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The Development of a Protective Headband for Car Occupants

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The Development of a Protective Headband for Car Occupants

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Abstract

This report addresses the development of a protective headband for car occupants. It focuses on the investigation of suitable materials for the headband by examining their impact absorbing properties. Tests consisted of: a series of impacts where material was interposed between a steel slab and the headform dropped from a height; a series a of drop tests where prototype headbands were attached to a headform and dropped against standard helmet testing anvils; and a series of tests with the most promising prototypes in which the headband was attached to the headform and then fired against an internal structure of a passenger car. Two prototype concepts appear worthy of further investigation: a headband constructed of polyurethane foam and a headband consisting of a cardboard honeycomb liner encased in a hard shell both significantly reduced the severity of impacts with the car structures. However, further investigation into optimising the selection of materials for their impact absorbing qualities and their comfort and durability in normal use is warranted. These tests demonstrate that a headband for car occupants could significantly reduce the severity of certain head impacts in a crash. The best prototype headband reduced the HIC and peak acceleration values by over 60 percent in a standard test with the interior of the car. The reduced impact was approximately equivalent in severity to an unprotected impact with the structure at half the speed.

Keywords

HEADBAND, HELMET, OCCUPANT PROTECTION, HEAD INJURY, PADDING, IMPACT

Executive summary

In 1997 McLean et al. (1997) demonstrated that energy absorbing headwear for car occupants might be effective in reducing the numbers of head injuries sustained by car occupants. The estimated benefits were greater than the estimated benefits of padding of the upper interior of vehicles to the requirements of the US Federal Motor Vehicle Safety Standard 201. This report investigates the suitability of selected materials for head protection, in the form of a headband that could be worn by car occupants.

The study is divided into three phases. Phase 1 surveys materials with a range of properties and impact behaviours. Impact tests provided the data by which assessments were made of the materials' effectiveness. The tests in this phase showed that a range of materials were able to attenuate the severity of the impact to a reasonable degree.

The materials identified in Phase 1 were tested further in Phase 2. Prototype headbands were constructed and attached to instrumented headforms which were dropped onto standard helmet testing anvils. The purpose of these tests was to examine the prototypes' response to concentrated loading. Several prototypes showed themselves to be unable to perform adequately in these tests; the anvils split or shattered the headband. Several prototype designs did perform well in Phase 2. These designs were tested in simulated head strikes with vehicle structures in Phase 3.

Phase 3 consisted of a series of preliminary tests in which a headform, protected by the prototype headband, was fired toward an interior structure that commonly causes head injury to car occupants in crashes.

Two prototype concepts appear worthy of further investigation. A headband constructed of polyurethane foam and a headband consisting of a cardboard honeycomb liner encased in a hard shell both significantly reduced the severity of impacts with the car structures. However, further investigation into optimising the selection of materials for their impact absorbing qualities and their comfort and durability in normal use is warranted.

These tests demonstrate that a headband for car occupants could significantly reduce the severity of certain head impacts in a crash. The best prototype headband reduced the HIC and peak acceleration values by over 60 percent in a standard test with the interior of the car. The reduced impact was approximately equivalent in severity to an unprotected impact with the structure at half the speed.

Robert Anderson, Principal Investigator

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1. Introduction

1.1. Background

Car crashes remain a significant source of head injury in the community. Car occupants have an annual hospital admission rate of around 90 per 100,000 population. Of drivers who are admitted to hospital, the most serious injury is usually to the head (O'Conner and Trembath, 1994).

In a previous study, McLean et al. (1997) estimated the benefits that are likely to accrue to Australia from the use of padding of the upper interior of the passenger compartment. This study specifically examined the effects of the ammendment to the United States Federal Motor Vehicle Safety Standard 201 (FMVSS 201) in which passenger cars have to pass head impact tests with the upper interior. That report estimated the total annual reduction in harm to the Australian community to be around $123 million. But more impressive were the estimates of introducing protective headwear for car occupants. The authors of the report estimated that the annual reduction in harm would be in the order of $380 million. The benefit of padding the head is that the head is protected from strikes with unpadded automotive components, exterior objects and in vehicles that predate any eventual introduction of padded interiors.

The same report examined the distribution of impacts to the head of occupants who sustained a head injury. The data were drawn from a sample of crashes that occurred in South Australia and had been investigated by members of the Road Accident Research Unit. Impacts tended to be distributed about the cranium of the head rather than to the face, and significant proportions of impacts occurred about the side and front of the head (see

Figure 1). In 44 per cent of these cases, the impact was to a region of the head that could have been covered by some sort of protective headband.

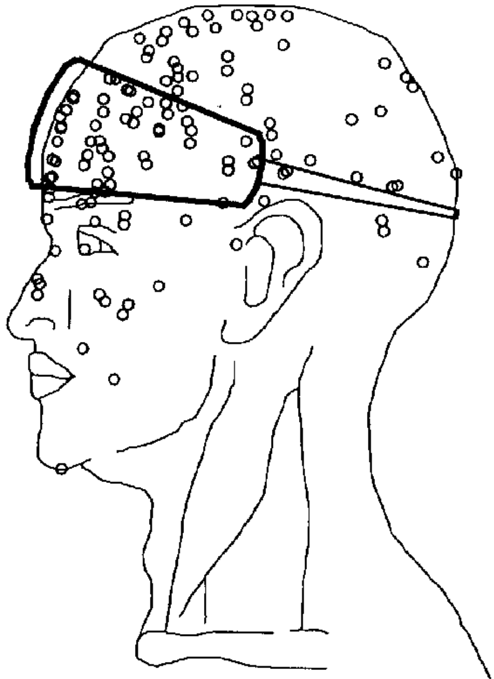

Figure 1 Head impact locations recorded in McLean et al. (1997) are displayed as dots. The 'RARU headband' is superimposed. It covers 44% of the recorded impacts (from McLean et al. 1997)

1.1.1. THE REQUIREMENTS OF FMVSS 201

FMVSS 201 requires vehicles to pass a test in which a 15 pound (6.7 kg) headform is fired at upper interior structures of the passenger compartment at 15 mph (24.15 km/h). The design requirement is that the headform acceleration should not exceed 80 g for more than 3 ms.

1.1.2. CHARACTERISTICS OF PADDING

Padding materials commonly used in applications where crash protection is required can be broadly classified as *rigid* or *semi-rigid*. Rigid foams used in crash protection are stiffer than semi-rigid foams and deform primarily in a plastic (non-recoverable) manner. Semi-rigid foams generally recover their shape after deformation and deform in a more elastic or viscoelastic manner than rigid foams. Lockett et al. (1981) tested the characteristics of a series of materials commonly used in crash padding. They found that rigid materials exhibited characteristically different force/deflection behaviour than semi-rigid materials. The differences in their behaviour are illustrated in Figure 2, which shows dynamic force/deflection curves for rigid and semi-rigid materials. Rigid materials (Figure 2, left) are stiff up to their yield strength and so they resist deformation. Beyond this yield strength, they deform with little change in resistive force. During the unloading phase, the force rapidly drops to zero, and very little energy is returned to the system. This is due to the plastic nature of the yielding phase. Semi-rigid materials (Figure 2, right) may show some yielding behaviour during their loading phase, but behave in a more elastic manner, with the load increasing with deformation more or less constantly. These materials may return more energy to the system than a rigid material during the unloading phase.

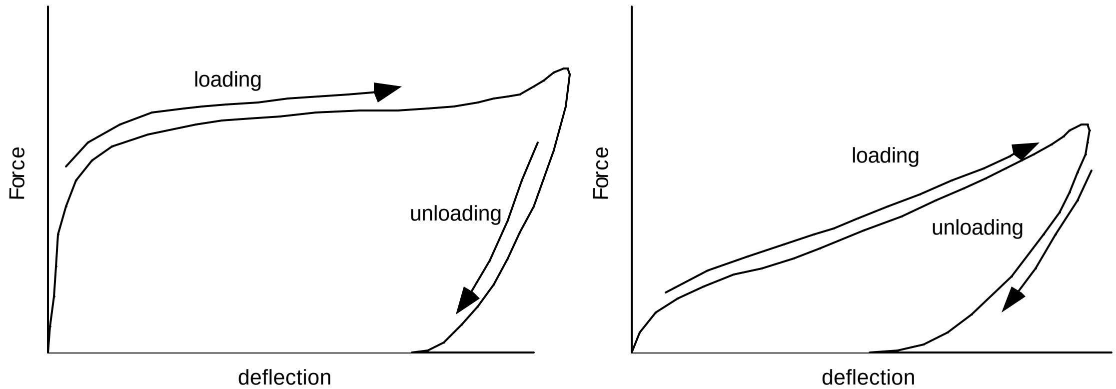

Figure 2. Force/deflection characteristics of rigid materials (*left*) and semi-rigid materials (*right*)

In addition to these variations in behaviour, the characteristics of many materials are also rate sensitive. This means that the exact nature of their force/deflection curve is dependent upon the initial velocity of the object striking the material. The characteristics of rate sensitive materials are often described in terms of viscoelasticity.

1.1.3. PADDING FOR INJURY PREVENTION

Padding protects the body by absorbing some of the energy of impact and by reducing the peak loads applied to the part of the body being struck by spreading the change in velocity of the body over a longer period. Padding may also protect the body by spreading the load over a larger contact area.

The selection of padding is linked to the design criteria used to assess the risk of injury. For the prevention of head injuries, the requirement may be to minimise the peak acceleration of a testing headform, the level of the Head Injury Criterion (HIC) or the peak 3 ms acceleration of the headform. It has been widely reported that these types of measures may not sufficiently describe the risk of head injury for a given impact; the measures say nothing of any localised loading, which may increase the risk of skull fracture, and they ignore the angular acceleration imparted to the head. Angular acceleration is hypothesised to be a significant mechanism of diffuse type brain injuries. Nevertheless, these measures probably bear some relation to the risk of some forms of head injury and minimising these measures is likely to reduce the risk posed by other mechanisms of injury.

1.1.4. SELECTION OF PADDING FOR HEAD PROTECTION

There is published research on the selection of crash padding materials based on particular design applications for minimising the risk of head injury in an impact. The work of Monk and Sullivan (1986) is relevant to preventing injuries from head impacts with the upper interior of the passenger compartment. They reported a methodology for the selection of padding materials for protecting the head in strikes with the A-pillar of vehicles. The methodology starts with an analytical representation of a head impact and an approximation function for the Head Injury Criterion (HIC). From the analysis, they were able to construct a curve that describes the maximum allowable stiffness of a material that would produce a HIC value of 1000 (the maximum allowable), for impacts with a 4.7 kg headform, over a range of impact velocities. That curve is reproduced in Figure 3. The notable feature of the curve is that the stiffness requirements of effective crash padding materials is not constant for all impact speeds.

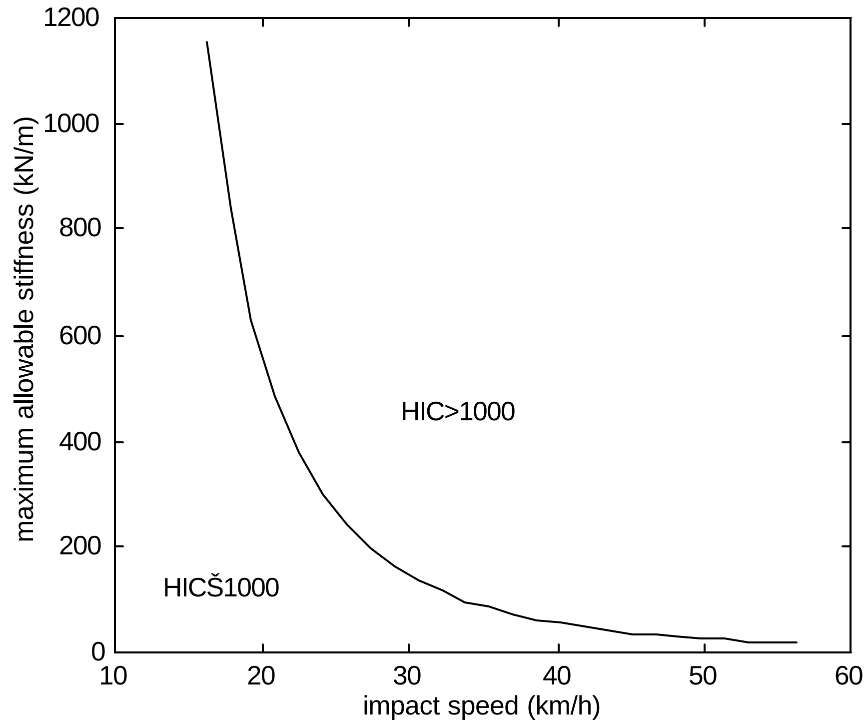

Figure 3. Approximate relationship between padding stiffness and impact speed for HIC<1000, assuming a head mass of 4.7 kg (Monk and Sullivan, 1986)

Monk and Sullivan went on to conduct a series of static and dynamic tests to discern the stiffness and energy absorbing characteristics of a range of crash padding materials. The padding material was placed against a rigid surface for the tests so that only the stiffness of the material (and not its supporting structure) was measured. They used the results and the analytical techniques they had developed to estimate the characteristics of desirable foams and to aid their selection of materials for the next stage of the testing. A headform was fired at a simulated A-pillar and the candidate materials that had been identified from the previous testing were interposed between the headform and the A-pillar. All padding samples were one inch thick and they all significantly reduced the severity of the impact. Based on their research they concluded that one inch of padding could significantly reduce the severity of the impact between the head and A-pillar at 25 mph (40 km/h).

