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EXECUTIVE SUMMARY

When buses and automobiles are involved in a collision or emergency braking, many injuries that may occur can be attributed to passenger impact with unpadded or inadequately padded structures such as steel seat framing and stanchions.

The Australian Design Rules (ADR) provide some guidelines for the prevention of life threatening injuries caused by head impact, but neglect to address the problems of "less serious" head injuries such as fractures and non-fatal facial (disfiguring) injuries.

Although many bus seat manufacturers routinely apply padding to new seats only potential lethal head injuries are considered during design and testing. Also there are many older style buses in service that have exposed metal framing around seats and as stanchions. This bare framing is a potential source for serious fractures and disfigurement. Public and private bus transport operators are thus faced with the necessity of applying padding to interior framing, such as seat rails and stanchions, to protect passengers against injury in the advent of a crash or rapid deceleration

This project was carried out to evaluate the impact attenuation properties of padding material to reduce the severity of those less critical injuries. The impact attenuation properties were evaluated with respect to maximum deceleration (g_{max}), Severity Index (SI) and Head Injury Criteria (HIC). Several readily available materials were evaluated and ranked according to those criterion.

It was possible to provide some preliminary ranking using static tests on materials samples and adopting minimum and maximum loads (generated) for some specific penetration. For example, using 50 mm x 50 mm samples, at a loading rate of 25 mm/min, could use a minimum load of 0.3 kN (to eliminate materials which are too soft) and a maximum load of 1.0 kN (to eliminate materials which are too stiff).

It is suggested that upper limits of HIC of 300 and a g_{max} of 100 be used to control impact performance, from some specified (crucial) speed (head impact velocity). A good estimate of the potential of a material to provide protection in low speed impacts is using the headform test from a drop of 0.75 m, representing about 14k/h impact. The impact values at this level should not exceed a HIC value of 300, nor a g_{max} value of 100, for 30 mm thick materials supported on a rigid test bed.

PADDING IN BUSES TO REDUCE THE SEVERITY OF NON-LETHAL INJURIES IN LOW IMPACT CRASHES

Keywords

injury, padding, impact attenuation, severity index (SI), Head Injury Criteria (HIC), trauma, deceleration, hazard, Hybrid III,

INTRODUCTION

When buses and automobiles are involved in a collision or emergency braking, many injuries that may occur can be attributed to passenger impact with unpadded or inadequately padded structures. In the case of buses there is an added variable in that passengers may be standing and thus more prone to suffer impact with the bus internal framing structure if deceleration occurs. The danger areas for impact are steel seat framing, stanchions, upper vehicle structures (sun visors and roofs) and steering columns.

The Australian Design Rules (ADR) provide some guidelines for the prevention of life threatening injuries caused by head impact, but neglect to address the problems of "less serious" head injuries such as fractures and non-fatal facial (disfiguring) injuries. This project was carried out to evaluate the impact attenuation properties of padding material to reduce the severity of those less critical injuries. The impact attenuation properties were evaluated with respect to maximum deceleration (g_{max}), Severity Index (SI) and Head Injury Criteria (HIC). The data collected was used to suggest some design guidance and to identify methodologies for future use in modelling the constitutive material properties of crash padding. The application of the research will result in cost effective reduction in injuries caused by low velocity impacts.

Although many bus seat manufacturers routinely apply padding to new seats only potential lethal head injuries are considered during design and testing. Also there are many older style buses in service that have exposed metal framing around seats and as stanchions. This bare framing is a potential source for serious fractures and disfigurement.

Public and private bus transport operators are thus faced with the necessity of applying padding to interior framing, such as seat rails and stanchions, to protect passengers against injury in the advent of a crash or rapid deceleration. They must also protect themselves against negligent torts by demonstrating "duty of care". Their problem is how much and what type of padding to apply to reduce injury potential to an acceptable level, thus demonstrating due duty of care. Previous research has evaluated the performance of the metal elements but little work has been carried out on the prevention or reduction of less serious injuries.

Significance and Importance

The benefits of improved padding to road safety are an improved travel environment for passengers in public and private bus transport. The use of low cost, and effective padding materials will reduce the number and severity of injuries caused when buses and automobiles are involved in a collision or undergo rapid deceleration. Injuries caused by exposed metal framing are infrequently life-threatening and most injuries sustained during rapid deceleration are fractures or facial disfigurement.

PRIOR RESEARCH AND LITERATURE

Head injuries are the most frequent and costly of all severe injuries to occupants of motor vehicles and 40% to 50% of the severe injuries are head related. Thus research has concentrated on the reduction of head injury in car and motorbike crashes and failed to address the "less important injuries" which can occur in public transport. Research has also been concentrated on pedestrian/car conflicts and helmet effectiveness for motorbike riders. In these cases very detailed and comprehensive neuropathology can be carried out as part of the postmortem process, and cadaver studies can be used to validate research findings. Thus car pedestrian impact zones and helmet effectiveness can be improved as crash analysis is relatively simple and post mortem and cadaver studies can be used for correlation.

The availability of data on non-lethal injuries is scant. Post crash analysis involves the careful investigation of crashes by matching injury type and severity with information about the crash environment, contribution of the vehicle furniture and any contributory negligence of the accident victim. In non-fatal bus accidents accident investigators are rarely involved as their scarce skills are required elsewhere such as providing data on fatal crashes. Thus little information is available on non-fatal bus injuries, and the small amount which is available is often suppressed due to legal proceedings and confidential terms of settlement.

