation. Polystyrene foam recovers considerably from the maximum strain in the impact (Gale and Mills 1985) so the permanent strain does not represent the maximum strain.

The helmet test rig for the ABS helmets was based on the United Nations Regulation 22/02 impact test which is used in the draft European standard prEN 398. The magnesium alloy headform was supplied by UTAC. It contains a triaxial accelerometer supplied by Kistler. The acceleration time traces were captured by a Burr Brown data acquisition board in an IBM microcomputer. The traces were filtered after capture by the use of a FIR filter with a cutoff frequency of 2.2 kHz; this was necessary because the magnesium headform resonates at a frequency of 5 kHz. The force on the headform was calculated from the vector sum of the acceleration components multiplied by the 4.732 kg mass of the headform. Although there can be some rotation of the headform after the impact, the motion is sufficiently rectilinear, before the headform comes to a halt, for the double integral of the acceleration to be used to calculate the position of the headform. Hence it is possible to compute headform force versus helmet shell deflection graphs. The headform falls vertically and is guided before the impact by a frame; it is free to rebound after the impact. The initial tests on the Kevlar shells were carried out while the helmet was supported on a fixed aluminium headform and hit by a flat striker.

Impacts on to a steel hemisphere of radius 50 mm

For the ABS helmet on the hemispherical anvil the headform force versus helmet shell deflection graphs are linear (fig 3) while the force is increasing. The slope of the linear portion is 333 N/mm which is similar to the values measured for bicycle helmets(Mills 1990). Although this motorcycle helmet has a much thicker shell than the typical 2 mm for a bicycle helmet the shell is only sufficiently stiff to double the slope of the loading curve due to the polystyrene foam. The measurement of the force on the headform rather than the anvil means that force oscillations, associated with the mass of the shell vibrating on the elastic foam liner, are absent.

The pressure distributions across the liner of the ABS helmet (fig 4) show a concentration of pressure on a disc of radius 40 mm. Contact marks on the outside of the shell show that a radius of 20 mm was in contact with the anvil, so the shell has caused the yielded area of the foam to be 4 times larger than the contact area. Within the 40 mm radius the pressure is uniform; there is no central pressure peak that would occur if the foam had bottomed out and there was solid polystyrene between the headform and the shell. The pressure on the inside of the liner is smaller than that on the outside (except at the rear site) showing that the bending stiffness of the liner has transferred some of the impact force to surrounding areas of the headform. The deformation grid for these impacts (fig 2) shows that there is uniform strain through the thickness of the foam, rather than the outer layers being crushed more than the centre.

For the Kevlar fibre helmet impacting the hemispherical anvil at 7.7 m/s two types of result were observed. Either the force remained less than 5 kN and the maximum pressure on the Prescale film was less than 0.6 MPa, or the foam bottomed out and the force rose rapidly to more than 11 kN. In the former case the calculated maximum deflections were about 55 mm compared with the 36 mm foam thickness, but there was noticeable rotation of the headform after impact. In the latter case there was a disc of 20 to 30 mm diameter over which the pressure exceeded 6 MPa, showing that the strain in the foam was at least 95% - these results occurred either at the front of the helmet where the foam is only ~30 mm thick, or for an impact at the the top of the helmet where the headform rotated less after impact.

Impacts on to a flat steel plate

For the Kevlar helmet hit on the crown by the flat anvil the main features of the striker force versus helmet shell deflection graph(fig 5) are large force oscillations, that are the result of the

500g shell mass oscillating on the LDPE foam. The response is similar to that for crown impacts on industrial helmets, where the response has been successfully predicted by a spring and damper model(Mills et al 1988). There is a uniform pressure for a distance of 140 mm across the headform (fig 6); the lower pressure at the centre is due to a slight dip in the liner at that point. The headform is effectively compressing the liner from the inside rather than the outer shape of the shell changing with the impact. Hence this helmet behaves differently to the ABS one.

Impacts on to a deformable steel panel

For the ABS helmet hitting the centre of a car door panel, the headform force versus helmet shell deflection graph(fig 7) shows that the panel deforms by 100 mm without the force rising above 2.5kN. This low force is not enough to cause much yielding of the polystyrene foam liner; the pressure distribution graphs(fig 8) show that the pressure has exceeded the yield pressure only close to the impact points(one at the front and one at the crown). The grid marked on the helmet liner edge shows no permanent strain so the maximum strains must have been low. The magnesium headform has a smaller radius of curvature than the inner surface of the polystyrene liner so the contact area between the two bodies is not that large.

It is expected that there would be a uniform high pressure for a more severe impact of this kind.

COMPARISON WITH THEORETICAL MODELS

The two models of the deformation mechanism are :-

1 Flexible shell, so the foam contact area is determined by the headform and anvil geometry

The contact geometry between a flat impactor and the spherical outer surface of the foam liner is shown in Figure 9a. So long as the amount of liner crush x is much less than the radius of curvature R_1 of the spherical outer surface of the helmet, or R_2 the radius of the anvil, then the contact area A is given by

$$A = 2\pi x\left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1} \qquad (1)$$

This equation will only be accurate for soft shell helmets; a stiff shell cannot bend to the small radii required at the edge of the contact area when $R_2 = 50$ mm, so A becomes the area over which the foam yields. It is assumed that this latter area is proportional to the true contact area.