1.2. Aims of this Project

The work cited above indicates that some form of protective headwear might reduce the severity of impacts and resulting injuries to car occupants in crashes. This report examines the technical feasibility of such headwear by measuring the characteristics of candidate materials and the performance of such headwear in simulated crash situations. Specifically, the aims of the study are to:

- test the characteristics of materials suitable for use in a headband, and to
- test prototype headbands to evaluate their effectiveness in reducing the severity of headform impacts with vehicle structures in simulated crash situations.

1.3. Methodology

Candidate materials were assessed using three methods as outlined below.

PHASE 1

A headform simulating the mass of a human head was dropped onto candidate materials at different velocities. The materials were placed on a rigid and massive steel slab, so the test measured the impact characteristics of the material only. The design of the test accounted for the temperature of the material, the thickness of the material and the durability of the material where appropriate.

PHASE 2

Prototype headbands were constructed from the materials that performed well in Phase 1. The headform, with the headband attached, was dropped onto standard helmet testing anvils to see how the performance of the headbands compared to standard measures of helmet performance. Two anvils were used; a hemispherical anvil, and a sharp edged anvil.

PHASE 3

The better performing prototype headbands were attached to a headform and fired at various internal structures of a vehicle. The impact severity was compared to tests in which no padding was attached to the headform.

2. Phase 1

2.1. Method

The tool used for testing the performance of the materials in Phase 1 was the 'adult' headform proposed by Working Group 10 of the European Experimental Vehicles Committee for the assessment of pedestrian head protection[1]. This headform consists of a sphere of phenolic resin with a diameter of 165 mm. The sphere is covered with a silicon rubber skin to simulate the compliance of the scalp and bone of a human head. A steel insert in the sphere is used to adjust the weight of the headform to 4.8 kg and to house a tri-axial accelerometer to measure the acceleration of the headform on impact. The headform is illustrated in Figure 4.

Each material was tested by placing it on a massive steel slab. Some materials were tested at elevated temperatures by heating for several minutes in a stream of hot air prior to the test. The temperature of the material was measured immediately following the test. The headform was suspended above the material and dropped from a predetermined height. The resulting impact acceleration was recorded using a high-speed data acquisition system (50 kHz) after being passed through a 10 kHz analogue filter. The resulting acceleration data was then filtered according to SAE CFC 1000. The test setup is illustrated in Figure 5.

The peak acceleration was noted and the Head Injury Criterion (HIC) was calculated for each test. The HIC is the criterion most commonly used for head injury risk assessment. It is calculated according to the formula

$$HIC = (t_2 - t_1)\left[\frac{\int_{t_1}^{t_2} a\,dt}{t_2 - t_1}\right]^{2.5}$$

where t_2 and t_1 are chosen so that the function is maximised. Impacts that produce HIC values of more than 1000 are considered to be unacceptably severe.

[1] The headform will be referred hereafter as the EEVC WG10 headform

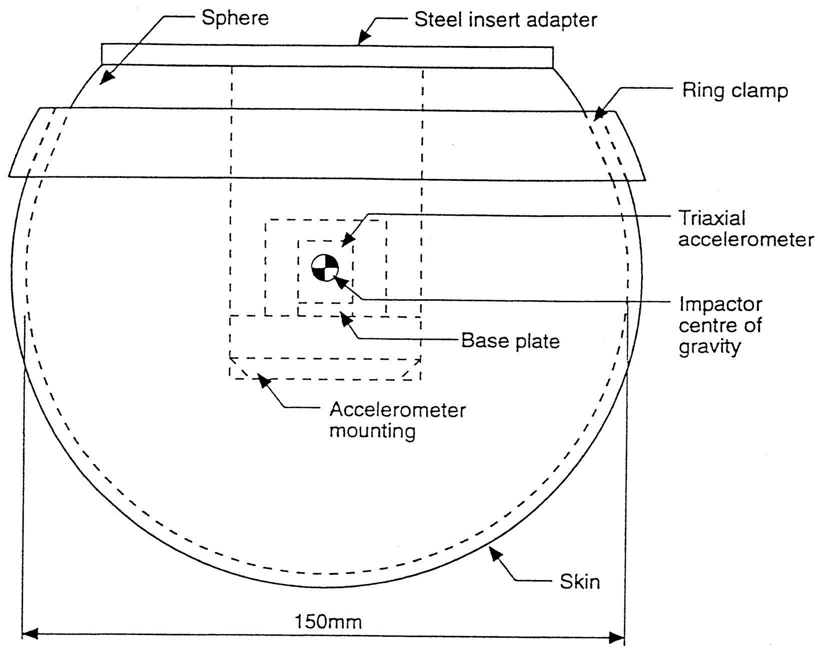

Figure 4. The EEVC WG10 headform used in the study

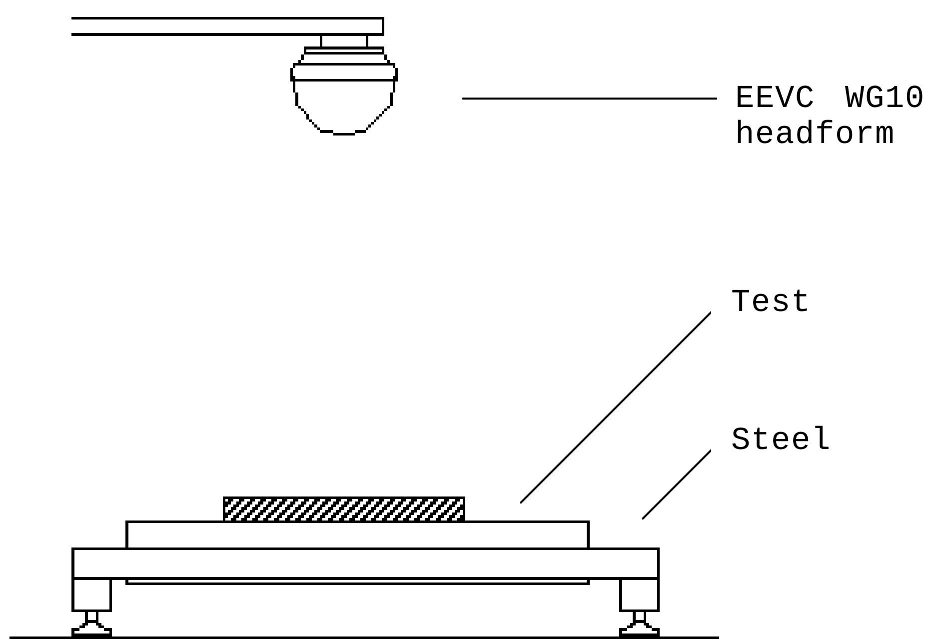

Figure 5. The test setup used in Phase 1

The force experienced by the headform was calculated and plotted against the displacement of the material in each test. The displacement was calculated by identifying the beginning and end of the acceleration and integrating the acceleration twice within those bounds. In some tests the beginning of the pulse is difficult to identify and so there may be some error in the maximum displacement calculated in each experiment. The force was calculated by multiplying the acceleration experienced by the headform by the mass of the headform.

2.2. Candidate Materials

2.2.1. CLOSED CELL POLYOLEFIN FOAMS

Five samples of cross-linked closed cell polyolefin foams were obtained from Pilon Plastics Pty Ltd. According to the suppliers, the foams have been used for impact protection in cricket helmet linings, rugby headgear and jockey vests. The samples varied in thickness from 2 mm to 17 mm. The supplier suggested that a certain combination of materials may work well, and this combination was tested along with the individual materials. The last two materials are examples from the Pilon "Playground Softfall Underlay" range. These materials are designed to absorb impacts in playground falls.

The materials tested were:

- SPS2515 Beige, 15 mm thick
- E3015 White, 15 mm thick
- S1002 Black, 2 mm thick
- S3004/Weave/S3008 Black, 12 mm thick
- S1002/Weave/E3015 Yellow/Grey, 17 mm thick

2.2.2. VISCOELASTIC FOAMS

Confor Foam exhibits viscoelastic behaviour. If it is struck slowly it is relatively soft, but it is stiffer if struck at a higher velocity. At higher velocities, the foam becomes stiffer, maximising the energy absorbed over the crush depth of the material. Confor foam is often used to represent human flesh on crash test dummies, as its dynamic behaviour is similar to that of flesh.

Two grades of Confor Foam were tested; CF45100 Blue, and CF47100 Green, both obtained in 25 mm thick sheets.

2.2.3. HONEYCOMB CARDBOARD

Honeycomb cardboard is made of kraft paper that is glued together in a honeycomb pattern, then sandwiched between two sheets of kraft paper, so that the cells of the honeycomb run perpendicular to the surface of the sheet. In an impact normal to the surface of the sheet the paper cells buckle and crush, absorbing the energy of the impact. Honeycomb cardboard is used for packaging, and the samples tested were sourced from the packaging of automotive parts.

Two grades of honeycomb cardboard were tested, at various thicknesses. The fine grade had cells approximately 12.5 mm in size, and the coarse grade had cells approximately 18 mm in size. Figure 6 shows the structure of the cells after the outer sheet of kraft paper has been removed. The sample on the left is the fine grade, the sample on the right is the coarse grade.

Figure 6. Photograph of the cells in the honeycomb cardboard

2.2.4. POLYURETHANE FOAMS

Polyurethane foams exhibit a range of material behaviours; they can be designed to behave in flexible, semi-rigid or rigid manners.

Several semi-rigid polyurethane foams were obtained from the Woodbridge Group, an American automotive materials developer and manufacturer. An Australian company, Orica supplied several equivalent (and Australian made) automotive polyurethane foams. Several of the grades of polyurethane that were tested are being promoted by their producers as appropriate foams to pad the upper interiors of vehicles, in response to FMVSS 201.

2.2.5. POLYSTYRENE FOAMS

Polystyrene is the primary material used for the energy absorbing liner of bicycle and motorcycle helmets in Australia. Polystyrene is an obvious candidate material for head protection for car occupants. The grade of polystyrene tested in this study is one used in helmet manufacture. Samples 6 mm to 25 mm thick were tested.

Table 1 lists the materials surveyed in Phase 1 of the study.

Table 1. Materials tested in Phase 1 of the study

Material name	Supplier	Category	Thickness tested
SPS251	Pilon Plastics Pty Ltd.	Closed cell foam	15 mm
E3015	Pilon Plastics Pty Ltd.	Closed cell foam	15 mm
S1002	Pilon Plastics Pty Ltd.	Closed cell foam	2 mm
S3004/Weave/S3008	Pilon Plastics Pty Ltd.	Closed cell foam	12 mm
S1002/Weave/E3015	Pilon Plastics Pty Ltd.	Closed cell foam	17 mm
CF45100	E-A-R Specialty Composites	Viscoelastic foam	25 mm, 50 mm
CF47100	E-A-R Specialty Composites	Viscoelastic foam	25 mm
Honeycomb cardboard 12 mm cell	Unknown*	Honeycomb cardboard	15 mm, 30 mm
Honeycomb cardboard 18 mm cell	Unknown*	Honeycomb cardboard	45 mm, 70 mm
E175	Woodbridge Group	Automotive EA polyurethane foam	25 mm
E900, 5.6 pcf	Woodbridge Group	Automotive EA polyurethane foam	25 mm
E900, 6.0 pcf	Woodbridge Group	Automotive EA polyurethane foam	25 mm
BB-38	Woodbridge Group	Automotive EA polyurethane foam	25 mm
Polystyrene foam	Lactec Foam Products	Polystyrene Foam	6 mm. 10 mm, 15 mm, 20 mm, 25 mm

*Sourced from packaging material for automotive body panels

2.3. Results

2.3.1. BASELINE RESULTS

For comparison with the results of tests in this report, Figure 7 shows the force/deflection characteristics of the unprotected EEVC WG10 headform, in a drop test onto the steel slab from a height of 1.0 m. This test produced a peak acceleration of 650 g and a corresponding HIC value of 4640.