HEAD-NECK INJURIES

Goldsmith and Ommaya (1984) studied the determination of tolerances of the human head-neck system to non penetrating blows or impulsive loading. Such tolerances cannot usually be determined by direct measurements in living humans and must be deduced from indirect data using a variety of techniques. These include the examination of human accident data and the use of suitably instrumented human surrogates, e.g. human cadavers and animal models subjected to controlled impact (rapid deceleration) or acceleration loading. Human volunteers have been used to obtain low level data e.g. non injurious head/neck kinematics. Other ingenious physical models including anthropomorphic dummies (headforms) of more exacting proportions which seek to replicate the more crucial structural details of the head and or neck and these have also been developed to examine their response using suitable instrumentation. Data collected from these methods have been used to develop tolerance levels in human beings by either direct application, extrapolation, scaling or other procedures using mathematical techniques. The damage processes described were presumed to cause trauma observed in the neck. These range from absence of any effect, to lethality.

The first theoretical and experimental studies on head injury mechanisms were conducted several decades ago during World War II at Oxford and Wayne State University (WSU). Experiments using cadavers carried out at Wayne State from early 1940 led to the still widely used WSU head injury tolerance curve. This curve still forms the basis for specifying most impact criteria although it has been said (Glaister 1982) that the WSU curve is a hodgepodge of data from cadavers, animal experiments and human whole body experiments which does not relate to brain injury (Newman 1982). It should also be noted that more recently that the early WSU work has been questioned, as inadequate experimental design and data acquisition may have led to inaccurate deceleration being measured.

Since the development of the Wayne State tolerance curve mathematical modelling of impact processes have developed to increasing levels of complexity. Goldsmith and Ommaya (1984) emphasised that either a rigid-body system consisting of a few spring-mass-dashpot elements as well as of a large number of lumped parameters or a continuum-mechanical approach can be applied for these mathematical processes. Such tools have been used to reconstruct the dynamics of real world accidents where the initial conditions and impact configuration were reasonably well known to establish a tolerance level by relating the critical mechanical variable to the observed level of trauma.

The use of mathematically modelling using finite elements methods (FEM) is often viewed with some skepticism due to the complexity in modelling the response of the human head and neck to transient impact loads. The problems are caused by:

- The skull material which is formed of 2 outer hard layers separated by the diploe cellular layer. Skull thickness varies accordingly to location, age, sex and many other variables.

  The pressure distribution within the skull is influenced by the shape of the skull and its deformation characteristics (which will vary as indicated above).

  Impact may be dampened (attenuated) by scalp material, the durs layer and cerebral fluid.

  The muscle system of the neck and shoulders is complex, extremely variable and the response very difficult to model in elastic, visco-elastic and even non-linear elastic models.

As desk top computing power becomes more available the FEM techniques will be developed to a point where simplistic modelling can be successfully applied for a limited range of variables.

DEFINING INJURY LEVEL AND IMPACT CRITERIA

The following are some definitions of injury severity levels, injury criteria and tolerance levels types of Head Injuries from the EEC Biomechanics program. A consensus report was produced defining these terms.

Injury Level and Injury Severity Level

This term denotes the magnitude of changes in terms of physiological changes and/or structural failure which occurs in a living body as a consequence of mechanical violence. The AIS scale is wide used for this purpose but other scales have also been proposed. Clinicians group head injury victims into the following 5 categories.

1. Head injury with no brain damage
2. Head injury with brain damage, but no clinical sequelae
3. Head injury with survivable brain injury, but which result in clinical sequelae
4. Head injury with survivable head injury, but in where death occurs due to secondary complications
5. Head injury which is primarily non-survivable.

The type of head injury, including facial damage, which is the subject of this project would tend to lie in categories 1 and 2. In some cases injuries may occur which are considered as non-hospital admittable or may be treated by dental surgeons.

Injury Criterion

This term denotes a physical parameter which correlates well with the injury severity of the body region under consideration. Currently the HIC is the accepted criterion for head injury but the precision of its correlation is being questioned.

Tolerance

This term denotes the magnitude of loading of a living body or body part which produces a specific type of injury and injury severity level. When used this term must be specified by defining the following aspects: the physical parameter expressing the magnitude of loading, the type of living body (animal or human, sex and age), the type of body part what kind of injury and what injury severity level is being considered.

Severity Index (SI)

The first of the current practice to separate the brain injury generation mechanisms into those resulting from linear or angular motion is the Wayne State Tolerance Curve. This shows the demarcation line of the onset of concussion. The curve is based on the hypothesis that the dominant head injury mechanism is linear acceleration. As indicated earlier the initial work was based on six experiments on embalmed cadavers striking rigid surfaces at the forehead in the duration range of 1 m/s to 6 m/s. These results were correlated with concussive effects generated in animals and were later supplemented by additional experiments on primates and cadavers and the employment of long-duration acceleration tolerance information from human volunteers. The work carried out by Wayne State represents one of the cornerstones for a biomechanical injury criterion serving as a standard comparison for more recently suggested models. Within a few years a more concentrated effort was made to represent WSTC in following analytical form:-

$$SI = \int_{t1}^{t2} [a(t)]^{2.5} dt$$

A tolerance level of SI<=1000 was stipulated as acceptable. Because of certain uncertainties the possibility of replacing the weighting factor 2.5 by a acceleration dependent quantity was considered.

Head Injury Criteria (HIC)

NHTSA has mandated the use of the following modified term based on a time averaged, weighted acceleration expressed in the form of the Head Injury Criteria and defined by the relation:

$$HIC = Max \left[1/(t2 - t1) \int_{t1}^{t2} a \, dt \right]^{2.5} (t2 - t1)$$

where the times t1 and t2 are two arbitrary instances of the pulse history chosen to obtain the maximum value of the function. This was supposedly an improvement over the SI by concentrating on the most dangerous part or portion of the acceleration/time-history which was bound to take into account the rate of load application. The limit of 1000 was placed on the permissible HIC value, although there is some literature suggesting a tolerance level of 1500 based on free-fall cadaver investigations.