It is assumed that the foam has a constant yield stress σ_y. The force transmitted by the foam is

$$F = 2\pi x\left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1} \sigma_y \qquad (2)$$

so long as the strain is increasing. Once the foam begins to unload the force drops rapidly as the cell walls do not fully recover from their buckled state. Substituting typical values of R_1 = 100 mm, R_2 = 50 mm, σ_y = 0.7 MNm^{-2} for the front of a motorcycle helmet liner into the equation gives an effective foam 'spring' constant on loading of

$$K = F/x = 146 \text{ N/mm}$$

The fact that the experimental value of 333 N/mm is more than double this confirms that the yielded foam area is larger than that predicted by equation 1.

2 Rigid helmet shell, so the foam contact area is equal to the projected area of the headform

When the top or rear of a motorcyclist's helmet hits a thin steel panel on an automobile, the panel will deform at first more readily that the shell of the helmet. In doing so it will absorb some of the kinetic energy of the impact. However eventually the panel will be bent and stretched into a stable concave shape (figure 9b), and the force on the outside of the helmet shell will rise. The force exerted by the motorcyclist's head on the **inside** of the foam liner can be calculated. For a polystyrene foam of yield stress 0.7 MNm^{-2}, and the 20,000 mm^2 projected area of the back of a skull of 590 mm circumference, the force required to initiate yielding from the inside of the liner is 14 kN. This assumes that the area of yielding is the same as the projected area of the skull. Impacts into deformable panels to verify this prediction would require impact velocities of the order of 20 m/s. It is intended to carry out these higher energy impacts. So far it has been shown that the steel panel itself absorbs a large amount of energy at a low force that would not cause head injury.

DISCUSSION OF RESULTS

Impacts of thermoplastic shelled motorcycle helmets onto rigid anvils can be successfully modelled by the 'flexible shell' model of the last section. The pressure measurements show that the yielded area of the polystyrene foam is the same on the interior as on the exterior of the foam, confirming the geometrical assumptions in fig 9a. This type of helmet requires a high yield stress foam liner to meet the hemispherical anvil impact test in standards, because the shell has a limited load spreading capability. The experimental helmet with the stiffer Kevlar / epoxy shell is much better at spreading the load from impacts with rigid anvils. This is due to the higher ratio of the shell bending stiffness to the yield stress of the foam. Modelling of the helmet's impact behaviour cannot be done using the 'flexible shell' model as the area of compressed foam is large; there is also the phenomenon of force oscillations when the impact is with a flat anvil.

Impacts of the helmets at 7 m/s into car doors only show that the door deforms plastically at a low force of a few kN.Higher impact velocities would be needed to confirm that the polystyrene liner will not crush at forces below 15 kN(headform accelerations of 300 'g'). However if the external structure of vehicles deformed extensively for forces below 10kN when impacted by a helmet then the performance of the helmet foam is of secondary importance.

DISCUSSION OF OPTIMUM HELMET DESIGN

The test impacts on fullface motorcycle helmets in prEN 398 are at high energy levels of 150-170J. Currently foam thicknesses of up to 40 mm are used. There are other requirements, such as one for a penetration anvil with a 60° conical nose and a tip radius of 0.5 mm not to hit the headform when a 90 J impact is imparted to it (BS6658, 1985). This is one reason for UK thermoplastic helmet shells being so thick. This then means that in regions of the helmet where there is double convex curvature the shell itself is very stiff. Most UK manufacturers cut away, or replace with softer foam, some of the polystyrene foam in the crown of the helmet to solve this problem. If a impact test with a deformable flat panel, or alternatively with a concave rigid anvil, was introduced to cover the problem illustrated in fig 9b, then it would be impossible to meet this test requirement with current designs. The calculated force for the crushing of the polystyrene foam at the rear of the helmet of 14 kN means that the acceleration of the 5 kg head is 280 'g'. This is too close to the failure limit of 300 'g', and the 20,000 mm^2 projected area of the side of the headform would cause an acceleration exceeding 300 'g'.
If lower density polystyrene foams were used then a different mix of test responses could be achieved (fig 10). A foam liner with a yield stress of 0.35 MNm^{-2} would, when the helmet side hit a deformable flat panel, crush from the inside at a force of about 9 kN. Given that the foam was 40 mm thick then for an impact on a rigid flat surface, a helmet with a side radius of 170 mm would by equation (2) have a linear loading curve of slope 375 N/mm that is near optimal; this would allow a 133 J impact to be absorbed safely. However the hemispherical impact test could not be met; impact energies in excess of 45 J would cause excessive head acceleration. The conclusion is that one of the test requirements must be relaxed.
In the draft European CEN motorcycle helmet standard prEN 398 the penetration test is proposed at an energy of 30 J (rather than the 90 J in BS 6658) which will allow thinner shells to be used. Nevertheless the Standards committee must decide which of the potential risks to motorcyclists is greatest, and set test requirements that save as many lives as possible. For instance a survey by Otte et al (1984) showed that the most frequent impact sites were at the front and sides of fullface helmets, with very few impacts on the crown. It is ironical that UK manufacturers have modified the design of the crown of the helmet to meet BS6658. Accident statistics from Birmingham showed that it was extremely rare (2 of 52 cases) for a motorcylist to hit a sharp pointed object (Pedder et al, 1982). Further statistics might persuade the Standards committees to reduce the energy levels for the rigid hemisphere anvil impact test, and introduce a deformable panel test or a test with a concave anvil representing a deformed panel.