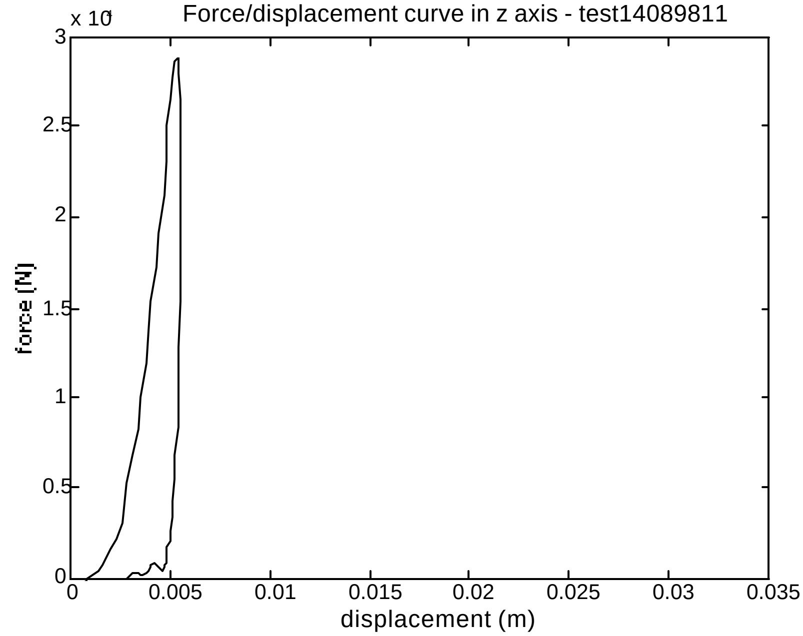

Figure 7. The force/displacement characteristics of the EEVC headform in a drop test onto the steel slab from a height of 1.0 m

2.3.2. CLOSED CELL POLYOLEFIN FOAMS

Five samples of closed cell polyolefin foams were tested alone, and in combination, as suggested by the supplier. The foams were initially tested from a drop height of 1.0 m, and it was intended that all foams be retested from a larger drop height, but as the closed cell foams did not perform as well as other materials, it was decided that no further tests should be done. A summary of the results for the closed cell foams is given in Table 2.

Table 2. Results for closed cell polyolefin foams, drop height 1.0 m

Material type	Thickness (mm)	Peak acceleration (g)	HIC	Test number
#5 yellow side up	17	323	1720	24089801
#5 grey side up	17	290	1440	24089802
Combination of #1, #2 and #3 (repeat tests)	32	205	900	24089804
	32	214	970	24089805
	32	223	1050	24089806
	32	237	1130	24089808
	32	234	1100	24089809
	32	229	1090	24089810
#3 on #2	17	322	1870	24089807
#4	12	352	2020	24089811

Material type	Thickness (mm)	Peak acceleration (g)	HIC	Test number
#5 yellow side up on #2	32	183	800	24089812
#1	15	425	2920	24089813
#2	15	379	2080	24089814
#1 on #2	30	263	1320	24089815

1. SPS2515 Beige, 15 mm thick
2. E3015 White, 15 mm thick
3. S1002 Black, 2 mm thick
4. S3004/Weave/S3008 Black, 12 mm thick
5. S1002/Weave/E3015 Yellow/Grey, 17 mm thick

The average HIC value for 32 mm of closed cell foam, made up of a combination of foams 1, 2 and 3 was 1040, and the average HIC for 17 mm of closed cell foam was 1680. These results were judged poor by comparison with the results of tests using alternative materials.

2.3.3. VISCOELASTIC FOAMS

Two types of viscoelastic foam were tested, both forms of Confor foam. They were CF45100 and CF47100. The materials were compared in a test where the headform was dropped onto the material from a height of 1 m. The results are shown in Table 3, and illustrated in Figure 8. CF45100 and CF47100 performed similarly, with resultant HIC and peak acceleration within 10%. CF47100 is slightly stiffer however (as indicated by the steeper slope of the force displacement curve).

Table 3. Results comparing two grades of Confor foam

Material type	Drop height (m)	Velocity (km/hr)	Thickness (mm)	Temp. (°C)	Peak acceleration (g)	HIC	Test number
CF-45100	1.00	16.0	25	17	102	300	14089810
CF-47100	1.00	16.0	25	16.5	91	270	27089812

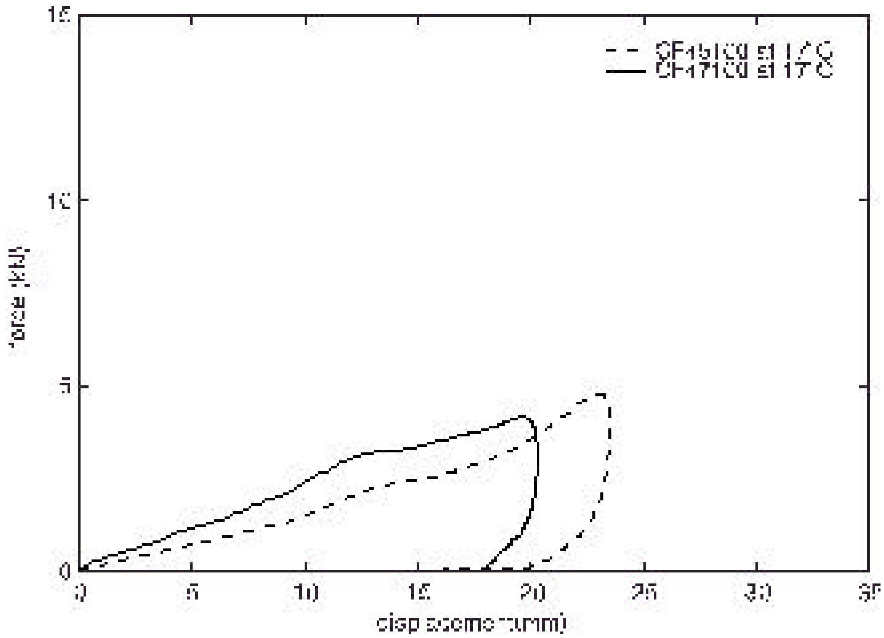

Figure 8. Effect of type of 25mm Confor foam, drop height 1.0 m

Confor foam CF-45100 was also tested from a drop height of 1.45 m. The results of tests at the two drop heights and two temperatures are presented in Table 4. The results show that increasing drop height from 1.0 m to 1.45 m (an increase in velocity from 16 to 19.2 km/h, and a 45% increase in impact energy) caused HIC to more than double, and increased the peak accelerations by between 50 to 100%. The force displacement curves for the first pair of tests at 15° C, in Table 4 are shown in Figure 9. The figure shows that the increase in impact severity was due to the material *bottoming out*; i.e. the material crush depth was fully utilised before the headform's energy had been absorbed by the material.

Figure 10 shows the force displacement curves for the pair of tests performed at 25 ° C (see Table 4). Both Figure 9 and Figure 10 show that the peak force increases with drop height, and that the initial stiffness of the CF45100 (indicated by the slope of the curve) was not affected by the increase in impact velocity from 16 to 19.2 km/hr.

Table 4. Results for Confor foam from two drop heights

Material type	Drop height (m)	Velocity (km/hr)	Thickness (mm)	Temp. (°C)	Peak acceleration (g)	HIC	Test number
CF-45100	1.0	16.0	25	17	102	300	14089810
	1.45	19.2	25	15	204	880	14089802
	1.0	16.0	25	27	191	660	27089812
	1.45	19.2	25	25	282	1490	14089808

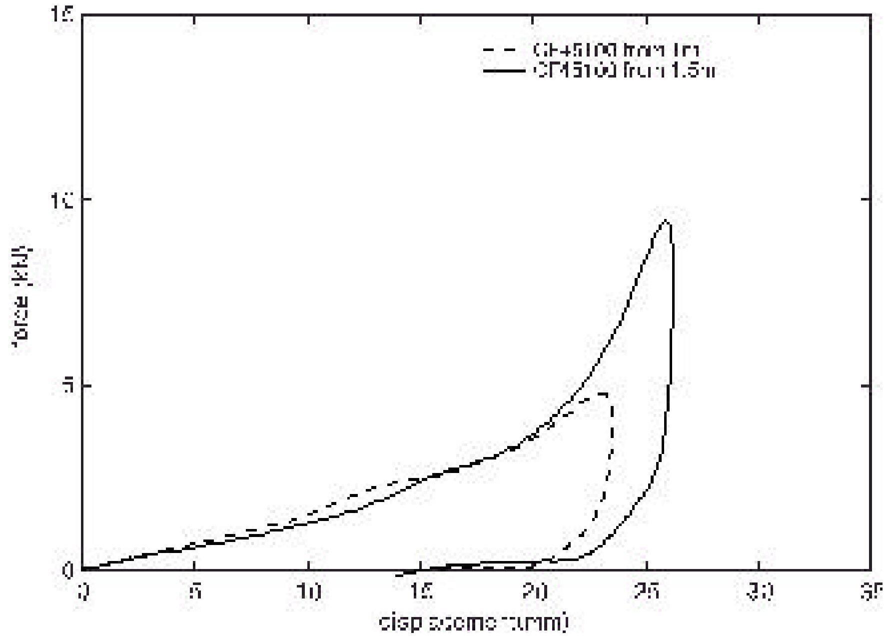

Figure 9. Effect of drop height on 25 mm CF45100 at 15° C

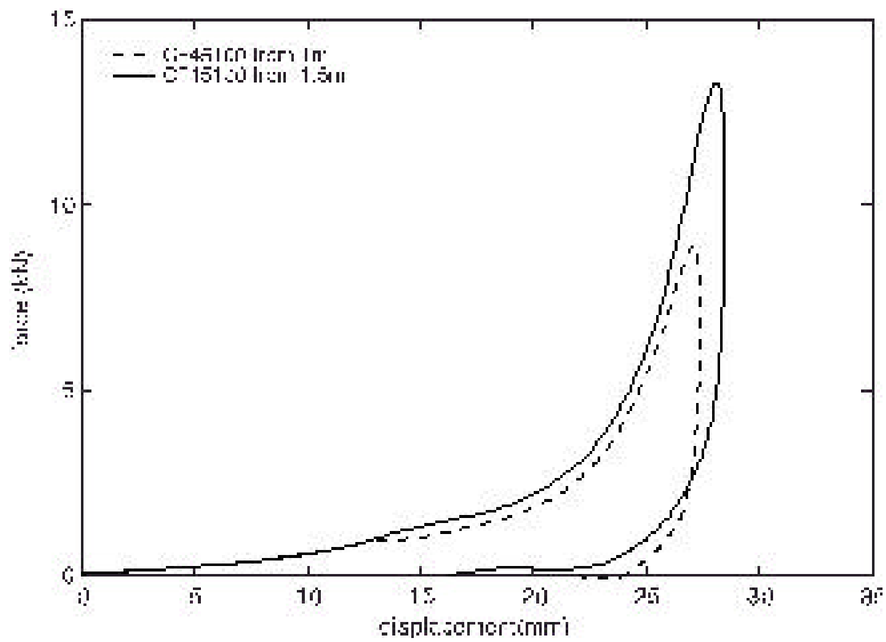

Figure 10. Effect of drop height on 25 mm CF45100 at 25° C

The effect of doubling the thickness of the foam is shown in Table 5. In these tests the foam was tested at a low temperature and at an elevated temperature and at drop heights of 1 m and 1.45 m.

Table 5. Effect of thickness of viscoelastic foam at various drop heights and temperatures

Material type	Drop height (m)	Velocity (km/hr)	Thickness (mm)	Temp. (°C)	Peak acceleration (g)	HIC	Test number
CF-45100	1.0	16.0	25	42	262	1120	27089808
			50	50	114	330	27089809
	1.45	19.2	25	15	204	880	14089802
			50	15	78	280	14089803
CF-47100	1.0	16.0	25	16.5	91	270	14099801
			50	16.5	67	180	14099802
			25	41	270	1190	14099805
			50	37	64	140	14099804

When the thickness of the Confor Foam was doubled, the resulting HIC was reduced by between 30 and 88%. The most dramatic reductions in HIC were obtained when the foam was hot (the first and last pair of tests shown in Table 5); the addition of a second layer prevented the test from bottoming out,. The effect of doubling the thickness of foam when testing the material at an elevated temperature is illustrated in Figure 11 and Figure 14. Even at the lower temperature of 15° C, there was a significant reduction in impact severity. The effects of foam thickness at this temperature are illustrated in Figure 12 and Figure 13.