The requirements have been in effect for the testing of vehicular restraint and padding systems in conjunction with designated dummies for nearly a decade. US Federal safety standards for restraint systems, occupant protection and dummy construction have stipulated a performance requiring a maximum HIC value of 1000 during a specified test operation. There is also a limitation of an 80 g level maintained for 3 ms or less in the impact of a 6.82 kg headform striking an instrument panel at a relative velocity of 24.2 km/h.

Head Impact Tolerance Levels.

Research from a different approach ie. from the testing and finding suitable materials for motor-cycle helmets (Corner, Costello and Whitney 1985) demonstrated that the head impacts are of similar biomechanical mechanisms. The most serious head injuries are those involving brain injury, with cerebral lacerations the worst, followed by cerebral contusions and cerebral concussions. These are more serious when accompanied by skull fracture, especially open fractures, with depressed fracture the worst case. The principal mechanism of head injury is impact. Soft tissue external injuries (ie., scalp and face injuries) occur at low impact energy levels and are dependent, to a large degree, on the surface characteristics of the impactor. At higher energies fractures occur, while at the highest levels the more serious head injuries of concussions, cerebral contusions and cerebral lacerations occur.

The mechanism producing skull fracture is force applied to the skull with sufficient magnitude to crack or break bone. The fracture is usually, but not always localised to the point of impact. The type of fracture is also predicted on the magnitude of the force and the shape, hardness and area of the impactor. The mechanism of skull fracture is localised to the area of the skull receiving the blow.

Table 1. Head Impact Tolerance

Researcher	Head Impact Tolerance	Comments
Slobodnik (1979)	150g	US Army helicopter helmets
Otte et al. (1984)	1000g	Motorcycle crashes
Sarrailhe (1984)	300g	Motorcycle helmet, rigid headform peak g.
Carden (1983)	120g	passengers in air crashes
Mohan et al (1979)	200 - 250g	brain damage in children
Jeavons (1984)	60g	no concussion in children
King and Ball (1989)	200 g	serious injury
	150 - 200g	moderate injury
	50g	no serious injury

In determining the tolerance levels, factors other than magnitude of the impact can have an effect on head tolerance levels. The following other factors need to be taken into account such as location , direction, surface area of impactor, surface hardness of impactor, surface roughness of impactor, impactor mass, impactor velocity, and crushing characteristics. However, with fractures the magnitude of the force needed to produce the fracture is the determining factor. In the case of motor cycle helmets, to be effective in mitigating fractures, it should transmit no more then 900 psi (6.2 MPa) at the forehead and no more than 450 psi (3.1 MPa) at the temporal-parietal region. Some of the suggested head impact tolerances recommended are listed in Table 1.

UPPER INTERIOR PADDING IN VEHICLES

The upper interior structure of a vehicle has been shown to be a significant cause of head injury. Published research by the National Highway Traffic Safety Administration (USA) shows that the head injury criterion (HIC) is reduced by 50% when 25 mm of an "optimum" padding is applied to the upper vehicle structure. Research by Digges et al involved applying a load to sun visors and he describes a test method for evaluating the effectiveness of their head protective padding. The head of a Hybrid III dummy was impacted against the sun visor and the resulting HIC used to measure the visor effectiveness in reducing head injury potential.

These preliminary test results of 20 sun visors from 1991 model cars shows a wide variation in the HIC readings measured by the dummy head. Some of Digges et al methodology has been adopted during this study as a basis for evaluating the head injury protection of padding material. Material to be tested are similar in shape to the padding used in sun visors. In the paper a HIC in the range of 300 - 350 was considered "low", with respect to injury potential. This threshold value may be of use in determining a maximum threshold value for preventing serious injuries.

SEVERITY AND EVALUATION OF FACIAL INJURIES

Research by Yoganandan et al (1991a) used "12 fresh cadavers heads" to determine the impact biomechanics of facial skeleton secondary to steering wheel loading. These tests were conducted using a vertical drop impact test system because of the particular relevance of the zygomatic bony complex in facial trauma in motor-vehicle accidents. The zygoma of the cadaver was impacted onto either a soft or rigid steering wheel surfaces at velocities up to 6.7 m/s.

The specimens were dropped from a predetermined height of 0.15 m to 2.29 m at velocities ranging from 1.7 m/s to 6.7 m/s. Velocities above 6.7 m/s were not considered in the study because airbag restraints systems deploy beyond this speed. The peak impact forces at the cadaver zygoma were computed from generalised force and deformation histories using matrix principles. Structural abnormalities were assessed using pre-test and post-test plain radiography, two or three dimensional computed tomography, and defleshing techniques, the latter to determine the level of facial fracture.

All data collected during impact tests were collected using a modular digital data acquisition system with pre-designed amplifiers and appropriate initialising filters. The sampling rate exceeded 8 kHz. The signals were processed according to the Society of Automotive Engineers (SAEJ211b) specifications. The data included the force and moment histories from the six axis load cell, deformations of the wheel under the impact site and acceleration of the specimen. At impact velocities of 1.7 to 6.7 m/s, the human cadaver zygoma did not exhibit clinically significant fractures if the peak force was below 1335 N for the soft wheel interface and 1153 N for the rigid wheel interface. Consequently, to mitigate facial injuries due to unsupported rim impact, the data from this study suggests that the peak dynamic force should be kept within these limits.

