An Experimental Evaluation of Crash Helmet Design and Effectiveness in Standard Impact Tests

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ABSTRACT

With respect to shock absorption, current motorcycle (crash) helmets are usually being developed towards one criterion only, specified in a regulation. From more basic research, however, various criteria are known to relate to head protection. This paper discusses the relationships between design parameters and helmet performance according to several criteria, on the basis of defined impact tests on a set of (approved) crash helmets. Main attention is given to outer and inner shell material properties.

The test set-up of ECE Regulation 22 (-03), is used to assess testhead and anvil responses in frontal (forehead) impact. From these responses helmet behaviour is determined, showing typically different deformation modes between fiber reinforced plastic (FRP) shelled helmets and polycarbonate (PC) shelled helmets. Energy absorption of FRP shelled helmets is predominantly caused by deformation of the inner (foam) shell "from the inside" and the load distribution is determined by the compatibility of inner shell dimensions and headform shape. PC shelled helmets predominantly show deformation "from the outside" and load distribution is determined by the geometry of the object hit as well as the load distribution capacity of inner shell material. FRP shelled helmets show higher maximum load and rate of onset while force distribution and time duration of the impact are more favorable compared to PC shelled helmets The total energy absorbed by helmet deformation is quite similar for all helmets tested.

INTRODUCTION

Effectiveness of Motorcycle Helmets

In practice, helmets have proven their effectiveness. Accident studies have shown that in a direct impact a head injury risk reduction can be achieved from ca. 35 % up to over 90 % (various authors in [1,2][1]). Differences in the reported reduction rates primarily relate to differences in methodologies but also to different injury severities, types of accidents and impact velocities. These figures nevertheless indicate the effectiveness of motorcycle helmets especially with regard to severe head injuries leading to fatalities. The effectiveness of helmets is primarily due to a reduction of the head injury risk through their shock absorption capacity.

Minimum requirements for shock absorption are specified in helmet standards, usually in terms of maximum acceleration (with or without a time limit) of a headform or the maximum force acting on this headform. Helmet manufacturers primarily optimize their products to these minimum requirements since shock absorption is the primary function of a helmet. Standards also address other safety aspects but these will not be discussed here. In a critical evaluation of the use of the Wayne State Tolerance Curve (WSTC), the Severity Index (SI) and the Head Injury Criterion (HIC), Newman identifies 5 general phenomena being associated with the probability of head injuries in direct head impacts [3]:

- the (kinetic) energy involved in the impact,
- the maximum load experienced by the head,
- the local pressure on the skull,
- the rate of onset of loading, and
- the time duration of the impact.

Requirements in helmet standards should reflect these phenomena in order to effectively reduce the risk of head injuries. Helmet optimization to shock absorption should thus be more than optimizing towards one criterion only.

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[1]: The numbers between brackets designate the references at the end of this paper.

Objective of this Study

This study is performed mainly to indicate how characteristics of the outer and inner shell of a helmet relate to the helmet's performance in standard impact tests. This study only addressess the shock absorption characteristics of helmets. A secondary objective is the qualitative evaluation of various proposed and accepted (linear) criteria for head protection, based on the experiments performed in this study. The results of this study therefore contribute to further optimization of helmet design and to discussions on criteria for helmet standards. This paper does, however, not address the fundamental relationship between head injury risk and head protection criteria. It is also not the intent of this paper to propose alternative requirements for helmet standards but to discuss crash helmet effectiveness on the basis of various head/helmet responses.

HELMET DESIGN PARAMETERS

Helmet Construction

Roughly, a motorcycle or crash helmet consists of 3 main parts: the outer shell, the inner shell (also known as liner) and the retention system. Apart from these main parts, usually helmets are also provided with a comfort padding and a visor. The function of the retention system is to assure that the helmet will stay on the head during an impact. During the actual impact, however, the retention system plays only a minor role. Furthermore, the comfort padding does not (significantly) contribute to impact absorption. Some standards also include safety requirements for visors but these will not be considered here because these requirements only address impacts to the visor itself. With respect to shock absorption, only two main parts of the helmet significantly contribute to head protection: the outer and inner shell.

Usually the outer shell of a motorcycle helmet is made of a tough plastic, sometimes reinforced using glass or carbon fibers. Of course reinforcement of the plastic outer shell will affect its dynamic behaviour under impact. Differences between helmets with non-reinforced and reinforced outer shells are studied in the current test programme (see also "samples" under "test programme"). The only geometrical parameter of the outer shell considered in this study is its thickness since the helmets used show quite similar shape near the location of impact.

Most helmets currently on the market and all helmets included in this test programme incorporate expanded polystyrene (EPS) inner shells. This material comes in various blends and densities. Because the type of blend is not always known and the density of the inner shell material is considered to be of greater importance with respect to impact absorption, only the effect of density is studied here. Again only the thickness of the inner shell is studied as geometrical parameter.