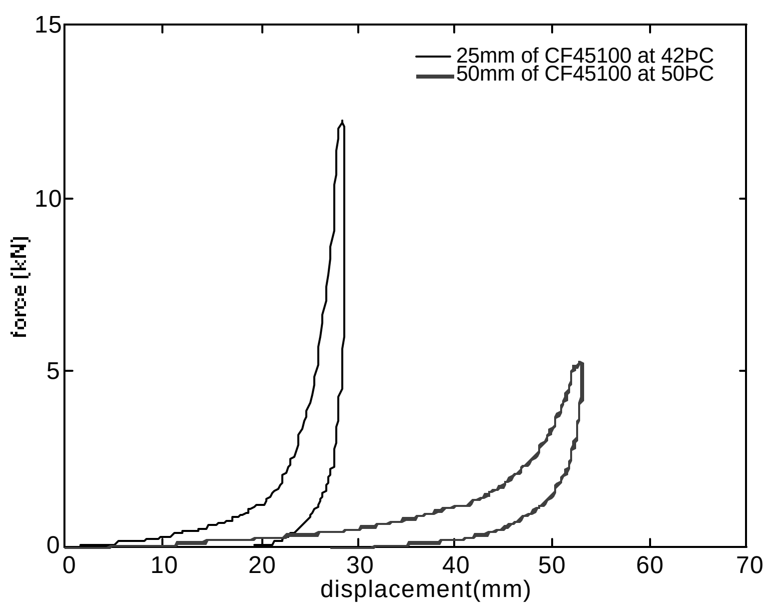

Figure 11. Effect of thickness on the effectiveness of CF45100 at elevated temperatures, drop height 1.0 m

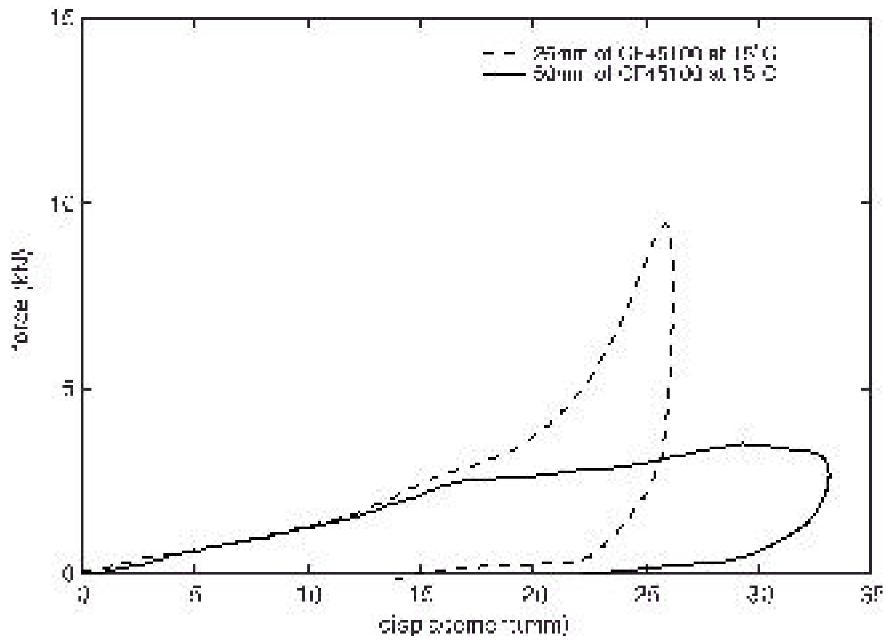

Figure 12. Effect of thickness on the effectiveness of CF45100 at lower temperatures, drop height 1.45 m

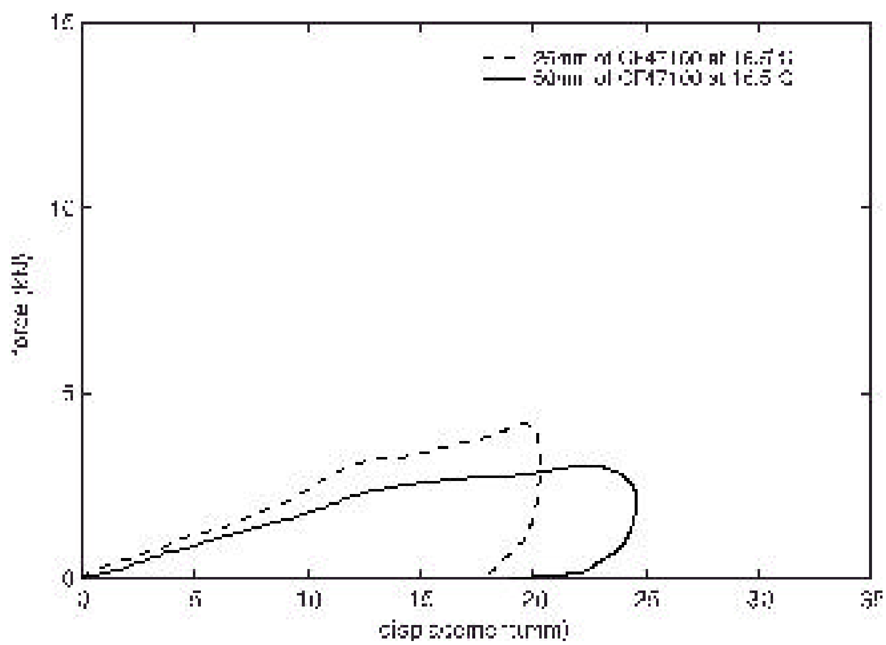

Figure 13. Effect of thickness on the effectiveness of CF47100 at lower temperatures, drop height 1.0 m

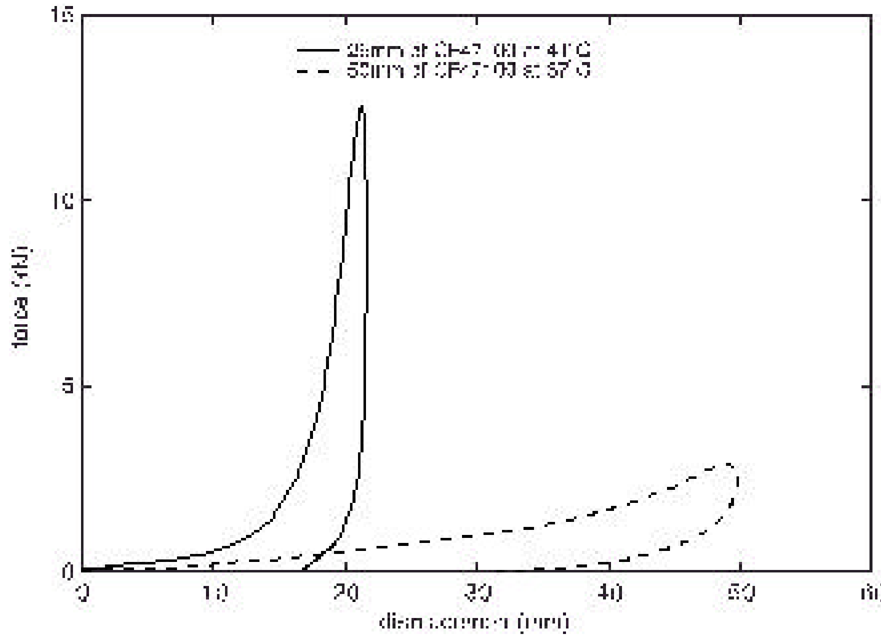

Figure 14. Effect of thickness on the effectiveness of CF47100 at elevated temperatures, drop height 1.0 m

At low temperatures, Confor foam performed well, absorbing energy and reducing the impact severity. But at temperatures approaching that of the human body (30°C and above) the foam became very compliant. Its ability to reduce the severity of an impact became compromised. A summary of the effect of temperature on Confor Foam is given in Table 6 which shows that increasing the temperature of CF45100 from 17° C to 27° C increases the HIC result from 300 to 660. Increasing the temperature to 42° C produced a HIC of 1120. Similar results are obtained in tests performed with a drop height of 1.45 m. CF47100 behaves similarly at elevated temperatures.

Table 6. Results showing the effect of temperature on Confor foam

Material type	Drop height (m)	Velocity (km/hr)	Thickness (mm)	Temp. (°C)	Peak acceleration (g)	HIC	Test number
CF-45100	1.00	16.0	25	17	102	300	14089810
				27	191	660	27089812
				42	262	1120	27089808
CF-45100	1.45	19.2	25	15	204	880	14089802
				25	282	1490	14089808
CF-47100	1.00	16.0	25	16.5	90.6	270	14099801
				31	219	800	14099803
				41	270	1190	14099805

Figure 15 shows the force/displacement curves for the first three tests shown in Table 6. It illustrates the effect of temperature on the performance of Confor foam in these tests. At low temperatures, the Confor foam exhibits near ideal impact absorption properties; the force is almost constant during the second half of the displacement. At higher temperature, the foam softens. With softening, the foam is no longer as effective in absorbing energy so the material bottoms out. This causes a sharp increase in the peak load applied to the headform.

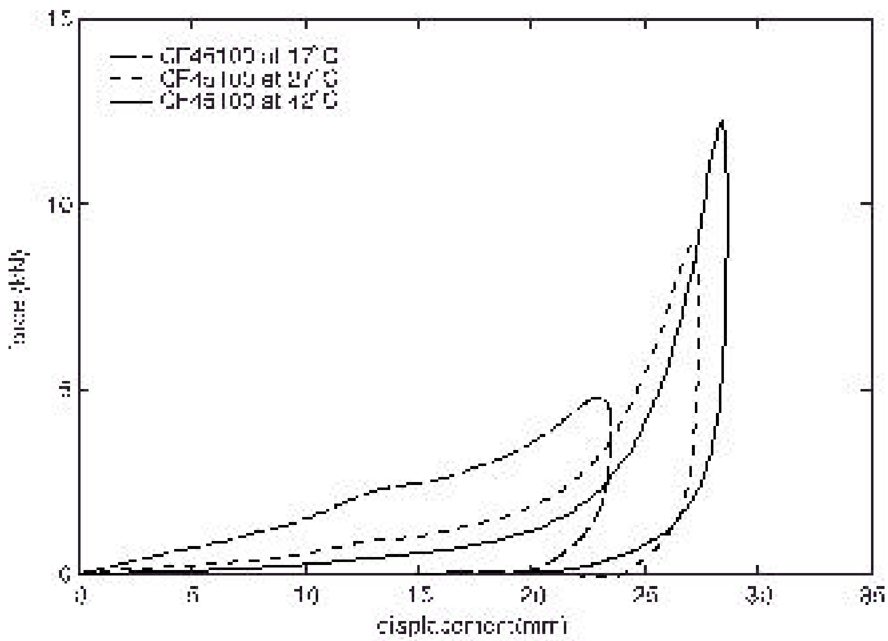

Figure 15. Effect of Temperature on the effectiveness of 25 mm CF45100, drop height 1.0 m

2.3.4. HONEYCOMB CARDBOARD

Two grades of honeycomb cardboard (12.5 mm and 18 mm cell size) were tested. Different thicknesses were tested at two drop heights. A summary of the results for the honeycomb cardboard is given in

Table 7.

The honeycomb cardboard performed well in Phase 1 tests. It had the lowest HIC of any material tested at the 1.0 m drop height. This low HIC is achieved because of the mechanism by which the cardboard absorbs energy under impact loading. In an impact normal to the surface of the sheet, the paper walls of the cells in the honeycomb buckle and crush under the load, absorbing energy, without returning any energy to the headform in the unloading phase.

Selecting an appropriate combination of cell size, paper thickness, and paper strength controls the crushing strength of the honeycomb. In Figure 16, the force during the impact reaches a maximum of about 2000 N at 20 mm displacement, and remains nearly constant for the remaining displacement. This represents near ideal energy absorption behaviour; the load reaches its maximum relatively quickly, then stays almost constant until all the impact energy is absorbed.