Further testing and analysis by Yoganandan et al (1991b) was carried out to evaluate injury criteria. Using the cadaver heads either zygoma was impacted at a velocity of 2.0 m/s to 6.9

m/s. Again the more severe fractures were associated with higher forces on the zygoma. With increasing velocities fractures initiated at the zygomatic region propagated to other unilateral regions such as the mandible and orbit or to the contralateral side. Less facial trauma was observed with energy-absorbing steering wheels compared with standard wheels at similar impact velocities. Bone mineral content did not correlate well with specimen age or with fracture severity. Variables such as depth of zygoma skin cover (8 to 15 mm) made it difficult to obtain any definitive correlation, however the work does suggest that only minor fractures will occur if the impact force can be kept below 1.0 kN to 1.5 kN, dependent upon level of padding.

Table 2. Summary of cadaver data after Yoganandan (1991b)

Test	Impact Vel. (m/s)	Vertical Force (kN)	Vertical Deceleration	HIC	Fracture Severity
A/EA	6.93	4.6	70-75	383	4
B/EA	6.93	4.6	70-75	341	4
C/EA	4.47	2.4	25-30	123	4
D/EA	3.58	1.8	20-25	58	4
E/EA	3.13	2.1	25-30	65	2
F/EA	2.68	1.5	15-20	33	0
G/SD	3.13	2.6	40-45	109	4
H/SD	2.68	1.6	25-30	42	3
I/SD	2.68	1.7	25-30	45	2
J/SD	2.24	1.9	25-30	45	4
K/SD	2.24	1.5	15-20	23	4
L/SD	2.01	1.4	15-20	30	0

It was not made clear in the analysis if the increased threshold force for padding was due to energy absorption or simply an increased impact area. If the work by Nyquist et al (1986) is also considered, which recommends a maximum force of 3.0 kN to avoid serious facial injury, then the 1.0 kN to 1.5 kN limits recommended by Yoganandan et al (1991b) seem to be of the correct magnitude.

CURRENT AUSTRALIAN BUS PADDING CRITERIA

The Australian Design Rules (ADRs) relevant to providing energy attenuation for impact are ADR21/00 and ADR 69/00 "Full Frontal Impact Occupation Protection" and ADR3/02 "Seats and Seat Anchorage. Testing commissioned by Queensland Transport in 1993-1994 at Queensland University of Technology could be summarised as follows (Schleimer 1994):

- old style metro style seats can meet ADR3/02 with existing steel structures.
- padding fitted to a metro seat handrail general reduced gmax but not the HIC.
- new style metro seats can easily meet ADR3/02 if structurally adequate
- typical stanchions can meet ADR21/00 criteria.
- padding a rigid round bar did not provide any significant improvement with respect to ADR21/00.

Queensland Transport probably are the leaders in Australia for the development of guidelines for provision of bus safety padding and a information bulletin VSS.12.6/94 was issued which provided information for the upgrading of bus padding safety standards. Those upgrades are to be completed by 1 January, 1996. Based on the testing carried out at the Queensland University of Technology, Queensland Transport indicated that the following padding materials (minimum 25 mm), "showed acceptable improvement in passenger protection when applied to a typical metro style seat", without qualifying what constituted acceptable improvement.

.	Moulded polyurethane	SG. 0.4 to 0.6
.	Ultrathon polyethylene	density 75 to 120 kg/m^3
.	Vinyl covered reconstituted foam	Grade 150

Schleimer also recommended that further research should be done to define a simple criteria for non life-threatening facial injuries and to develop a simple test procedure to measure that criteria.

PROJECT RESEARCH

The review of the available literature indicated that very little data existed which could be used in the project. The best data which could be applied to the project was that by Yoganandan et al (1991a, 1991b) which provided some guidance on the force and impact energy required to cause fracture of cadaver zygoma and that by Digges et al which suggested that a HIC of around 300 - 350 represented low injury serious potential. This level of injury was considered typical of the non-life threatening, but potential disfiguring, type of injury which may be sustained in buses with bare metal support structures or with inadequate padding. Since most tolerance levels (including those in the ADR) are based on g_{max}, HIC or SI, it was considered important that some correlation should be obtained for relating the recommendation proposed by Yoganandan to those other established tolerance criteria.

TEST DEVICE AND EXPERIMENTAL PROCEDURE

In selecting the test procedures and instruments for evaluating the energy absorbing (attenuating) properties of padding material, several requirements were considered. The test instrument must provide objective data which is representative of conditions which produce injury. The injury measure used must be applicable to the injury being evaluated. Finally the test must be accurate, repeatable, and economical to conduct.

The development of an objective test instrument to measure injury was based on many years of research previously by the US government and the automobile industry. The Hybrid III dummy and HIC are used in measuring head injury potential in the US Federal Motor Vehicle Safety Standards and that headform was adopted. This type of headform is also specified in the ADR and in the proposed standard for providing impact attenuating undersurfacing material in children's playgrounds. The headform was a rigid hemispherical shape with a radius of 82.6 mm and a total mass of 6.8 kg. An accelerometer was secured and fastened within the headform within $\pm$ 5 degrees of the vertical axis at impact.(Standards Australia Committee CS/5 on Playground Equipment).