Performance Criteria and Optimization of Helmet Design

With respect to the five phenomena mentioned in the introduction, current helmet standards actually only address reduction of the maximum load experienced by the head. Some standards do include a form of time dependency but this merely forces the shape of the response-time curve not to exceed certain maximum values. Different parameters are used for evaluating helmets, depending on the type of test method [3, 4, 5] but also different pass-fail criteria are found for a specific type of test method. The differences in criteria cannot be explained from fundamental biomechanics (e.g. differences in populations at risk) but seem to be associated with different discussions within standardization platforms as well as the discussions on head injury tolerances to impact. More important, perhaps, is the fact that all helmet standards only address linear head response. In this study, helmet performance is only related to the linear response of the headform.

The test method used here is the "guided free fall" system according to ECE Regulation 22 [6] (further referred to as "R.22"). For shock absorption, R.22 requires that the resultant acceleration of the headform does not exceed 300 g ($g = 9.81\ m/s^2$) and that the time duration for which the resultant acceleration exceeds 150 g does not exceed 5 ms.

Besides a direct comparison of the maximum acceleration response of the headform, head injury criteria are known that require processing of the acceleration. The two criteria of this type most commonly used are the Severity Index (SI) and the Head Injury Criterion (HIC). Both these criteria have been determined for the tests conducted in this programme. Other criteria based on displacements of masses of lumped parameter models (such as the Effective Displacement Index, Maximum Strain Criterion, etc.) using the acceleration response of the head as input, are not established in the current programme, mainly because these models lack extensive validation and little experience exists in using these models for helmet evaluations.

Skull fractures can almost entirely be prevented provided the load is distributed over a sufficiently large area [7, 8, 9]. Aldman has specified a minimum area of 13 cm^2 to prevent depressed skull fractures and proposes a test method to replace the current resistance-to-penetration test [10]. Also the shock absorption capacity is determined by the load distribution of a helmet. The test method developed by Aldman, however, only considers a small area of the headform (1 cm^2) to measure reaction force and thus focusses on material properties rather than the complete helmet design. Until now, no well established test method or criterion has been developed to evaluate the load distribution of helmets and this aspect will therefore only be discussed qualitatively in this study.

Newman has studied the influence of time duration, as incorporated in several criteria, for helmet evaluation [11]. Three different ways time is accounted for in failure criteria are discussed: the total time duration of a certain average acceleration, a limit to the time during which the acceleration exceeds a certain value and failure criteria which are based on a functional relationship between acceleration and time. Newman concludes that the significance of the shape of the acceleration response is not known unambiguously from various head injury models (or criteria) but that these models all indicate that for a given time duration, head injury risk increases with average or peak acceleration. In the current test programme several criteria are assessed to study their sensitivity to time dependency of the acceleration response of the headform for different types of helmets.

TEST PROGRAMME

Test Set-Up

The experimental set-up used in this study is based on the test described in ECE Regulation 22, including the 03 series of amendments (further referred to as "R.22") being the guided free fall test. All adaptions made to this test set-up enable the assessment of various parameters but do not change the procedure for testing according to R.22. All helmets are tested at point B (forehead) using the flat steel anvil under ambient conditions. The specific test set-up is shown in Figure 1.

Test Samples

Details of the helmets included in the test programme are given in Table 1. In total 19 approved crash helmets of the integral type are tested. Each helmet is given a unique code according to its type and number, e.g. C2 corresponds to the second helmet of type C.

Included in the test programme are 5 different helmet types having a fiber reinforced plastic (FRP) outer shell (types A, B, C, E and M) and 3 different helmet types having a polycarbonate (PC) outer shell (types G, H and K). All helmets included in the test programme have expanded polystyrene (EPS) inner shells. The inner shell thickness varies between 33 and 36 mm only; the inner shell density varies between 34 and 51 gram/l with the higher densities combined with PC outer shells, except for helmets type M. Outer and inner shell thickness as well as inner shell density are specified in Table 1. These measurements are all taken at impact point B (according to R.22) from helmets not previously subjected to impact and having the same approval number as other helmets of the same type.