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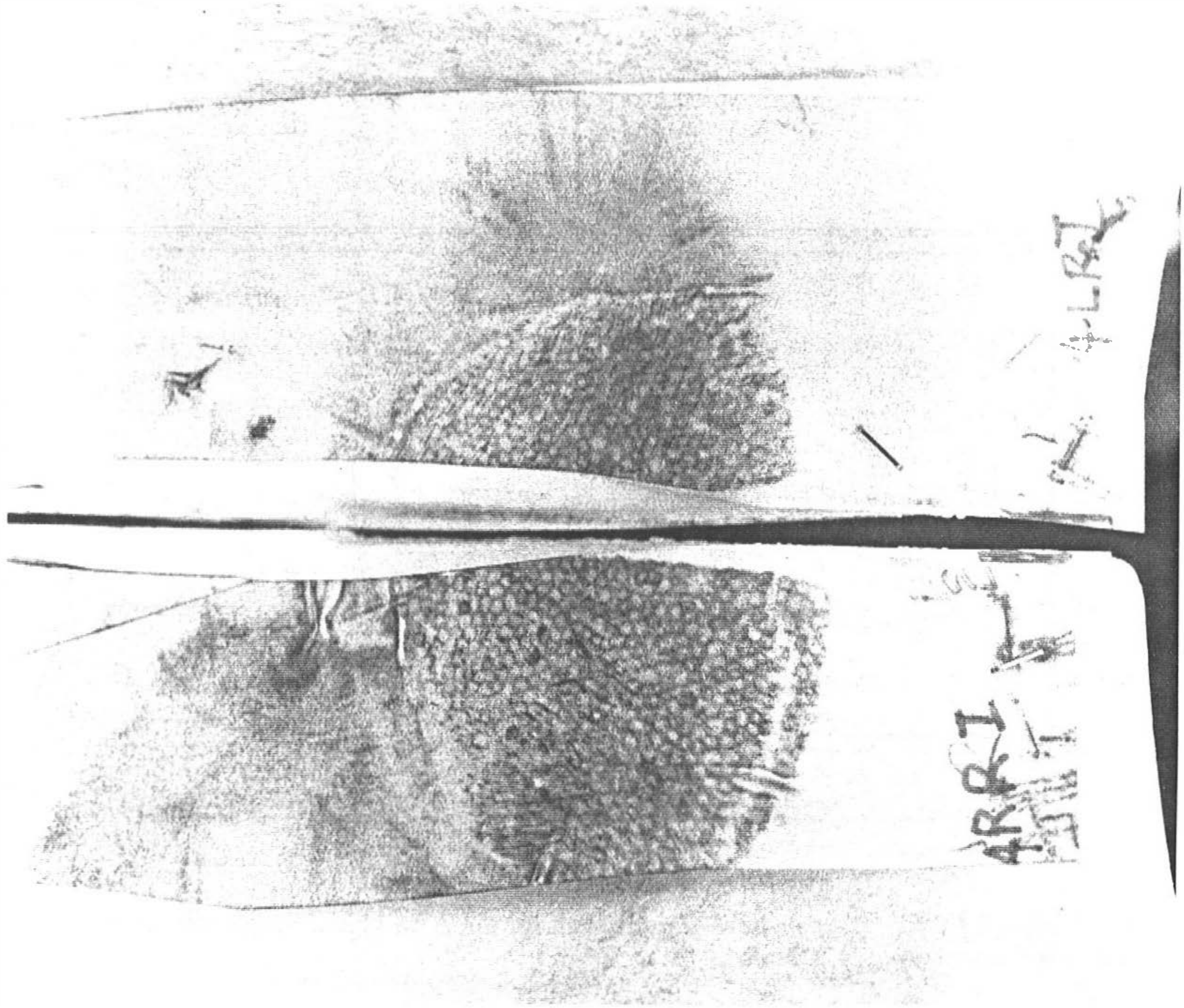


Fig. 1 The Fuji prescale film on the outside of the polystyrene liner, after a frontal impact of an ABS helmet onto a hemispherical anvil. magnification X1