Table 7. Phase 1 results for honeycomb cardboard

Test number	Drop height (m)	Velocity (km/hr)	Material type	Thickness (mm)	Temp. (°C)	Peak acceleration (g)	HIC
26059905	1.00	15.9	Small celled honeycomb cardboard	15	16.0	285	1190
17129820	1.435	19.1	Small celled honeycomb cardboard	2x15	25.5	104	440
17129801	1.43	19.1	Large celled honeycomb cardboard	45	25.5	51	140
17129821	1.405	18.9	Large celled honeycomb cardboard	70	25.5	66	210

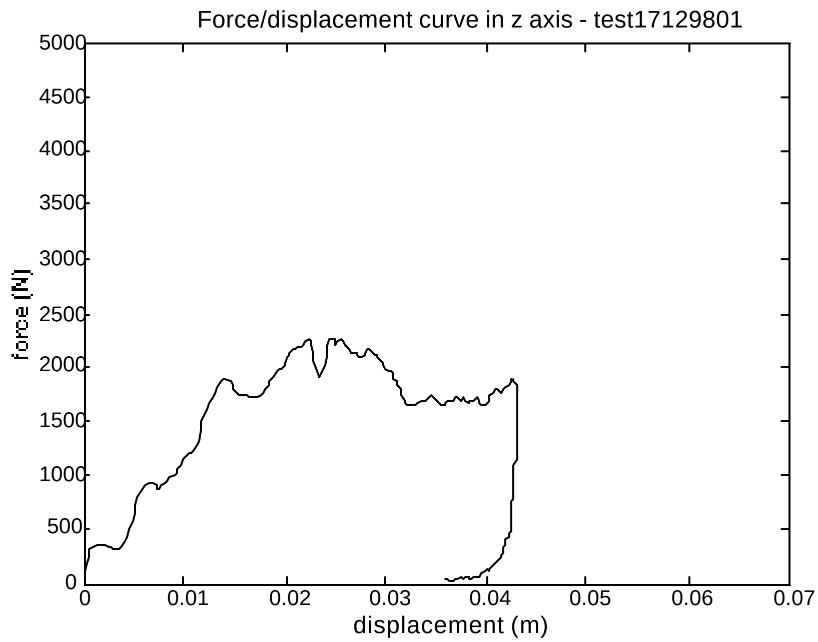

Figure 16. Typical Force Displacement Curve for 45 mm thick Honeycomb cardboard

There may be several disadvantages with using honeycomb cardboard as headband material. Being made of paper, it is sensitive to moisture. The presence of moisture (from perspiration, for example) may cause the performance of the headband to deteriorate. Also, the cardboard may not be durable in use, storage, and misuse. However, honeycombs made of alternative materials such as aluminium, polymers, or polymer-coated paper may overcome some of these problems. If so, honeycomb made from an alternative material may be a promising material for the headband.

2.3.5. POLYURETHANE FOAMS

Four types of Automotive Energy Absorbing (EA) Polyurethane foam were tested at 25 mm thickness, and two different drop heights. A summary of the results is given in Table 8. Figure 17 and Figure 18 show the force/displacement curves for the materials at each drop height. All the polyurethane foams that were tested performed similarly at the lower drop height. At the greater drop height, larger differences between the materials emerged.

Table 8. Phase 1 results for polyurethane foams

Drop height (m)	Velocity (km/hr)	Thickness (mm)	Temp. (°C)	Material type	Peak acceleration (g)	HIC	Test number
1.00	15.9	25	25	BB-38	140	560	15129801
				E175	129	450	15129805
				E900, 5.6 pcf	129	460	15129809
				E900, 6.0 pcf	135	490	15129813
1.45	19.2	25	25.5	BB-38	208	1119	17129804
				E175	198	962	17129808
				E900, 5.6 pcf	260	1532	17129813
				E900, 6.0 pcf	227	1234	17129816

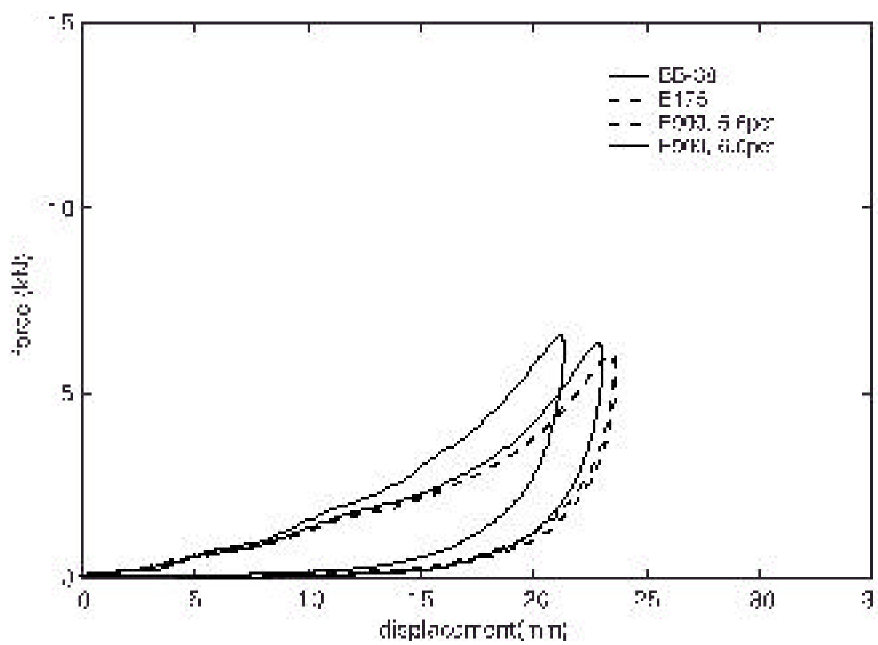

Figure 17. Force/displacement characteristics measured in tests on the polyurethane foams from a drop height of 1.0 m.

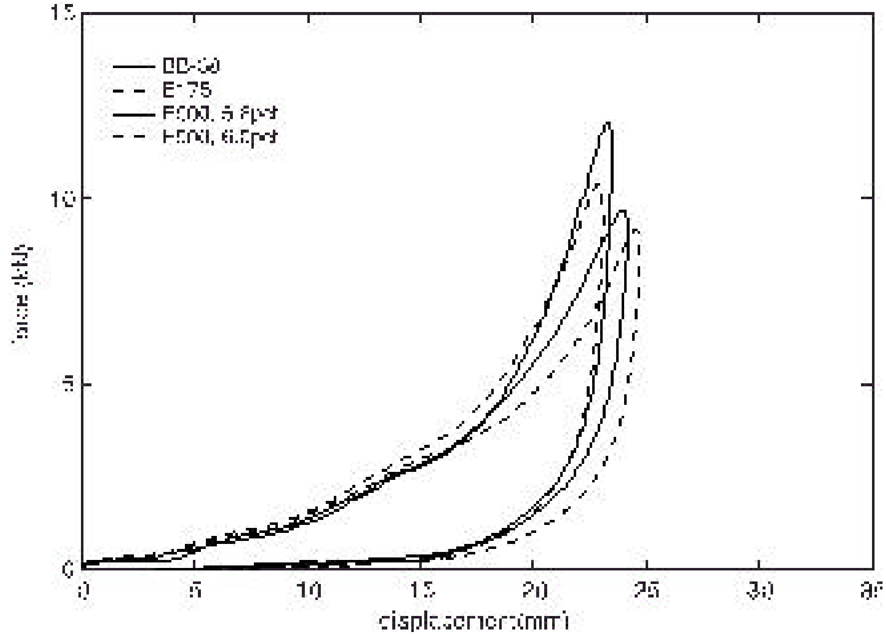

Figure 18. Force/displacement characteristics measured in tests on the polyurethane foams from a drop height of 1.45 m

Some of the materials appeared crushable when handled, and so tests were conducted to examine the durability of the foams. Each sample of material was tested four times at the one impact site at each drop height. A low level of durability is indicated by an increase in the peak acceleration recorded for subsequent tests. Figure 19 and Figure 20 illustrate the durability of the four foams.

Figure 19 shows that at drop height 1.0 m, BB-38 is relatively durable, with an increase in maximum acceleration of approximately 10 g (9% increase), whereas E900 5.6 pcf is less durable, with an increase in maximum acceleration of approximately 50 g (39% increase).

Figure 20 shows that at drop height 1.45 m, BB-38 is relatively durable, with an increase in maximum acceleration of approximately 20 g (9% increase), whereas E900 6.0 pcf is less durable, with an increase in maximum acceleration of approximately 90 g (40% increase). For both drop heights, BB-38 was the most durable polyurethane foam.

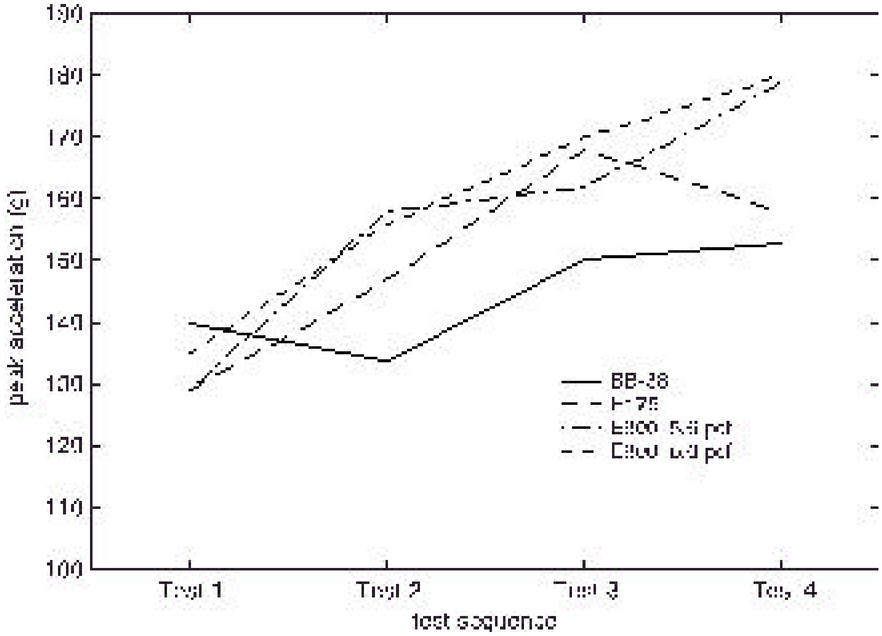

Figure 19. Durability of Polyurethane Foams, drop height 1.0 m

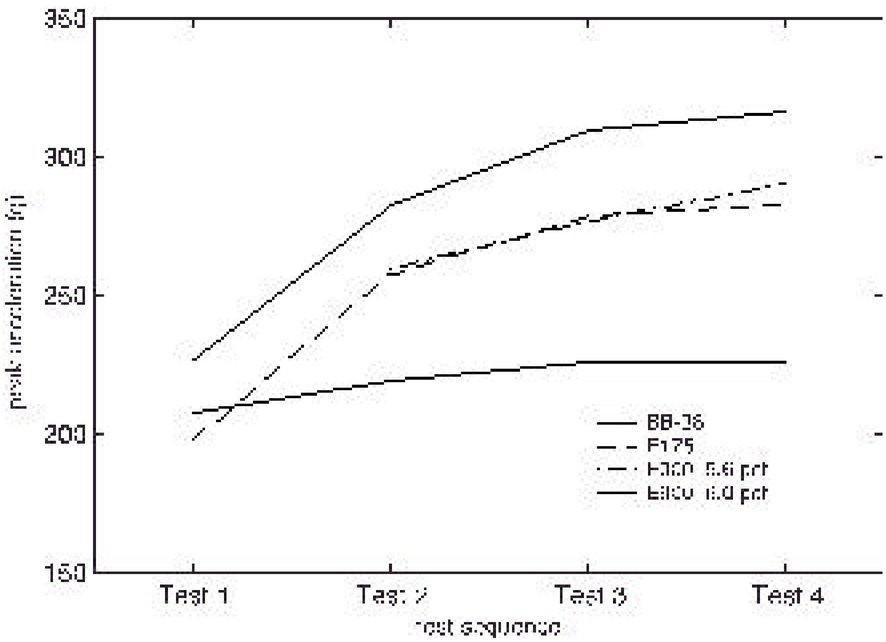

Figure 20. Durability of Polyurethane Foams, drop height 1.45 m

2.3.6. POLYSTYRENE FOAMS

Polystyrene foam was obtained in sheets of five different thicknesses, and tested at 1.0 m drop height. The two thickest samples were then tested at 1.45 m drop height. The thinner samples were not tested at the higher drop height, as their performances in the initial tests were poor. A summary of the results for polystyrene foams is given in Table 9 below, and is illustrated in Figure 21.