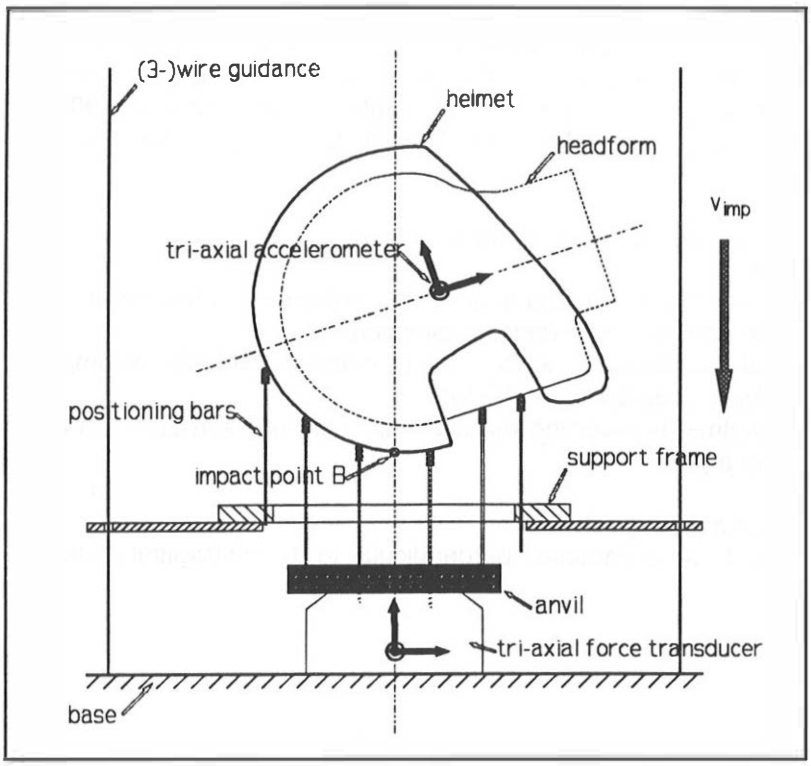

Figure 1: Schematic representation of the test set-up.

The helmets sizes are measured prior to impact and, although the marking sometimes indicated otherwise, all helmets are of size 60 to 61 cm ("large"). The test mass specified in Table 1 is the measured sum of the instrumented headform mass and helmet mass.

Table 1: Specifications of the helmets used in the test programme.

Helm No.	Test Mass (kg)	Outer Shell Material	Outer Shell Thickness (mm)	Inner Shell Material	Inner Shell Thickness (mm)	Inner Shell Density (gram/l)
A1	7.174	FRP	4.5	EPS	35	34
A2	7.080	FRP	4.1	EPS	35	34
A4	7.169	FRP	3.3	EPS	35	34
B2	7.093	FRP	3.3	EPS	35	35
C2	7.206	FRP	3.7	EPS	35	35
E3	7.088	FRP	3.7	EPS	34	34
E4	7.158	FRP	4.0	EPS	34	34
G2	7.193	PC	3.8	EPS	36	40
G3	7.196	PC	3.8	EPS	36	40
G4	7.190	PC	3.8	EPS	36	40
H1	7.119	PC	3.8	EPS	35	51
H2	7.173	PC	3.7	EPS	35	51
H3	7.191	PC	3.6	EPS	35	51
H4	7.183	PC	3.6	EPS	35	51
K3	7.070	PC	4.6	EPS	34	46
K5	7.169	PC	4.4	EPS	34	46
M1	7.156	FRP	2.3	EPS	33	45
M3	7.077	FRP	2.4	EPS	33	45
M4	7.136	FRP	2.9	EPS	33	45

Test Procedure

The helmets are subjected to one impact only, using a headform size 60 according to R.22. Table 1 shows that the test mass only slightly varies between the tests (from 7.07 to 7.21 kg). The impact velocity is set to $7.0^{+0.0}_{-0.1}$ m/s corresponding to a theoretical drop height of approximately 2.50 m. The impact velocity is recorded 6 cm or less, prior to impact. The kinetic energy involved in the impact thus equals ca. 174 J for all tests performed.

During the test programme the following parameters are recorded directly:

- the impact velocity, measured optically;
- total test mass (helmet and instrumented headform) and mass of the instrumented headform;
- testhead accelerations at the centre of gravity in 3 orthogonal directions;
- anvil reaction forces in 3 orthogonal directions of which one is directed vertically (in impact direction) using a triaxial force transducer (Denton® type 2375);
- the contact area between anvil and helmet is recorded using a Fuji® pressure sensitive film and determining the area of the print using a grid;
- vertical anvil acceleration (uniaxial);
- deformation of the inner shell 24 hours after impact;
- high speed film recording of the impact (5000 frames/s) perpendicular to the midsagittal plane of the helmet and testhead.

RESULTS

Table 2 provides a summary of the results of the test programme. Included are:

v_{imp} = measured impact velocity [m/s];
$a_{res,max}$ = peak resultant acceleration of the headform [g];
HIC = HIC value calculated from the resultant acceleration;
t_2-t_1 = time interval of the HIC calculation [ms];
SI = SI value calculated from the resultant acceleration;
$t(a_{res}>150g)$ = time duration the resultant headform acceleration exceeds 150g [ms];
cum3ms = level of resultant headform acceleration lasting 3 ms cumulatively [g];
con3ms = level of resultant headform acceleration lasting 3 ms continuously [g];
Fz_{max} = maximum vertical anvil force [kN];
$Fres_{max}$ = maximum resultant anvil force [kN];
A = maximum contact area between helmet and anvil determined form Fuji film (using a grid) [cm^2];
$d_{resid.}$ = residual deformation of the inner shell, 24 hours after impact [mm];
s_{max} = maximum headform displacement with respect to the anvil, determined from the resultant headform acceleration and the impact velocity [mm];
W_{total} = the maximum of W(t), with W(t) the (instantaneous) work of deformation calculated using $\int F_{head} \cdot ds$ with F_{head} the force experienced by the head ($= m_{head} \cdot a_{res}$) and s the headform displacement [J];
W_{pl} = the amount of energy absorbed by the helmet through plastic deformation, determined by calculating W(t) at t=12 ms (directly after impact thus until contact between helmet and anvil is lost);
$da/dt_{average}$ = average rate of onset of the headform acceleration determined from the slope of the line connecting the points at which 25% and 75% of the maximum acceleration has been reached.