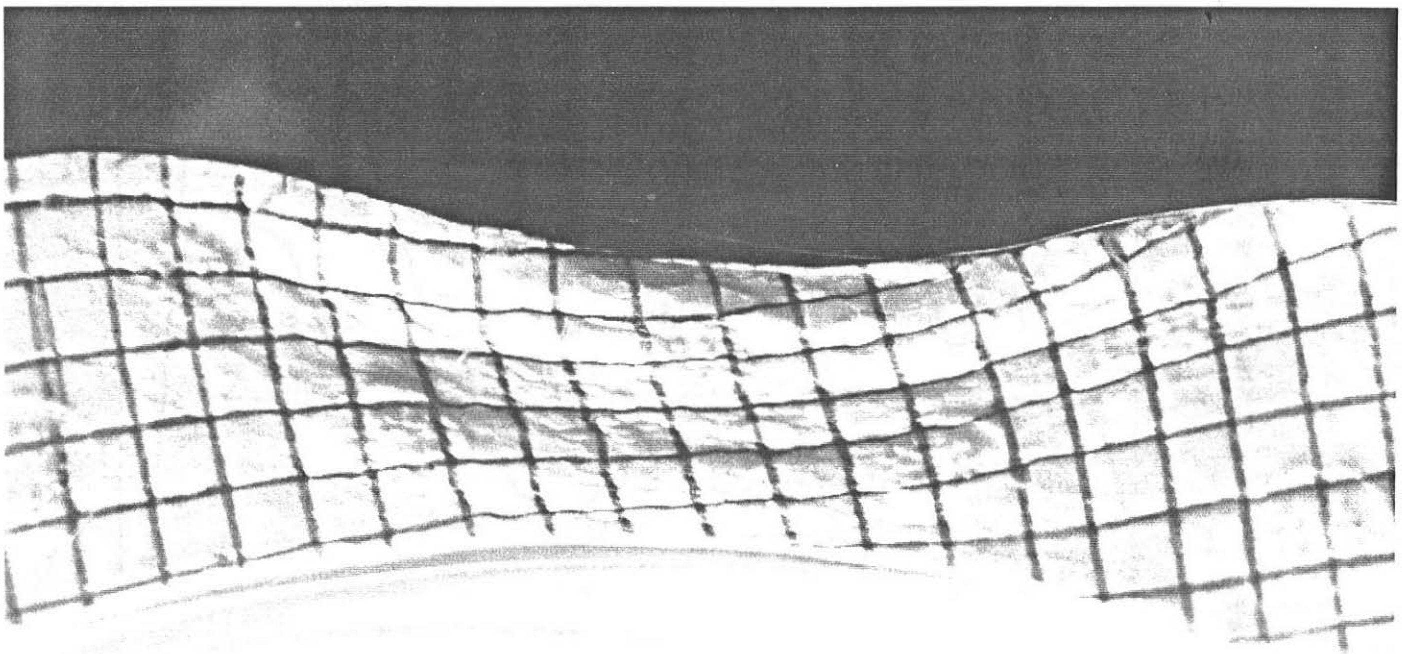


Fig. 2 The deformed grid on the side of the polystyrene liner (as in fig 1) magnification X2

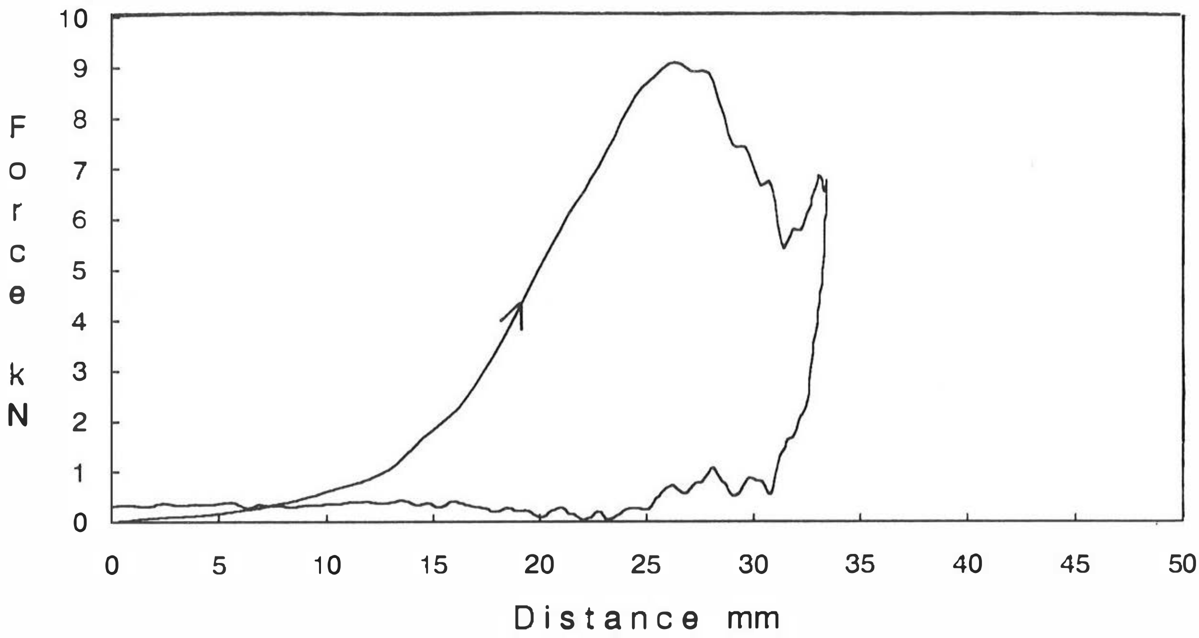


Fig.3 Headform force versus helmet deflection for the ABS helmet impacted at the front onto a hemispherical anvil at 7.2 m/s