The Hybrid III dummy head is used extensively in the US NHTSA (National Highway Transportation Safety Administration) to evaluate head protection in motor vehicles. The NHTSA researchers use a pneumatic propulsion device which accelerates a HYBRID III head to linear velocities of 20 to 25 mph (32 to 40 k/h). The headform is unconstrained at impact, and is consequently called a Free Motion Headform (FMH). There were some difficulties found by Ford on the repeatability and accuracy when evaluating the NHTSA, FMH. These were:

- part of the impact is mitigated through rotational acceleration which is not measured,
- the varying curvature of the dummy head produces varying impacts, and
- the facial projections such as the nose and chin produced variations.

By using the ADR headform as described above, the deceleration vector is in the direction of the centre of gravity of the head and rotational acceleration is thereby minimised. This test setup configuration is similar to that used in cadaver tests conducted by Wayne State University, upon which the HIC criteria for short duration impacts were based.

The drop test has been used because of its simplicity, low cost, and repeatability. The test consisted of a two piece carriage, an anvil on which the test specimen is placed (at least 100 times the mass of the headform) and an instrumented headform. The machine is operated by raising the carriage to the desired height and then releasing it, letting the headform fall and impact the padding material at the end of the fall. During the impact an accelerometer mounted at the headform centre of gravity measures the acceleration/deceleration. Impact velocity is calculated by the triggering of two light sensors as the headform passes. The second light sensor is also used to engage the data acquisition system immediately before impact. A PC based data acquisition system then records the data from the accelerometer. The total system should be capable of measuring impulses up to 500 g at frequencies from 2 to 1000 Hz with an accuracy of $\pm$ 5%.

The carriage is raised and lowered by hand and is guided by two cables with a maximum drop height of approximately 3.0 m. The carriage holding the headform is connected by a small hook and the head assembly aligns by its own weight. The carriage is released by a solenoid switch and the headform is guided by the wires to impact the test specimen. The material to be impacted is secured to the anvil (concrete block) which has a 30 mm thick steel plate fastened to its surface. This surface can be considered rigid when impacted by the headform.

Research Design

The research program was designed to link good experimental investigation with established criteria to produce guidelines for the use of padding material in buses. This will hopefully assist in the future preparation of predictive models for crash protection materials, formulated to assist in the evaluation of potential materials. At present seat manufacturers have limited knowledge of the performance of the available materials. The study will quantify safe deceleration and limiting velocity impact levels for some padding materials typically available on the market. The design incorporates a systematic approach where research is conducted in discrete stages, each acting as a building block as the study develops. Impact attenuation techniques were used to determine maximum deceleration (g_{max}), Severity Index (SI) and Head Injury Criterion (HIC). The data will then be correlated with the criteria proposed by Yoganandan et al (1991a,b)

Semi-Static Material Strength Parameters

The semi-static material strength and stiffness parameters were evaluated using an INSTRON servo-electric universal testing machine, and linear variable displacement transducers (LVDT) as well as high speed data acquisition apparatus. Each material type was subjected to compression using a standard 50 mm x 50 mm sample, over a wide spectrum of loading rates to identify the response of material stiffness to changes in load rate. This phase of the project allowed some preliminary ranking of materials and qualitative prediction of performance under high speed impact.

Subsequent to testing the 50 mm x 50 mm samples some larger specimens were also tested using the headform at load rates up to 500 mm/min.

Impact Attenuation and ADR (Australian Design Rules)

Some materials were subjected to impact from the same headform used in the semi-static testing. The headform was dropped from a range of heights to control impact velocity. Earlier work carried out for Queensland Transport (Bullen 1993, 1994) concluded that the total impact response is a combination of padding and the supporting structure. A rigid support was used to eliminate any impact attenuation caused by the material test anvil.

Testing was carried out according to ADR 3/02 "Seats and Seat Anchorage and ADR 69/00 "Full Frontal Impact Occupation Protection". The data acquisition equipment used met the requirements of SAE J211 1980. The padding tests involved subjecting the material to impact from a guided-falling steel headform, released from a range of heights with the impact velocity being measured in each case. The impact response of the accelerometer mounted in the headform was sampled and analysed using the "LABTECH NOTEBOOK" data acquisition system. The deceleration/time history profiles were established for each drop and HIC, SI and g_{max} data from these and example plots are provided later in the report.

TEST MATERIALS

In the earlier work carried out by QUT, testing was carried out for Queensland Transport to determine the impact resistance of the following materials. (refer to reports CET3903 and CET 3903/1, Bullen, 1993).

MCMU	McConnell Moulded Urethane Crash Pad
PMU03	Polyrim Moulded Urethane 20 mm 0.3 SG
PMU04	Polyrim Moulded Urethane 20 mm 0.4 SG
PMU05	Polyrim Moulded Urethane 20 mm 0.5 SG
D_PE60	Dunlop PE 60 30 mm
D_PE75	Dunlop PE 75 30 mm
D_PE120	Dunlop PE 120 30 mm
SUP32	Superlon 32 mm with Vinyl Cover
DUNC150	Dunlop C150 Crumbled Foam

MATERIAL TESTING

The project collated previous work carried out by Queensland Transport, and the new data to relate the dynamic loading of padding material to an equivalent semi-static load test. This would assist in the development of some guidelines which could be used by padding material manufacturers for evaluation of their products.

From the work by Yoganandan et al. (1991a,b) the theoretical threshold for breaking of bone (zygoma fracture force) is shown from literature in Table 4 below. Based on that data a maximum load of 5 kN was used in the semi-static testing, equating to a stress of 2.0 MPa on the 50 mm x 50 mm samples used.

Since it is generally considered that 200 psi (1.4 MPa) is the threshold for the breaking of bone (Schleimer 1994), the 5.0 kN force used was more than adequate as an upper limit in the static testing carried out on the materials.