The vertical anvil acceleration is measured to establish whether the anvil forces have to be inertia compensated. These accelerations proved, however, to be very low and no inertia compensation is considered necessary. The anvil acceleration is therefore not presented here. The film recordings showed that no significant rotation occured until maximum compression of the helmet which allows the calculation of the displacements s from double integration of the resultant headform acceleration. No measurements presented here are derived from film analysis directly.

Table 2: Summary of the results of the test programme.

Helm No.	v_{imp} (m/s)	$a_{res,max}$ (g)	HIC	t_2-t_1 (ms)	SI	t(a_{res}> 150g) (ms)	cum3 ms (g)	con3 ms (g)	Fz_{max} (kN)	$F_{res,max}$ (kN)	A (cm^2)	$d_{resid.}$ (mm)	s_{max} (mm)	W_{total} (J)	$W_{pl.}$ t=12ms (J)	da/dt average (·10^3 m/s^3)
A1	7.0	182	1341	4.5	1499	2.88	147	146	11.56	11.59	9	5.8	23.4	128	117	551
A2	6.7	169	1034	5.3	1155	1.25	135	134	9.90	10.30	16	5.0	25.6	134	128	511
A4	7.0	200	1716	4.8	1916	3.38	165	163	12.22	12.54	14	7.5	24.8	149	130	654
B2	7.0	197	1668	5.0	1862	3.38	164	161	11.79	12.08	15	7.5	25.1	147	126	645
C2	7.0	169	1070	5.8	1179	1.00	134	121	10.12	10.69	16	6.2	28.5	147	141	552
E3	7.0	208	1818	4.8	2028	3.38	167	167	12.30	12.67	14	6.0	23.7	149	130	742
E4	7.0	195	1607	4.5	1739	3.25	164	160	12.46	12.63	15	6.0	23.4	150	137	694
G2	7.0	162	1130	5.8	1295	2.13	139	138	10.22	10.63	44	9.2	31.0	145	130	375
G3	7.0	165	1070	5.3	1244	1.75	134	129	10.06	10.44	45	9.8	32.2	145	130	341
G4	7.0	162	1089	5.5	1255	1.88	136	133	9.98	10.41	44	9.7	32.9	146	131	353
H1	7.0	164	1059	5.3	1215	1.88	133	131	9.70	9.99	38	9.4	34.5	147	138	306
H2	7.0	162	906	4.8	1049	1.38	123	121	10.03	10.47	35	9.2	34.8	146	142	289
H3	7.0	156	923	5.3	1062	1.25	124	124	9.90	10.33	38	10.5	34.3	146	140	306
H4	7.0	167	1075	5.0	1238	2.13	131	131	9.94	10.37	40	11.0	34.1	147	138	313
K3	7.0	151	899	5.8	1000	0.38	119	117	10.83	11.02	38	9.7	33.2	145	142	296
K5	7.0	162	1035	5.5	1179	1.63	132	129	10.85	10.98	36	9.2	31.4	147	139	317
M1	7.0	172	1097	4.8	1253	2.13	135	132	12.13	12.21	20	7.9	26.5	132	128	421
M3	7.0	170	1173	5.0	1323	2.38	139	139	12.00	12.06	20	7.9	31.0	148	141	444
M4	7.0	171	1238	5.0	1398	2.63	143	143	12.07	12.18	17	7.9	29.8	148	137	480

A coarse comparison of the results between helmets of the same type shows a good consistancy, with the one exception of helmet A2. Helmet A2 shows a low HIC and SI value compared to A1 and A4. Also maximum resultant headform acceleration and anvil responses are lower for A2 compared to A1 and A4, although not as distinct as HIC and SI. After the test, helmet A2 showed a fracture of the outer shell and since this shell is made of FRP, it is known to dissipate a significant part of the impact energy when breaking. Furthermore the impact velocity was slightly too low for helmet A2. Both remarks explain the lower results for this helmet.

Also helmet C2 showed fracture of the outer shell after impact, however, the results of this helmet cannot be compared with results of other helmets of this type. Other helmets included in the test programme did not show significant fracture of the outer shell.

Table 3 shows the ranges of responses measured in the tests for FRP shelled helmets and PC shelled helmets separately. No mean values are presented since different helmet types are included in Table 3. In general FRP shelled helmets show higher headform and anvil responses while the deformation is less, compared to PC shelled helmets. Most criteria presented in Table 3 show an overlap except $a_{res,max}$, da/dt$_{average}$ and the deformation characteristics A, d_{resid} and s_{max}. Especially the deformations and the rate of onset of headform acceleration indicate that there is a significant difference in the dynamic behaviour of FRP and PC shelled helmets.