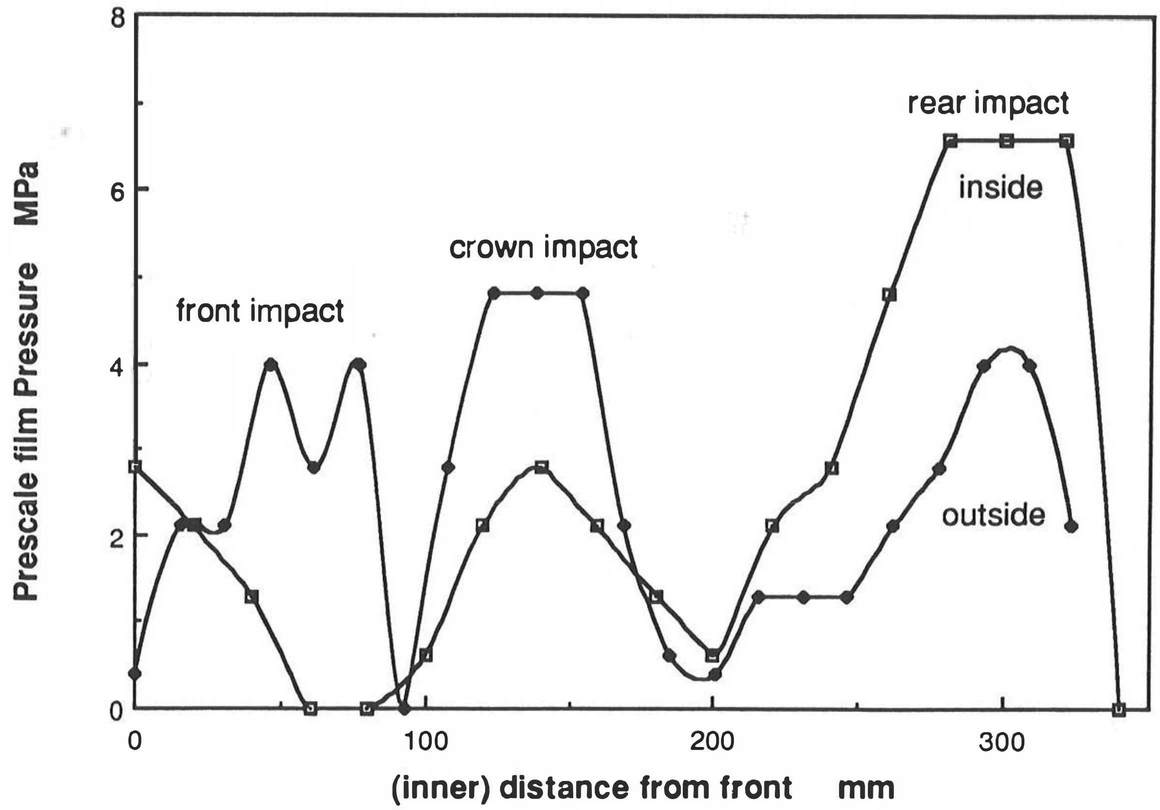


Fig. 4 Front to rear pressure distribution on the median plane of a polystyrene liner. The ABS helmet shell has impacted a hemispherical anvil three times at 7.2 m/s.