Table 9. Phase 1 results for polystyrene foams

Drop height (m)	Velocity (km/hr)	Temp. (°C)	Thickness (mm)	Peak acceleration (g)	HIC	Test number
1.00	15.9	20.5	6	420	2580	27089801
			10	380	2170	27089802
			15	290	1410	27089803
			20	194	760	27089804
			25	127	440	27089805
			6 + 6	300	1410	27089806
			10 + 15	118	410	27089807
1.45	19.2	25.5	25	232	1089	17129802
			20	344	1929	17129803

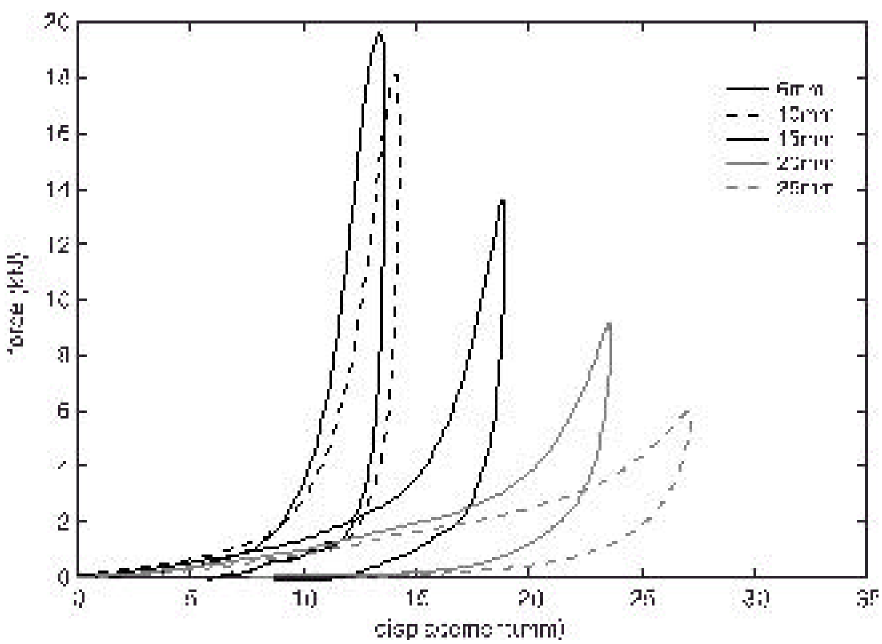

Figure 21. Force/deflection curves for polystyrene foams of varying thickness, drop height 1.0 m

Figure 21 illustrates that the material bottoming out dominated the tests with the thinner sheets of polystyrene. In every test, the displacement of the headform was at least the thickness of the material. The thicker samples showed less of the effects of bottoming, and gave results that were as good as the polyurethane foams.

2.4. Summary

A summary of the results for the tests performed in Phase 1 is given in Table 10 and Table 11. The corresponding force displacement curves are compared in Figure 22 and Figure 23.

These results indicate that the most promising materials at the end of phase 1 were the polystyrene, the polyurethanes and the cardboard honeycomb. Note that the 30 mm sample of honeycomb cardboard was not tested from a drop height of 1.0 m, as it performed well at 1.45 m drop height (see Table 11). The HIC obtained for the 30 mm sample of honeycomb cardboard is less than half that of the next best material (E175) at a drop height of 1.45 metres. Figure 22 clearly shows that the closed cell foam, and Confor foams at raised temperatures, had significantly higher peak loads when tested from a drop height of 1.0 m than the other materials. The results were more evenly spread (apart from the honeycomb cardboard) in tests performed from a drop height of 1.45 m (Figure 23). It should be noted however that materials that performed poorly at 1.0 m were not necessarily tested from a height of 1.45 m.

Although Confor foam performed well at low temperatures, its variations in properties with changes in temperature exclude it as a suitable material for padding which is likely to see a wide range of temperatures. As a result, the Confor foams along with the closed cell polyolefin foams were excluded from Phase II of the study.

Table 10. Drop Height 1.0 m, velocity 16.0 km/h, and material thickness 25 mm

Material type	Temp. (°C)	Peak acceleration (g)	HIC	Test number
Polystyrene	20.5	127	440	27089805
BB-38	25	140	560	15129801
E175	25	129	450	15129805
E900, 5.6 pcf	25	129	460	15129809
E900, 6.0 pcf	25	135	490	15129813
15 mm small celled honeycomb cardboard	16	285	1190	26059905
CF-45100	42	262	1120	27089808
CF-47100	41	270	1190	14099805
32 mm closed cell polyolefin foams	17	223	1050	24089806

Table 11. Drop Height 1.45 m, velocity 19.2 km/h, and material thickness 25 mm

Material type	Temp. (°C)	Peak acceleration (g)	HIC	Test number
Polystyrene	25.5	232	1090	17129802
BB-38	25.5	208	1120	17129804
E175	25.5	198	960	17129808
E900, 5.6 pcf	25.5	260	1530	17129813
E900, 6.0 pcf	25.5	227	1230	17129816
30 mm small celled honeycomb cardboard	25.5	104	440	17129816
CF-45100	25	282	1490	14089808

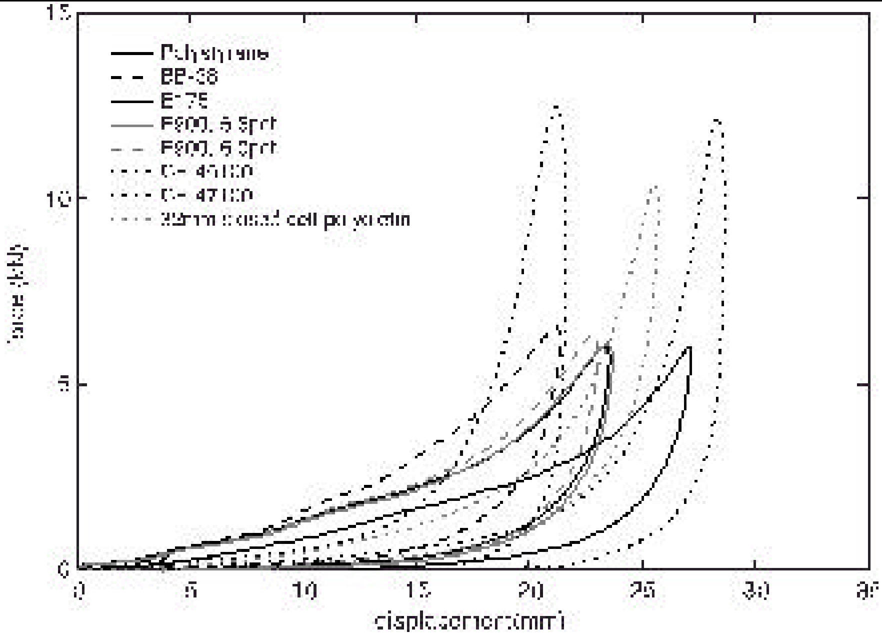

Figure 22. Force/deflection curves of various materials, 25 mm thick, drop height 1.0 m

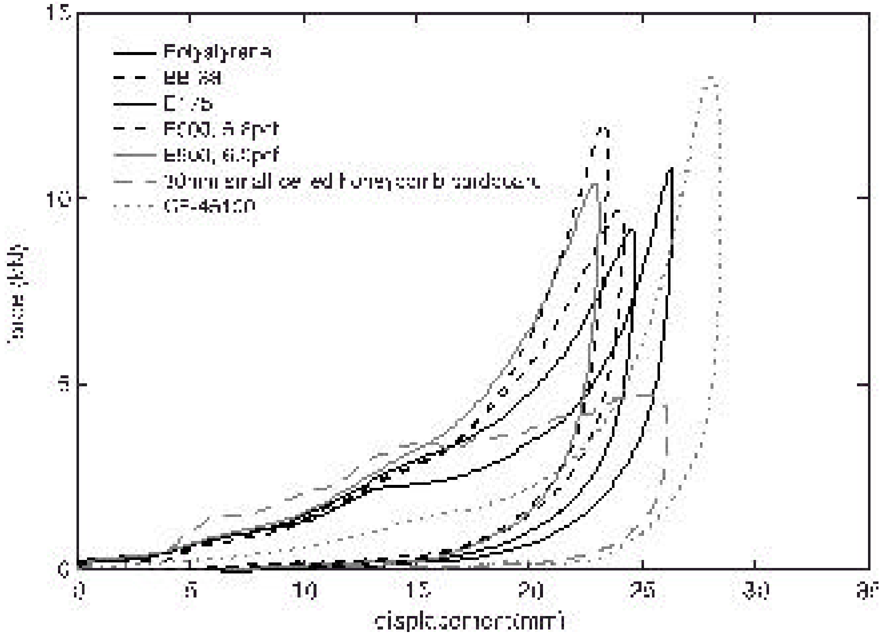

Figure 23. Force/deflection curves of various materials, 25 mm thick, drop height 1.45 m

3. Phase 2 testing

3.1. Method

Anvils are commonly stipulated by standards that govern the performance requirements of protective helmets. The helmets, attached to a standard headform, are dropped onto the anvils to test for the effects of concentrated loading. Under this type of loading, the energy absorption of the helmet will differ from that in an impact with a flat surface.

Phase 2 of this study used two standard helmet anvils; a sharp edged anvil, and a hemispherical anvil. The sharp anvil was constructed according to the Australian Standard "Helmets for horse riding and horse related activities" (AS/NZS3838:1998), and is illustrated in Figure 24. The hemispherical anvil was constructed according to the Australian Standard for methods of testing protective helmets "Determination of impact energy attenuation - helmet drop test" (AS2512.3.1), and is illustrated in Figure 25. Each anvil was mounted to the steel slab that was used for the phase 1 tests. A prototype headband was attached to the headform which was then dropped onto the anvil. The drop height was 1.3 m for the sharp anvil and 1.385 m for the hemispherical anvil, as specified in the relevant standard.

The criteria for the helmet standards is that the peak acceleration should be less than 300 g, and that the cumulative duration of acceleration should not exceed 3 ms for accelerations greater than 200 g and 6 ms for accelerations greater than 150 g. In this study, we have used the peak acceleration, the HIC value and the force/displacement curve as assessments of impact severity, to maintain consistency with the Phase 1 results. All data acquisition and signal processing was the same as in Phase 1 of this study. The drop testing setup is shown in Figure 26.

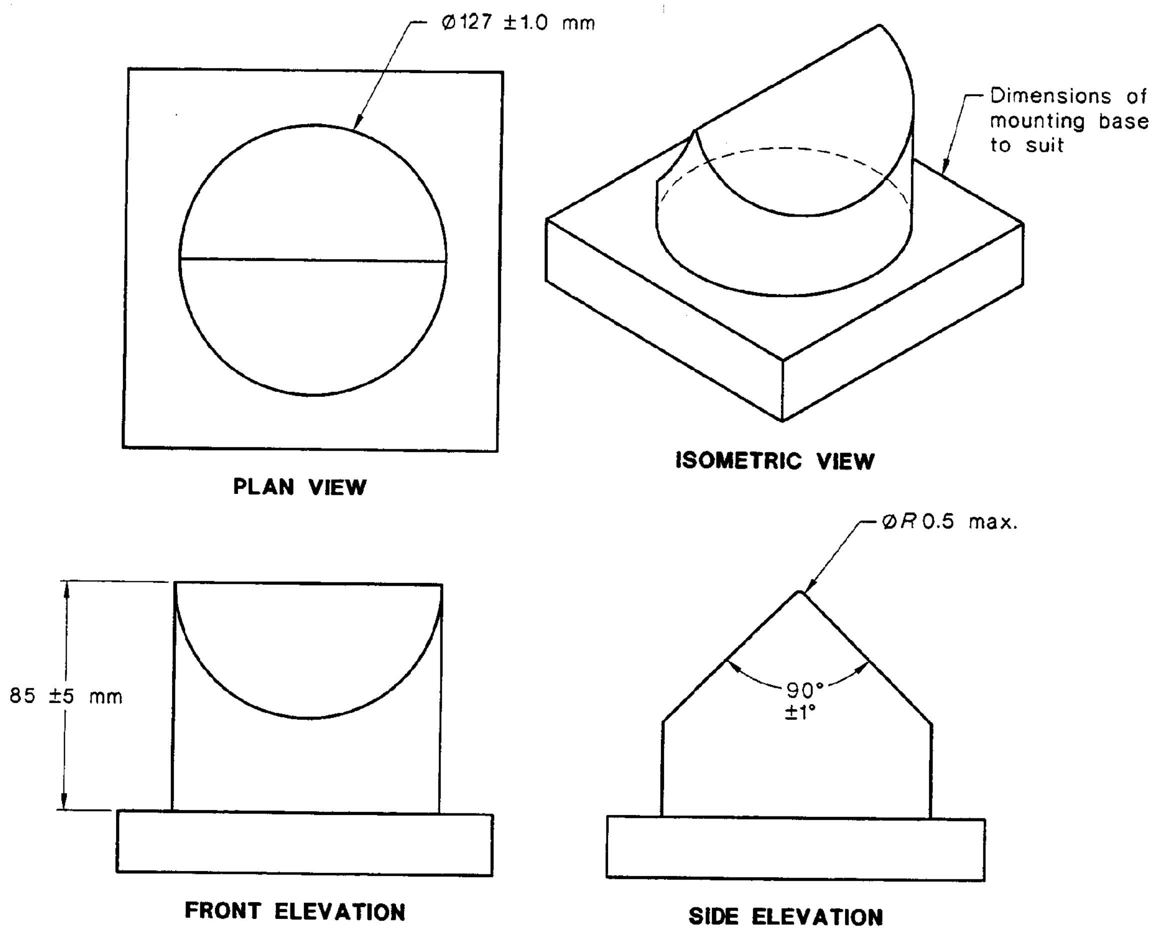

Figure 24. Sharp anvil for helmet testing from the Australian Standard "Helmets for horse riding and horse related activities" (AS/NZS3838:1998)