For 16 out of 19 (approved) helmets included in this test programme the HIC exceeds 1000 and for 18 out of 19 helmets the SI exceeds 1000 (the remaining helmet has a SI of exactly 1000). No HIC value obtained exceeds 2000 and only in one test a SI above 2000 is found. To study the possible differences in using $a_{res,max}$, HIC and SI for helmet evaluation or homologation, linear regression analyses are performed.

Table 3: ***Response ranges for FRP and PC shelled helmets.***

		$a_{res,max}$ (g)	HIC	t_2-t_1 (ms)	SI	t(a_{res}> 150g) (ms)	cum3 ms (g)	con3 ms (g)	Fz_{max} (kN)	$F_{res,max}$ (kN)	A (cm^2)	$d_{resid.}$ (mm)	s_{max} (mm)	W_{total} (J)	$W_{pl.}$ $_{t=12ms}$ (J)	da/dt $_{average}$ ($\cdot 10^3$ m/s^3)
FRP	**min**	169	1034	4.5	1155	1.00	134	121	9.9	10.3	9	5	23	128	117	421
	max	208	1818	5.8	2028	3.38	167	167	12.5	12.7	20	8	31	150	141	742
PC	**min**	151	899	4.8	1000	0.38	117	117	9.7	10.0	35	9	31	145	130	289
	max	167	1130	5.8	1295	2.13	138	138	10.9	11.0	45	11	35	147	142	375

A linear regression analysis of the HIC and SI values obtained shows a strong correlation between HIC and SI in the 19 tests: HIC = 0.932*SI-62.4 with a correlation (r^2) of 0.995. Even if the straight line approximation of HIC vs SI is forced to pass through (HIC=0, SI=0) a high correlation is found: HIC = 0.889*SI with $r^2 \approx 0.993$. Annex 1, Figure A1 shows the correlation between HIC and SI. For these tests HIC and SI thus show quite similar sensitivity to the acceleration response of the headform.

A similar regression analysis is performed using HIC and $(a_{res,max})^{25}$. Again a high correlation is established for both a linear regression passing through (0,0) or not (r^2 equals 0.956 and 0.958 respectively), presented in Annex 1, Figure A2. This indicates that the HIC is quite sensitive to the maximum resultant headform acceleration and thus less sensitive to the shape of the acceleration curve. This result is supported by others [11,12] and probably due to the index 2.5 in the definition of HIC (and SII).

Table 2 shows that the acceleration levels lasting 3 ms (cum3ms and con3ms) do not differ significantly between each other for the same helmet but do show differences between FRP shelled and PC shelled helmets as shown in Table 3. Linear regression analysis of all results obtained, indeed shows a high correlation between con3m and cum3ms: for a straight line approximation passing through (0,0) or not, r^2 equals 0.964 and 0.965 respectively. Also a high correlation between these two criteria and $a_{res,max}$ is found: $r^2 \approx 0.9$. The time duration that the resultant headform acceleration exceeds 150 g shows a lower correlation to $a_{res,max}$ in linear regression analysis. In a linear regression analysis r^2 equals 0.770. If the straight line approximation is forced to pass through (0,0) r^2 equals 0.344. This indicates that t(a_{res}>150g) is more sensitive to the shape of the acceleration response of the headform than both con3ms and cum3ms.

Not surprisingly, the vertical force on the anvil (F_z) higly correlates with the resultant force on the anvil (F_{res}) since the principal direction of impact is vertical. The maximum external force on the helmet (which in value equals $F_{res,max}$ given in Table 3) does, however, not correlate highly to the maximum internal force indicated by $a_{res,max}$.

Considering the abovementioned correlations between different parameters, the discussion will concentrate on the acceleration response of the headform (both in value and shape), the resultant anvil force, the contact area between helmet and anvil and headform displacement. The measurement of deflection 24 hours after impact ($d_{resid.}$) will not be further discussed since this does not necessarily represent the maximum deflection at impact [13, 14].

DISCUSSION

Mechanical phenomena related to head protection

The kinetic energy involved in all impacts is held constant at ca. 174 J. For helmets, this energy is to be considered an input and should be a reflection of the energy involved in head impacts in real accidents. From Table 2 it can be seen that the calculated amount of energy absorbed by the helmets (W_{pl}) for all helmets equals ca. 75% of the input energy. The rest of the energy is converted into elastic energy of the helmet (which recovers even much later than during the principal time duration of the impact), energy loss because of friction or other dissipation effects and the rebound of the helmetted headform. Film analysis shows both a linear as well as a rotational motion of the helmet/headform after impact. An accurate estimate of the kinetic energy in rebound is therefore not possible and the effectiveness of the helmets in terms of Δv cannot be assessed.

The choice of criteria for the evaluation of the effectiveness of crash helmets in terms of reducing the maximum load experienced by the head on the basis of the acceleration response of the head (-form) seems logical from fundamental (bio)mechanics of head impact as well as from the knowledge of measurement techniques. Table 3 shows that HIC, SI, con3ms and cum3ms of FRP shelled helmets are generally higher than those of PC shelled helmets. The high correlations observed between $a_{res,max}$ on one hand and HIC, SI, con3ms and cum3ms on the other hand, however, indicate that $a_{res,max}$ provides quite the same information in these tests. Helmet evaluation does not seem to change much if either of these criteria are used instead of $a_{res,max}$. Newman proposes a maximum force of 13.34 kN (3000 lbs) to be exerted on the head in guided fall tests with impact energies of ca. 136 J [3]. This would correspond to a maximum resultant headform acceleration of ca. 236 g in free fall tests. All helmets tested show lower acceleration responses, even with higher impact energy.