Table 4. Zygoma fracture forces

Investigator	Year	Tolerance Level	Salient Experimental Features
Hodgson	1964	1441- 6272 N 91 - 372 G	Rotary Impactor at 1.27 to 9.81 m/s, 64-91 years of age, embalmed specimens with skin removed, multiple blows
Swearingen	1965	50 - 80 G	Specimens 26-74 years of age, tissue filled gelatin, Impact using a catapult
Hodgson	1967	1121 - 1663 N 1761 - 3363 N	Using 1 inch square impactor. With 5.2 inch square area using 2.56 inch diameter impactor, multiple blows to embalmed specimens 53-87 years of age at velocities up to 7.86 m/s
Nahum et al.,	1968	912 - 2470 N	With 1 inch square impactor specimen 55 to 81 years of age
Schnelder and Nahun	1973	970 - 2850 N	Dropped 1.5 kg weight at velocities of 4.2 to 5.2 m/s specimen 45 to 80 years of age, multiple blows

Static Testing

A subset of the 9 material types tested previously by Queensland Transport was chosen to reduce the number of variables. The materials selected were:

PMU04	Polyrim Moulded Urethane 20 mm 0.4 SG
PMU05	Polyrim Moulded Urethane 20 mm 0.5 SG
D_PE60	Dunlop PE 60 30 mm
D_PE75	Dunlop PE 75 30 mm
D_PE120	Dunlop PE 120 30 mm
SUP32	Superlon 32 mm with Vinyl Cover
DUNC150	Dunlop C150 Crumbled Foam

The selected materials were cut into 50 mm x 50 mm squares and customised steel loading platens were fabricated to fit the load jaws of the INSTRON machine. Load rates of 5 mm/min, 25 mm/min and 100 mm/min were used and the load deflection plots obtained in an ASCII file format, later transferred to MS-EXCEL format.

A self calibrating 30 kN load cell was used for the compression tests. A cross head deflection check test was also carried out to verify accuracy using a 0.01 mm dial gauge. There was little difference between the compression tests at the 3 loading rates of 5 mm/min, 25 mm/min and 100 mm/min (also see Table 4 and Figure 2).

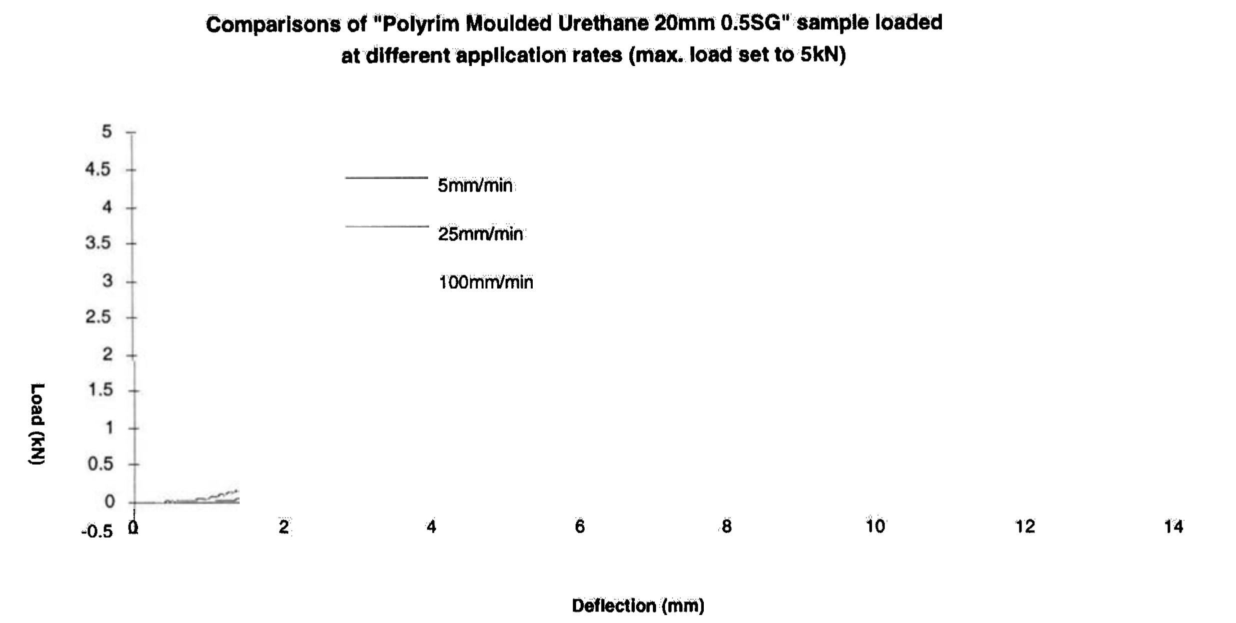

Figure 2 . MS Excel plot of results of load (kN) versus deflection (mm) tests,

The second phase was to use the impact headform for static testing of the samples at load rates of 25 mm/min and 500 mm/min). The 25 mm/min allowed correlation with the earlier static testing and the 500 mm/min was used to simulate low velocity dynamic impact. A larger steel base platen was fabricated to accommodate the headform and a larger 150 mm x 150 mm sample size used.

Impact Testing

The impact testing rig was set up according to ADR and the deceleration-time pulse recorded digitally by the appropriate instrumentation. These results were then down loaded and analysed using spread techniques for HIC, SI and g_{max} values. The materials tested are shown below.

- Dunlop C150 Crumbled Foam 30 mm
- Dunlop PE60 30 mm
- Dunlop PE75 30 mm
- Dunlop PE120 20 mm
- Polyrim Moulded Urethane 0.4 SG

The Dunlop PE120 material was not available in 30 mm form in 150 mm x 150 mm and a 20 mm thickness was used. The materials were impacted using the standard headform from different heights on the custom built test rig described earlier.