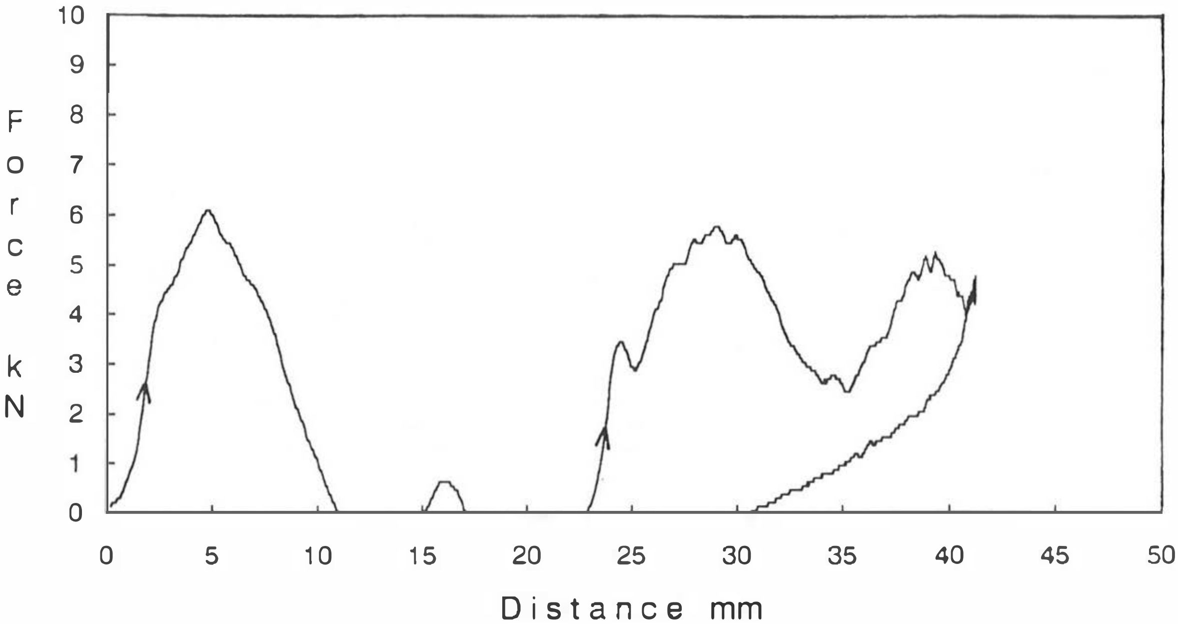


Fig. 5 Striker force versus helmet deflection for the Kevlar helmet impacted on the crown by a flat anvil at 7.0 m/s.

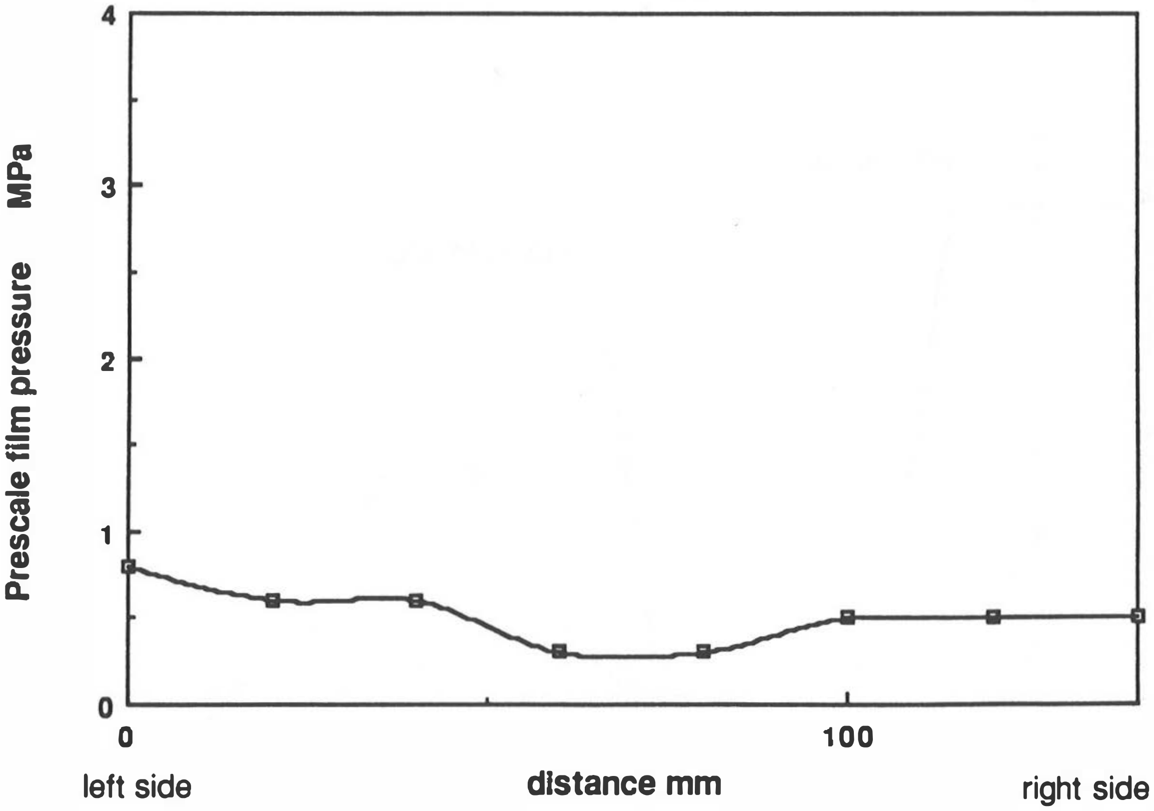


Fig. 6 Side to side pressure distribution across the LDPE liner for the impact shown in fig 4.