The impact area (A) provides an indication of the contact between helmet and anvil but does not necessarily reflect the amount of inner shell deformed during the impact. This is especially true for FRP shelled helmets [14]. The impact area can therefore only be used as a coarse indicator of differences in helmet behaviour, as is discussed later. The tolerance for load distribution proposed by Newman is ca. 2.76 MPa. The PC shelled helmets included in this test programme show impact areas of ca. 40 cm^2 and maximum resultant accelerations of ca. 160 g. This would equal ca. 2.26 MPa which is below but close to the proposed tolerance.

Only coarse time aspects of the headform response are established in the test programme. Already mentioned is the energy dissipation of ca. 75%, reducing the time duration to an acceptable level according to Newman [3]. The average rate of onset of the helmets tested in this programme stays well below the proposed limit of $2 \cdot 10^5$ g/s ($\approx 2 \cdot 10^6$ m/s^3) (Lunenfeld in [3]): the maximum average rate of onset determined in the test programme is ca. $0.74 \cdot 10^6$ m/s^3 (see also Table 2). The proposed limit might, however, concern the the maximum rate of onset rather than the maximum average rate of onset.

Effects of the outer shell

The results presented in Table 3 indicate a principal difference between the behaviour of PC and FRP shelled helmets. Figure 2 and 3 respectively show the acceleration time response and force deflection characteristics of all helmets tested.

Based on the helmet characteristics given in Table 1, the helmets are divided in 3 categories:

- FRP shelled helmets with outer shell thickness of ca. 4 mm (helmets type A, B, C and E), indicated in Figure 2 and 3 by the solid lines;
- PC shelled helmets with outer shell thickness of ca. 4 mm (helmets type G, H and K), indicated in Figure 2 and 3 by the dashed lines;
- FRP shelled helmets with outer shell thickness of ca. 2.5 mm (helmets type M), indicated in Figure 2 and 3 by the (gray) dotted lines.