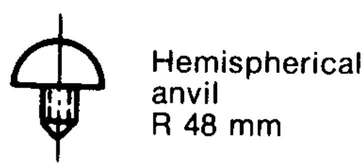

Figure 25. Hemispherical anvil for helmet testing from the Australian Standard "Determination of impact energy attenuation - helmet drop test" (AS2512.3.1)

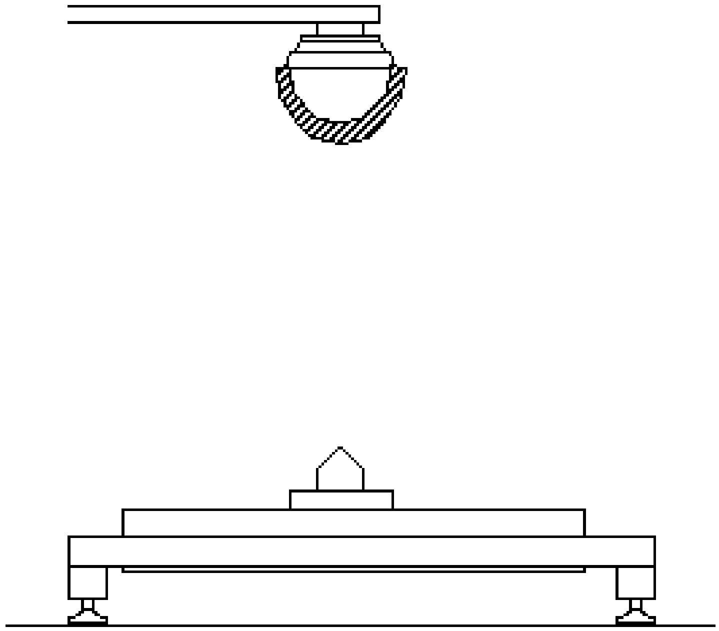

Figure 26. Phase 2 drop testing setup

3.2. Candidate Materials

From the analysis of the Phase 1 results, polystyrene foam, honeycomb cardboard and the polyurethane foams emerged as the most suitable materials for testing in Phase 2. The closed cell foams and viscoelastic foams were rejected from further testing as they did not perform well enough in the Phase 1 tests (see previous section). The materials tested in phase 2 are shown in Table 12. These materials were used to construct prototype headbands that could be attached to the EEVC WG10 headform.

Table 12. Materials tested in Phase 2

Material name	Supplier	Category	Thicknesses tested
Honeycomb cardboard 12 mm cell	Unknown*	Honeycomb Cardboard	15 mm, 30 mm
E175	Woodbridge Group	Automotive EA polyurethane foam	25 mm
E900, 5.6 pcf	Woodbridge Group	Automotive EA polyurethane foam	25 mm
E900, 6.0 pcf	Woodbridge Group	Automotive EA polyurethane foam	25 mm
BB-38	Woodbridge Group	Automotive EA polyurethane foam	25 mm
Polystyrene foam	Lactec Foam Products	Polystyrene Foam	25 mm

* Sourced from packaging material for automotive body panels

3.3. Results

3.3.1. HEMISPHERICAL ANVIL TESTS

The hemispherical anvil test is derived from the Australian Standard "Determination of impact energy attenuation - helmet drop test" (AS2512.3.1). The drop height specified in this standard (1.385m) was used in these tests. Table 13 summarises the results of tests that used this anvil to test the prototype headbands.

The results show that the best material was the 30 mm honeycomb cardboard with a hard shell, as it had the lowest HIC, at 260. This result is less than a third that of the next best performing material, BB-38, with a HIC of 860. Interestingly, the honeycomb cardboard without the hard shell performed similarly to the BB-38, with a HIC of 970. The remainder of the materials tested all had poor results in comparison with the BB-38 and the honeycomb cardboard, with HIC values between 1410 and 1740. The polystyrene sample shattered completely during the impact, which suggests that it is not suitable for a headband material without additional support (such as a hard shell).

Table 13. Results of headband tests on the hemispherical anvil (drop height 1.385 m, velocity 18.8 km/h)

Prototype description	Peak acceleration (g)	HIC	Test number	Damage to prototype
30 mm honeycomb cardboard	241	970	02069901	none
15 mm honeycomb cardboard in 4 mm PVC shell	290	1410	02069903	none
25 mm E175, polyurethane foam	286	1470	02069904	none
25 mm E900, 5.6 pcf, polyurethane foam	289	1520	02069905	none
25 mm E900, 6.0 pcf, polyurethane foam	320	1740	02069906	none
25 mm BB-38, polyurethane foam	185	860	02069907	none
25 mm polystyrene foam	348	1650	02069908	shattered
30 mm honeycomb cardboard in 4 mm PVC shell	87	260	09069910	none

The results of the hemispherical anvil test are shown in Figure 27. The 30 mm thick honeycomb cardboard with the hard PVC shell is clearly the best material in this test. The peak force is significantly lower than for the other materials. The next best material is the BB-38 polyurethane foam. All the other materials show about the same peak force.

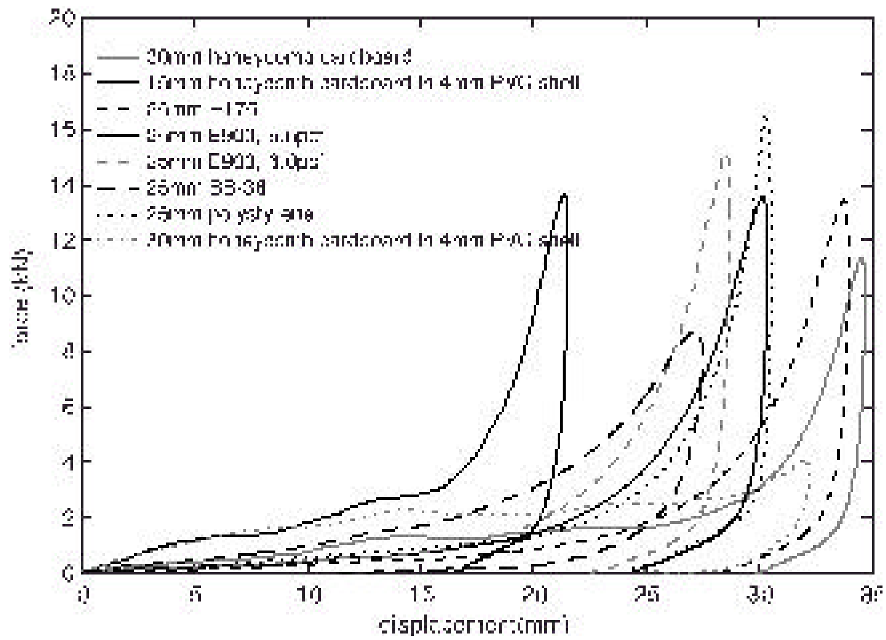

Figure 27. Hemispherical anvil drop test results

3.3.2. SHARP ANVIL TESTS

The purpose of the sharp anvil test was to ascertain the penetration resistance of the headband. It is derived from the Australian Standard "Helmets for horse riding and horse related activities" (AS/NZS3838: 1998). In that standard, the drop height is specified as 1.3 m. Tests were first performed at drop height 0.65 m, half the drop height given in the standard. This was so that the performance of the materials could be compared without risking damage to the headform. It was predicted that the sharp anvil might penetrate some of the test materials from the higher drop height.

The results from the tests performed from a drop height of 0.65 m are given in Table 14. The HIC results for all materials tested were very similar, ranging from 130 for the 30 mm honeycomb cardboard in a 4 mm PVC shell, up to 230 for 25 mm E900, 5.6 pcf. A better indicator of penetration resistance for this test is the condition of the material after the test. The headband made from 25 mm thick E900 (5.6 pcf) was cut halfway through by the sharp anvil, indicating a poor resistance to penetration. The polystyrene also performed poorly, shattering on impact with the sharp anvil. The BB-38 and honeycomb cardboard in the hard shell suffered no permanent damage from the test. The remaining polyurethanes (E175 and E900, 6.0 pcf) had a visible dent where the impact with the sharp anvil occurred.

Because of their good results in the tests performed from 0.65 m, the headbands made from 30 mm thick honeycomb cardboard (with a hard shell) and from 25 mm thick BB-38 polyurethane foam were tested from the full drop height specified by the standard. The intention was also to test, from this height, those headbands that suffered only denting at the lower drop height. However, only one of these tests was performed. The results from the tests at drop height 1.3 m are given in the second half of Table 14. The honeycomb cardboard with hard shell produced the lowest HIC, at 260. The BB-38 had the highest HIC, at 730. The 25 mm thick E900 polyurethane foam produced a HIC of 620, but was cut through completely by the sharp anvil. This headband provided little protection for the headform from the anvil; the headform sustained such damage that further tests on the sharp anvil at 1.3 m drop height were abandoned.

Table 14. Results of tests on the sharp anvil

Prototype description	Drop Height (m)	Velocity (km/hr)	Peak acceleration (g)	HIC	Test number	Damage to prototype headband
25 mm E175, polyurethane foam	0.65	12.9	86	190	09069900	Dent
25 mm E900, 5.6 pcf, polyurethane foam			97	230	09069901	Cut halfway through material
25 mm E900, 6.0 pcf, polyurethane foam			92	210	09069902	Dent
25 mm BB-38, polyurethane foam			77	180	09069903	None
25 mm polystyrene foam			111	220	09069904	Shattered completely
15 mm honeycomb cardboard in 4 mm PVC shell			92	210	09069905	None
30 mm honeycomb cardboard in 4 mm PVC shell			53	130	09069906	None
30 mm honeycomb cardboard in 4 mm PVC shell	1.3	18.2	71	260	09069907	None
25 mm BB-38, polyurethane foam			170	730	09069908	Dent
25 mm E900, 6.0 pcf, polyurethane foam			148	620	09069909	Cut through completely, and damage to headform

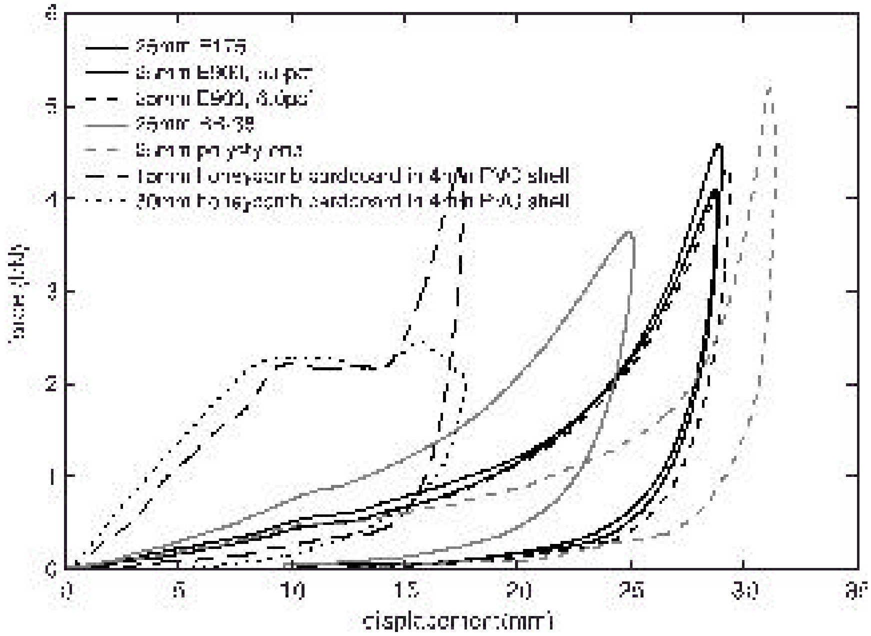

Figure 28. Sharp anvil drop test results

3.4. Discussion

The results presented in the previous two sections clearly show that the best performing headbands in these two tests involving concentrated impacts are the 30 mm honeycomb cardboard with the hard shell, and the 25 mm BB-38. Figure 28 shows that the honeycomb cardboard headbands are stiff in the initial phase of their deformation. The force is limited, however, by the crushing strength of the material, and it is only when it bottoms out that the force increases. It is noteworthy that the headband constructed from 15 mm of honeycomb had almost identical characteristics to the headband constructed from 30 mm of the material. Only when the displacement of the material approached 15 mm do the characteristics diverge. This suggests that the crushing strength of the honeycomb is not dependent on the thickness of the material.