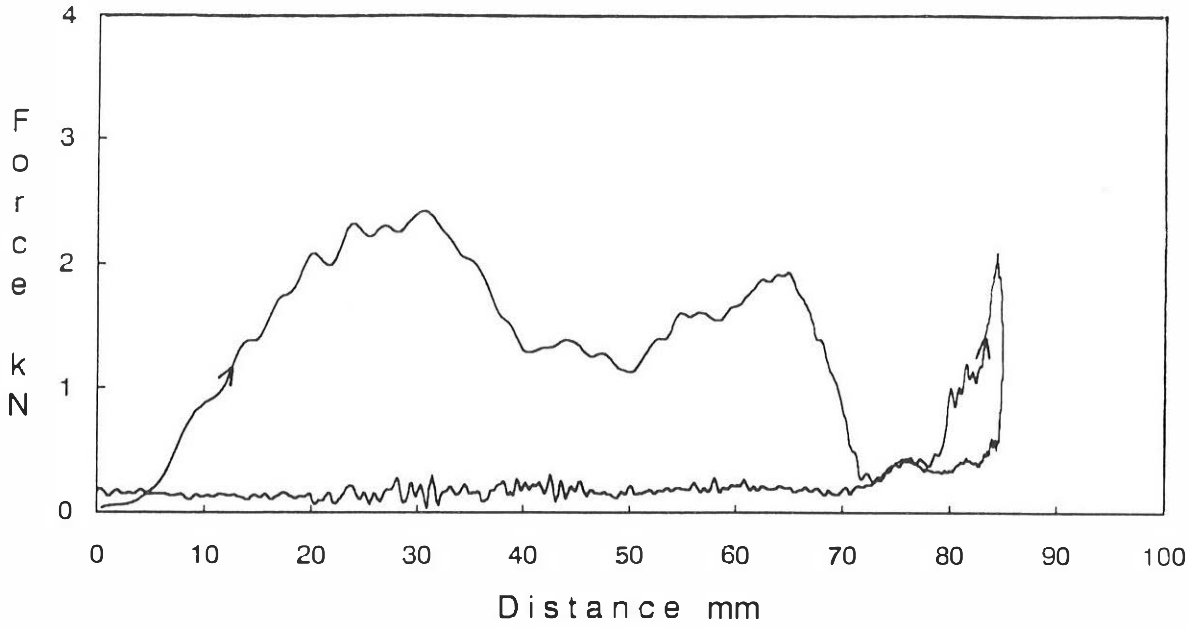


Fig. 7 Headform force versus helmet deflection for the front of an ABS helmet impacting the centre of a car door at 7 m/s.

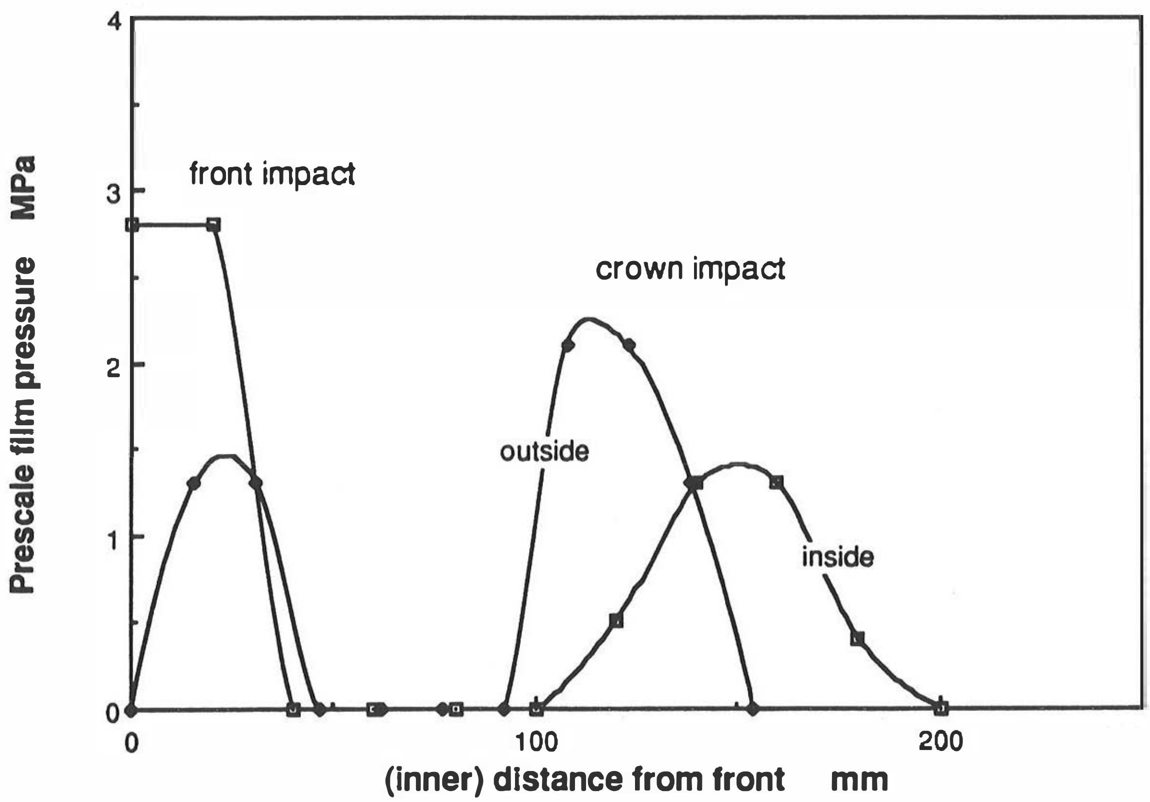
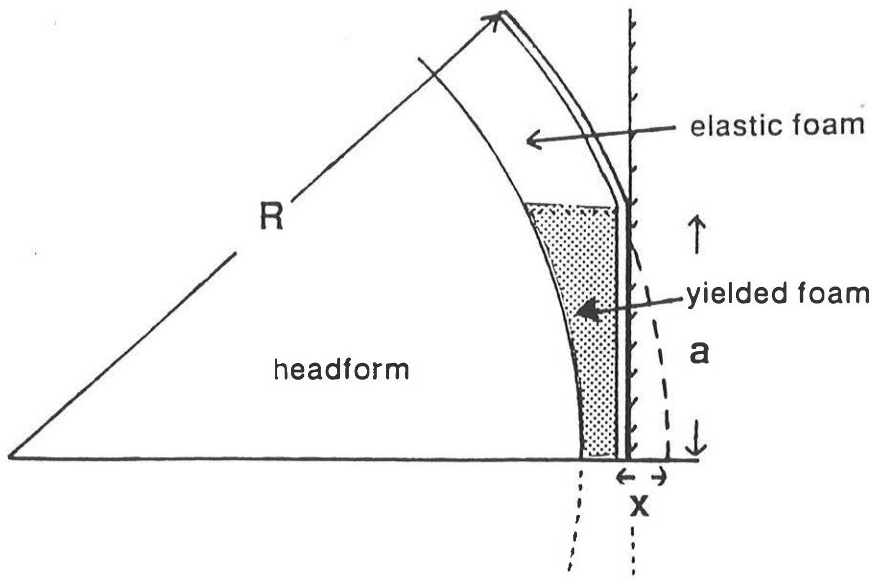