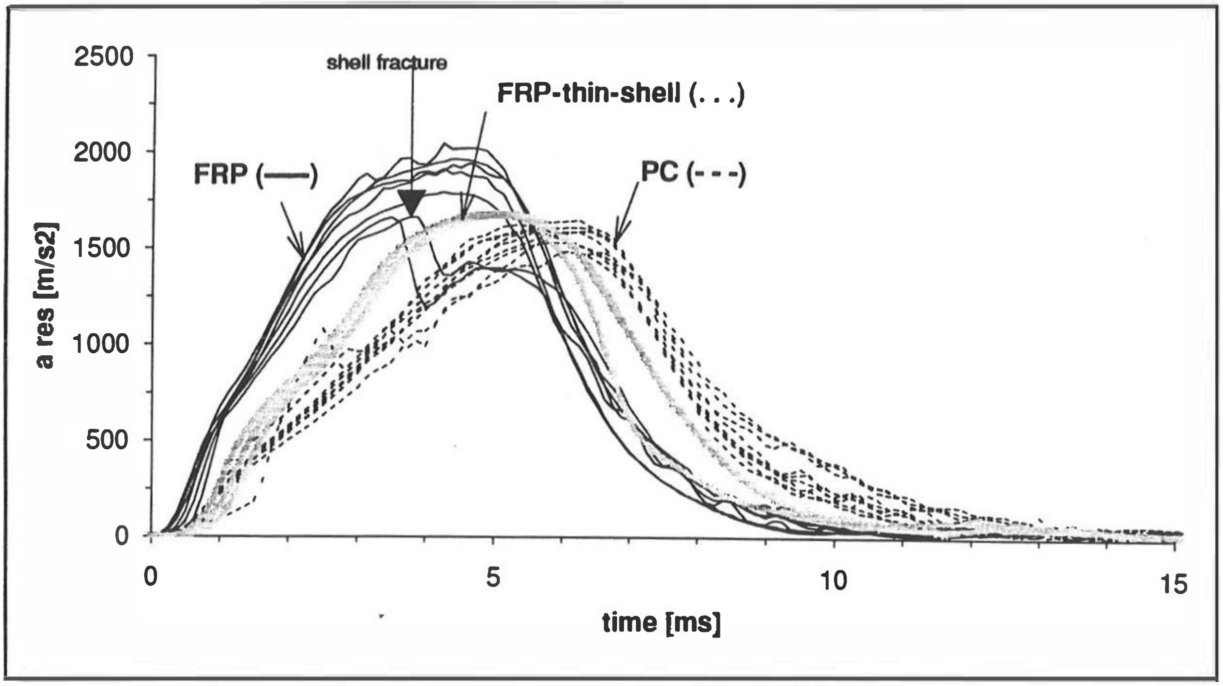

Figure 2: ***Resultant headform acceleration time histories (all helmets).***

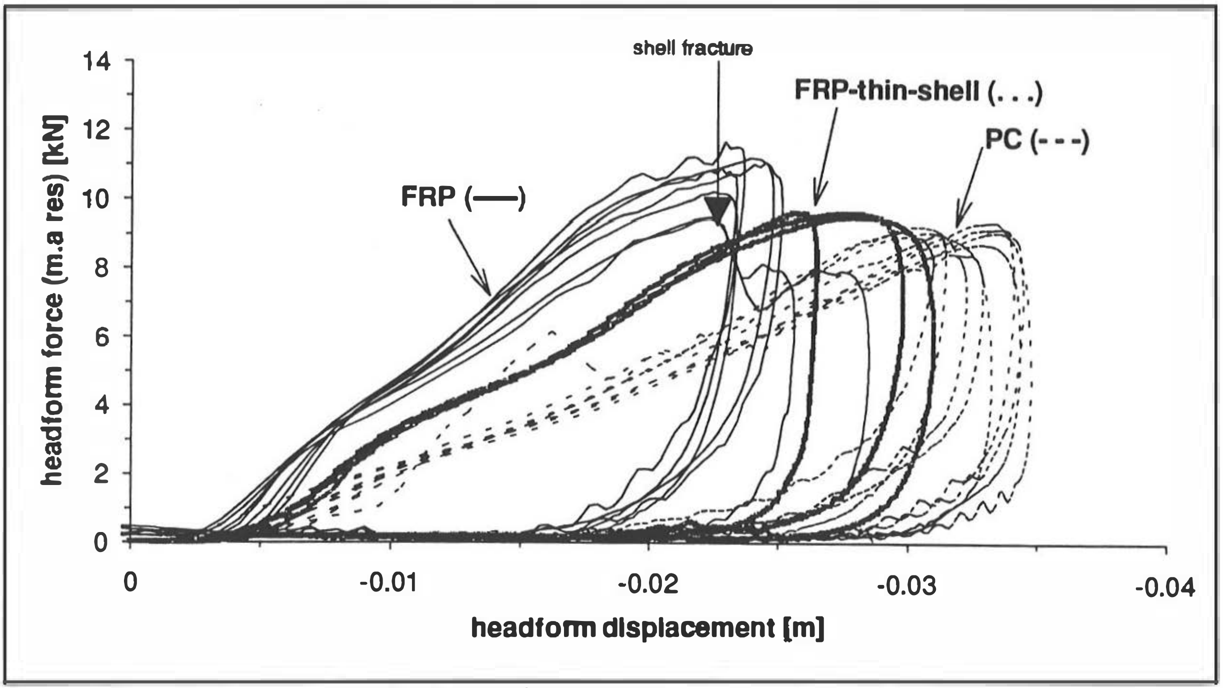

Figure 3: ***Headform force vs. headform displacement (all helmets).***

Figure 2 and 3 show that FRP shelled helmets give a higher rate of onset as well as a higher maximum load compared to PC shelled helmets. All helmets show a quite similar energy absorption (area under the headform force - displacement curve) and thus the displacement is less (and the time duration of impact decreases) for FRP shelled helmets compared to PC shelled helmets having similar outer shell thickness. Especially the higher rate of onset tends to be associated with outer shell stiffness: in case of a FRP outer shell (which is known to be stiffer than a PC outer shell), the deformation is predominantly caused by headform intrusion in the inner shell. This phenomenon is supported by the fact that the maximum difference between anvil force and headform force is larger with FRP shelled helmets compared to PC shelled helmets (see also Table 2) and occurs during the first few miliseconds of the impact. For FRP shelled helmets, this force difference reaches maxima up to ca. 5 kN, which corresponds to a helmet deceleration of approximately 400 g (using an average helmet mass of 1.2 kg) and thus illustrates that the helmet is decelerated more rapidly than the headform. This force difference is less for PC shelled helmets (ca. 2.5 kN) thus these types of helmets tend to be decelerated approximately similar to the headform itself. The deformation of PC shelled helmets is predominantly caused by outer shell deformation. Figure 4 illustrates these different modes of helmet deformation.