The drop heights were 0.5 m, 0.75, 1.0 m, 1.5 and 2.0 m as heights above this resulted in very high HIC values and the headform penetrating the material. Duplicate tests were carried out for each drop height on each material. Typical impulse plots are shown in Figures 3 and 4.

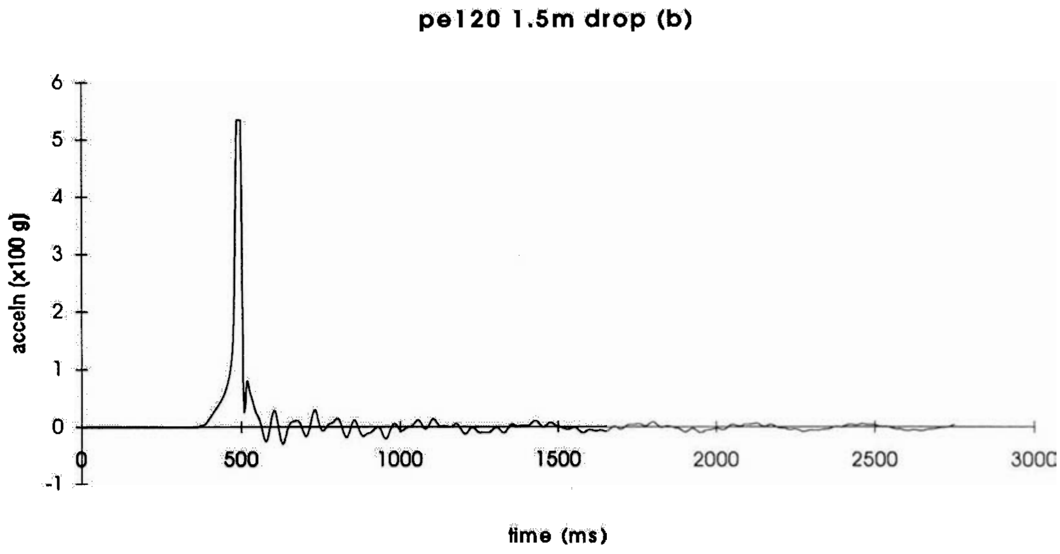

Figure 3. Deceleration impulse for PE120, from 1.5 m.

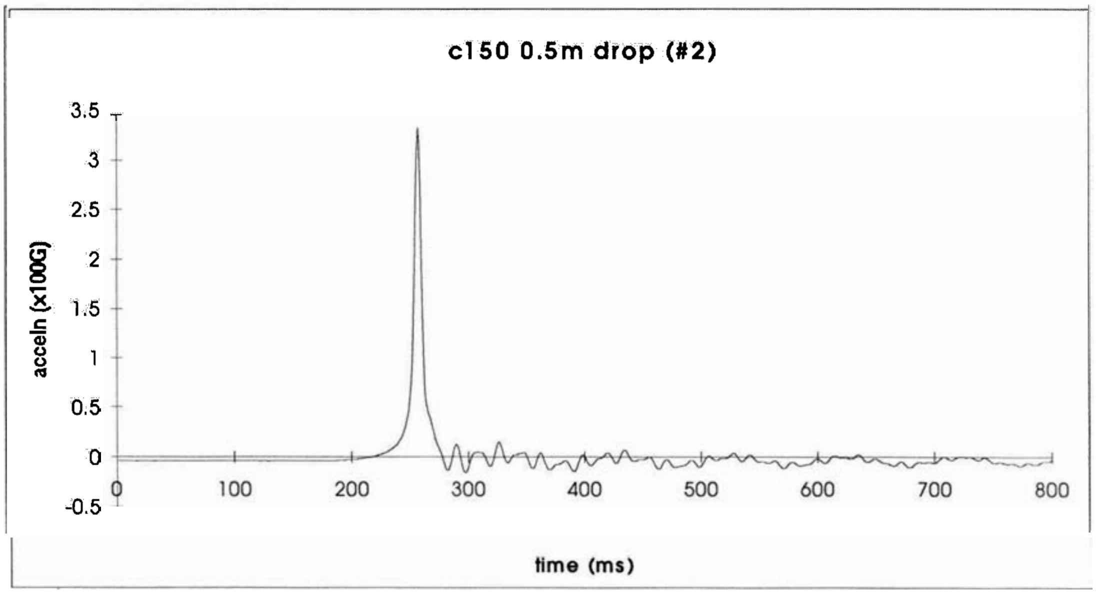

Figure 4. Deceleration impulse plot for C150 from 0.5 m

TEST DATA

STATIC TESTING

The test data from the INSTRON testing machine were ranked using 2 criterion. They are described below. Those rankings will be compared to those obtained for HIC and SI under dynamic testing. The **bolded** data in Table 4 is for material tested using the headform.

- The force required to penetrate 15 mm into the material, and
- The distance penetrated at a force of 2.0 kN.