Fig. 8 Front to rear pressure distribution on the median plane of a polystyrene liner. The ABS helmet shell has impacted the centre of a car door twice at 7.0 m/s.



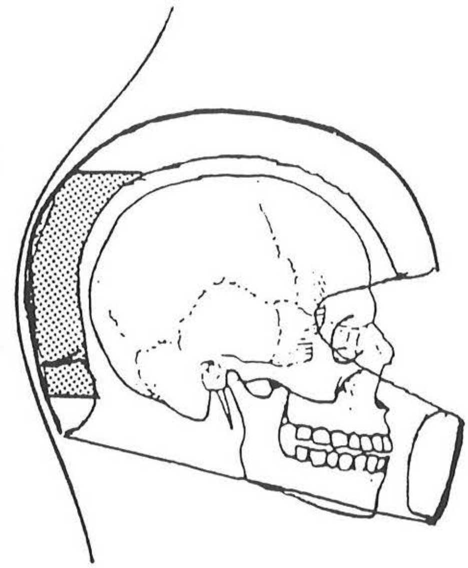


Fig. 9 The contact geometry between
a) a flexible shell helmet and a flat anvil:- **R** is the shell radius, **a** is the contact area radius, and **x** is the foam crush distance.
b) Rear of a fullface motorcycle helmet impacting a deformable metal panel.

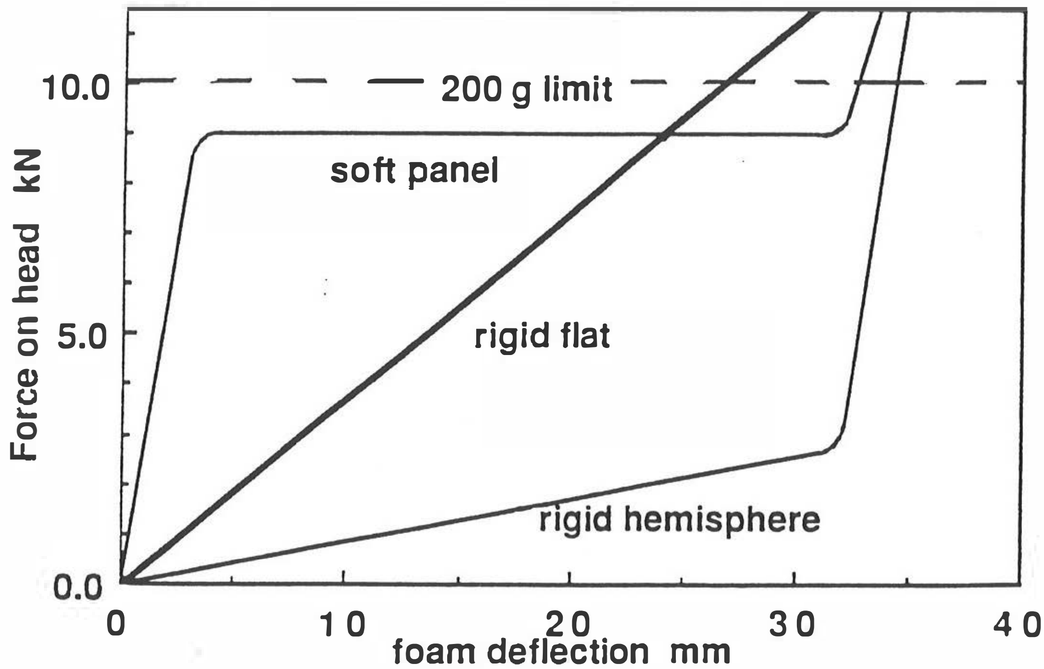


Fig 10 Design force deflection relationships for the side of a motorcycle helmet, with 40 mm of polystyrene foam of yield stress 0.35 MNm^{-2}, hitting three types of object.