Some of the poylurethanes are not suitable as headband materials on their own, due to a lack of penetration resistance. The polystyrene in the configuration tested (a simple 25 mm sheet) completely disintegrated in both tests. The results from the hemispherical anvil tests show that BB-38 polyurethane foam has good load spreading capabilities on its own, with out the need for a hard shell. The ease of manufacture that this would seem to imply indicates that this grade of polyurethane is also worthy of further investigation.

4. Phase 3 testing

4.1. Method

In phase 3, prototype headbands were constructed from the most promising materials identified in phase 2. These headbands were attached to an aluminium headform. The headform was fired at various internal structures of a vehicle to see how the headband reduced the severity of the impact. The EEVC WG10 headform could not be used in these tests because at the test speed (24 km/h) the guidance system did not prevent the headform from rotating before the impact. The aluminium headform did not suffer this problem at the test speed because it used an different guidance system.

The aluminium headform was designed by the Road Accident Research Unit for use in the reconstruction of pedestrian/car collisions. The headform has a spherical contact surface of 165 mm diameter, but is cylindrical about its long axis (Figure 29). This headform, which has a mass of 4.8 kg, is fired from a launcher at any angle between vertical (toward the ground), and horizontal. The machine is not currently configured to fire the headform at angles higher than horizontal.

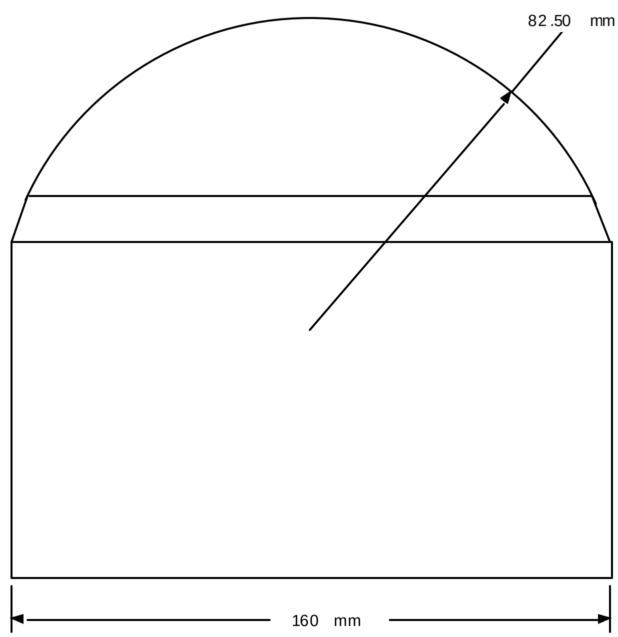

Figure 29. The aluminium headform used in Phase 3 tests

A 1977 Toyota Corolla station wagon was used for phase 3 testing. The site for testing was chosen based on three criteria: a) its involvement in impacts causing severe head injury in real life, b) its ability to sustain repeated tests without damage and c) the ability of the launcher to access the impact location. Unfortunately, this precluded sites where we felt that the headband should also be evaluated; the windscreen, front header rail, side rail, roof and door could not be tested as they were inaccessible to the launcher. The instrument panel, steering wheel rim and the D-ring assembly of the seatbelt were not tested as they were judged to be sites where tests would not be repeatable on one vehicle.

The site that was tested was the driver's side B-pillar. The tests were performed horizontally. We also attempted to test the hub of the steering wheel, and the A-pillar, but initial tests showed that the hub was deformed by each test and the impact angle for the A-pillar test was problematic, producing inconsistent results.

The tests were performed at a nominal speed of 24 km/h (15 mph), which is the speed stipulated by FMVSS 201. The criterion in FMVSS 201 is that the maximum acceleration in the impact should not exceed 80 g for more than 3 ms. However, the peak acceleration, the HIC value and the force deflection curves were used to assess each impact, to remain consistent with earlier phases of this study. The test setup is illustrated in Figure 30.

Figure 30. Test setup for B-pillar test. The photo was taken immediately after a test (Note that the RARU headform was used in the tests reported on in this report, not the EEVC WG10 headform as shown).

4.2. Candidate Materials

Phase 2 showed that the best prototype headbands were the ones constructed from the BB-38 grade of polyurethane and the one constructed from 30 mm of honeycomb cardboard with a hard PVC shell. Prototypes were constructed and attached to the aluminium headform (Table 15).

Table 15. Prototypes tested in Phase 3

Material name	Supplier	Category	Thickness tested
Honeycomb cardboard 12 mm cell, with a 200 mm diameter PVC shell	Unknown*	Honeycomb Cardboard	30 mm, with 4 mm PVC shell
BB-38 polyurethane	Woodbridge Group	Automotive EA polyurethane foam	25 mm

* Sourced from packaging material for automotive body panels

4.3. Results

4.3.1. B-PILLAR

A summary of results for B-pillar tests using the aluminium headform is given in Table 16. The force/displacement characteristics for these four tests are presented in Figure 31.

Table 16. Results from Phase 3 - Tests at 23 km/h horizontally against the B-pillar of a 1977 Toyota Corolla station wagon

Prototype description	Velocity (km/hr)	Peak acceleration (g)	HIC	Test number
30 mm honeycomb cardboard in a 4 mm PVC shell	22.8	78	280	17069901
25 mm BB-38 polyurethane	22.5	130	600	17069902
25 mm BB-38, repeat test	22.7	137	640	17069903
No headband	23.0	193	850	17069905

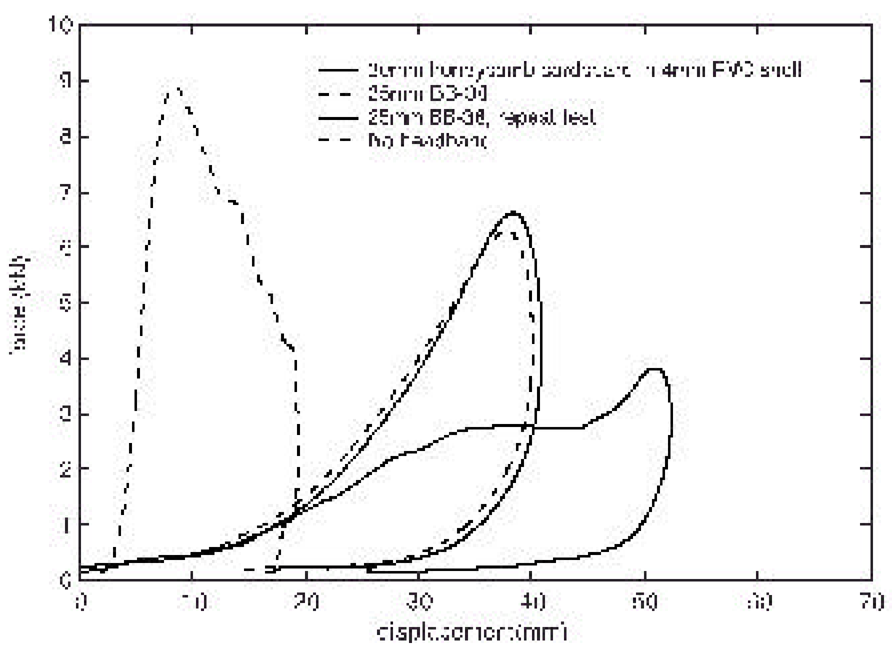

Figure 31. Phase 3, B-pillar Test Results

4.4. Discussion

Figure 31 clearly shows the headband's protective effect. The result of the test with no headband shows that the force rose sharply during the initial contact. The maximum displacement of the headform during this impact was around 20 mm. From the shape of the force/displacment curve it can be concluded that the deflection in this test is largely due to the dynamic deformation of the B-pillar structure.

In each of the headband tests, the contact between the headform and the B-pillar is less stiff than the contact between the headform and B-pillar with no headband. In each case, the peak acceleration and the HIC value were significantly reduced. BB-38 polyurethane reduced the peak acceleration by 29 percent and the HIC value by 25 percent. The honeycomb cardboard headband was even better at reducing the severity of the impact; the peak acceleration was reduced by 62 percent and the HIC by 67 percent. The peak force in this test was limited to between 2 and 3 kN, until the effects of bottoming out became apparent. This limiting value of the force was consistent for the honeycomb cardboard through all phases of the study.

By integrating the force/deflection curve, the work done in crushing the honeycomb can be calculated. The initial energy of the headform in test 17069901 was 96 Joules (calculated as $^{1}/_{2}mv^{2}$). By plotting the work done by the headband, against the displacement during the impact, it is apparent that approximately 70 Joules of work had been done by the headband before the honeycomb began to bottom out (Figure 32). This left the headform with approximately 27 percent of its initial energy at this point in the impact event. This is equivalent to the energy in an impact at about half the test speed (which would have 25 percent of the energy).

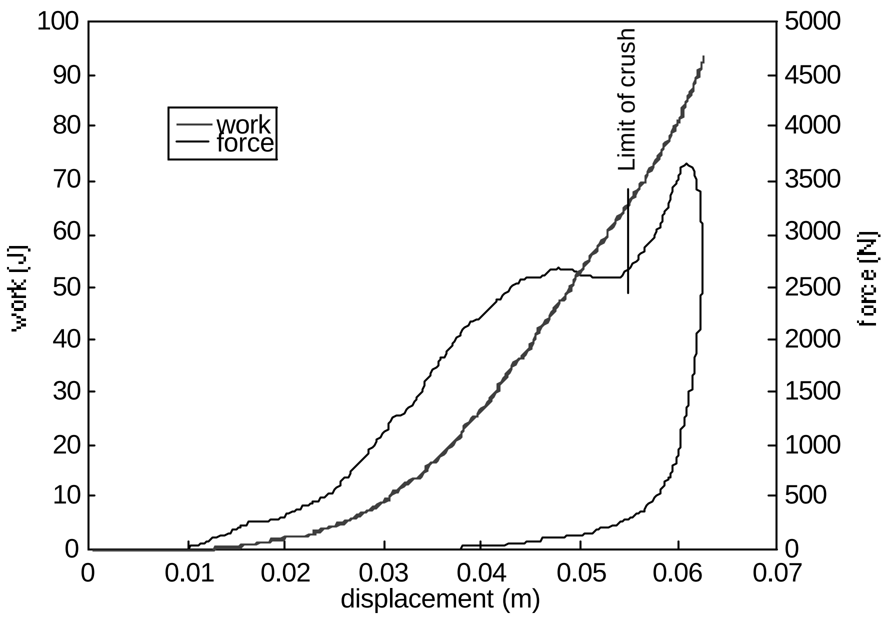

Figure 32. Force defelection curve and work done by the headband in test 17069901. The vertical line indicates the displacment at which the headband begins to bottom out. At this displacement, around 70 Joules of work had been done.

5. Conclusions and recommendations

The results from Phase 3 indicate that a headband can greatly reduce the severity of an impact to the head. HIC was reduced by 25 percent with the use of 25 mm of BB-38 polyurethane, and 67 percent with the honeycomb cardboard prototype, when compared with an impact with no headband. It is also noteworthy that the peak force produced in the test using the honeycomb headband was less than half the force produced by the headform alone. The honeycomb cardboard absorbed around three quarters of the impact energy before it began to bottom out.

The tests indicate that a crushable material, such as honeycomb, has the most effective characteristics for a headband. The ideal material would be one which

- Limits the peak force applied to the head
- Does so at a constant level from the initiation of the deformation
- Returns little energy to the head
- Does not bottom out

Practical considerations limit the thickness of the headband, so the challenge is to absorb the maximum amount of energy while limiting the peak loads transferred to the head of the wearer. In this way, the maximum amount of energy can be absorbed before the material bottoms out. Honeycomb is stiff initially when loaded, compared to polymer foams, but the peak load is limited by its inherent properties. The material stores little elastic energy, so the head of the wearer would be unlikely to rebound as severely as with some other materials.

One concern we had with the honeycomb cardboard is its durability. The material may deteriorate dut to environmental factors. There are several alternatives to paper, however, for the construction of a honeycomb structure. These include aluminium, polymers, and coated paper. These materials would give the same benefits as the honeycomb cardboard: energy absorption, force limiting characteristics, lightweight structure, but with the benefits of water resistance, and durability, in storage and handling.

The polyurethane headband also performed reasonably well in all phases of the tests. The BB-38 grade was the best performer of the polyurethanes. It may be possible to formulate a polyurethane with improved properties. However, at this time we have not seen a polyurethane which can match the honeycomb material in its behaviour.

We recommend that further investigation is made into materials of a honeycomb structure to find a material of the correct crushing strength and durability. We also recommend that prototypes be developed further to be included in a testing program that would include other vehicle structures tested over a range of velocities.

6. References

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