Table 4. Summary of material ranking under static loading

Material	Load Rates (mm/min)	Load (kN) at 15 mm	Penetration (mm) at 2 kN
Dunlop C150 30 mm	5	0.10	26.7
	25	0.10	27.7
	100	0.15	27.0
	25	**0.11**	**21.8**
	500	**0.19**	**28.5**
Dunlop PE60 30 mm	5	0.41	26.0
	25	0.43	25.3
	100	0.46	25.6
	500	**0.96**	**22.4**
Dunlop PE75 30 mm	5	0.46	24.6
	25	0.53	24.5
	100	0.55	22.9
	500	**1.08**	**21.4**
Dunlop PE120 30 mm	5	0.89	22.0
	25	0.96	21.7
	100	0.96	21.4
Polyrim 0.4 SG 32 mm	5	0.36	23.6
	25	0.41	22.5
	100	0.46	22.9
	500	**0.58**	**22.9**
Polyrim 0.5 SG 30 mm	5	>5.0 (12.8)	10.9
	25	>5.0 (13.1)	11.0
	100	>5.0 (12.5)	10.2
Superlon Vinyl 32 mm	5	0.06	27.1
	25	0.07	25.9
	100	0.08	25.8

There was about a twofold increase in "static" load as load rates were increased from 25 mm/min to 500 mm/min, using the headform as the penetration device. Such a rapid load rate gives some approximation of the forces generated in dynamic situations. Unfortunately material manufacturers would not have access to such sophisticated testing apparatus and the lower load rates, with an appropriate correction factor would need to be used.

DYNAMIC TESTING

The dynamic test using a headform to load and impact 5 different padding materials was conducted according to the relevant ADR standards used for this type of testing to obtain HIC and SI values. The tests will be used to determine whether the padding material used in buses and automobiles would be suitable for the prevention of low impact crashes and the accompanying rapid deceleration, especially for facial trauma.

Table 5. Comparison of free fall and impact velocities

Drop Height (mm)	Free Fall Velocity (m/sec) (k/h)	C150	PE60	PE75	PE120	PMU0.4
500	3.132 (11.3)	2.433	2.433	2.433	2.433	2.434
750	3.836 (13.8)	3.291	3.291	3.291	3.291	3.291
1000	4.429 (15.9)	3.967	3.967	3.967	3.967	3.967
1500	5.424 (19.5)	5.054	5.054	5.054	5.054	5.054
2000	6.264 (22.5)	5.946	5.946	5.946	5.946	5.946

Table 6. Summary of HIC and SI values

Drop Height (mm)	C150 (30 mm)			PE60 (30 mm)			PE75 (30 mm)			PE120 (20 mm)			PMU0.4		
	HIC	SI	g	HIC	SI	g	HIC	SI	g	HIC	SI	g	HIC	SI	g
500	238 233	417 435	323	64 72	1 1	49	66 75	1 1	50	130 136	4 4	70	212 202	10 10	108
750	621 611	1018 976	450	290 276	2 2	90	241 146	2 1	75	358 376	20 23	120	NA	NA	NA
1000	504 505	1423 1262	515	481 485	50 81	210	405 721	15 21	160	662 664	159 160	290	579 637	128 87	242
1500	813 850	1948 2020	541	1138 925	1686 1449	530	1053 1020	1137 790	540	1586 1350	645 768	520	NA	NA	NA
2000	Punch	Punch	Punch	1191 1116	1704 1750	545	1113 1070	1707 1633	550	1264 1361	2019 1901	520	NA	NA	NA

Impact Velocity

The free fall velocities were calculated using the usual equations of motion. The velocity of the head form immediately prior to impact was determined for each drop using 2 photoelectric cells set 150 mm apart (accuracy of gap measurement was 0.1 mm).

Impact Severity

From preliminary investigation the results show that the headform when dropped from heights below 1.0 m produced HIC and SI values which are acceptable ie. below the 1000 value recommended for critical head injury. This is with the exception of the Dunlop C150 foam which had excessive SI values at 1.0 m drop. All materials failed either the SI or HIC level of 1000 at the 1.5 m drop height.

RECOMMENDATIONS AND CONCLUSIONS

The capacity of materials to prevent injury due to low speed impacts, and the accompanying rapid deceleration/acceleration may be evaluated by HIC, SI or g_{max}. The literature suggests that HIC and g_{max} provide better limitation criteria.

Padding material should be a minimum thickness of 25 mm to 30 mm to ensure that adequate impact protection is provided. The thickness required for low stiffness materials is much too high while stiff thin materials do not provide adequate protection against high g_{max} values.

All materials intended for use as padding in buses should be tested under dynamic conditions to obtain HIC and g_{max}. Static testing can be used as an initial guideline for material selection by testing material 30 mm thick and applying a maximum and minimum load at some specific deformation (penetration). For example, using 50 mm x 50 mm samples, at a loading rate of 25 mm/min, could use a minimum load of 0.3 kN (to eliminate materials which are too soft) and a maximum load of 1.0 kN (to eliminate materials which are too stiff) at a penetration of 15 mm.

Based on the work done by Yoganandan et al (1991a,b) a upper HIC limit of around 100 could be used as guide for reducing serious facial injuries such as fracture of the zygoma. Digges et al use a HIC of 300 as representing non serious injury. King and Ball (1988) use a g_{max} value of 50 as a level for no concussion in children. It is suggested that realistic and achievable, upper limits of HIC of 300 and a g_{max} of 100 be used to control impact performance. However some crucial speed (head impact velocity) must also be adopted. A good estimate of the potential of a material to provide protection in low speed impacts is using the headform test from a drop of 0.75 m, representing about 14k/h impact. The impact values at this level should not exceed a HIC value of 300, nor a g_{max} value of 100.

Reference to Table 6 suggests the material best suitable for reduction of serious injury would be 30 mm of Ultrathon polyethylene foam with density 75 to 120 kg/m^3 (note that the PE120 material used and reported in Table 6 was only 20 mm thick). The C150 material did not provide adequate protection for g_{max} or HIC and the PMU0.4 material (by interpolation) also had excessive HIC and g_{max} values.

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