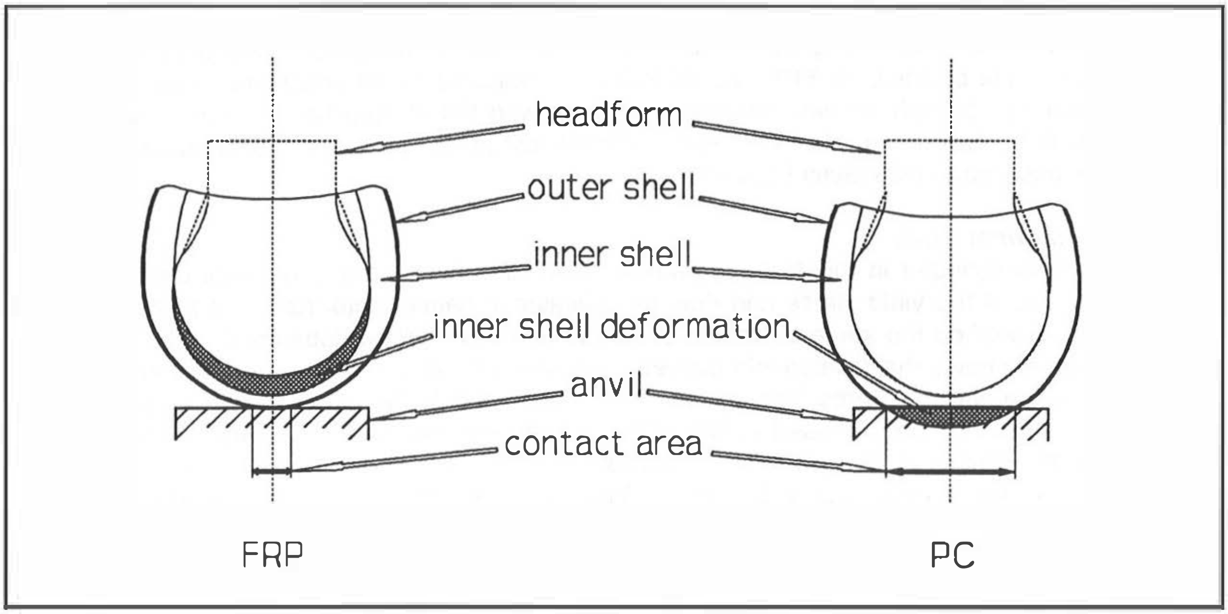

Figure 4: ***Helmet deformation modes with FRP (left) and PC (right) shelled helmets.***

Because of these different deformation modes, the load distribution is different and more favorable with FRP shelled helmets provided all helmets have equal compatibility of inner shell dimensions with the shape of the headform. The fit of a helmet is thus very important with respect to the shock absorption effectiveness of crash helmets. This is also assessed in a comparison study between a "standard" PC shelled helmet with an EPS inner shell and an experimental FRP helmet using a low density inner shell material known to have a low yield stress [14]. Especially important in this respect is the recti-linear deformation observed with EPS inner shells. The abovementioned deformation modes thus only relate to FRP and PC shelled helmets combined with EPS inner shells.

Outer shell fracture affects both the acceleration response as well as force-displacement characteristics of the helmets. In Figure 2 and 3 the two FRP shell fractures observed in the test programme are indicated by the solid arrow (▾) showing a decrease in loading of the head and an increase in helmet deformation. The second (lower) part of the force-displacement curve for these two helmets indicates a deformation mode similar to PC shelled helmets which is to be expected since fracture of the outer shell causes concentrated loads on the outside of the helmet. This reduction in load distribution may give cause for an increased severe head injury risk [15].

Helmet type M is an FRP shelled helmet but with reduced outer shell thickness and increased inner shell density compared to helmet types A, B, C and E. This particular combination of outer and inner shell characteristics causes an "intermediate" head/helmet response for all of the mechanical phenomena discussed here.

Rentschler compared 5 types of crash helmets on the basis of their energy absorption in standard impact tests conducted at different energy levels [5]. The comparison between an FRP shelled helmet with a PC shelled helmet having almost equal inner shell characteristics (material, density and thickness), did not reveal significant differences in maximum load experienced by the head. The tests of Rentschler were, in contrast to the current test programme, conducted at the top of the helmets (impact point P according to R.22). At this location helmets are known to be stiffer compared to the front (impact point B according to R.22) which could account for the difference with the current test programme, especially concerning the PC shelled helmets. Furthermore, no information is available on the thickness of the outer shells which also affects helmet stiffness.

The influence of shell material on the incidence of head injuries in motorcycle accidents is established in [16] on the basis of an in depth investigation on 131 accidents. This study showed a significant higher risk of minor to moderate head injuries with FRP shelled helmets compared to helmets with a lower stiffness, such as PC shelled helmets, in relatively low severity impacts. As indicated in the current test programme, this higher risk can be associated with higher maximum load and higher rate of onset for FRP shelled helmets compared to PC shelled helmets. The observation of lower risk of high severity injuries associated with PC shelled helmets compared to FRP shelled helmets [1] cannot be addressed in the current test programme since these injuries concern head injuries associated with facial fractures.

Effects of the inner shell

Since all helmets included in this test programme have EPS inner shells, the shell density can be used as indicator of the yield stress and thus as indicator of helmet deformation. If all other helmet characteristics would be the same or similar, the head response will be dependent of the inner shell density. Figure 5 shows the relationship between maximum headform force and inner shell density for the tests conducted by Rentschler and the tests conducted in the current test programme. The dashed line represents the proposed relationship between the maximum headform force and inner shell density of Rentschler [5]. The solid squares (■) represent the average head response per helmet type of the current test programme. The open triangles (▵) represent the results of Rentschler concerning helmets having an EPS inner shell. The open circle (o) represents the one helmet tested by Rentschler having a poly-urethane (PU) inner shell.

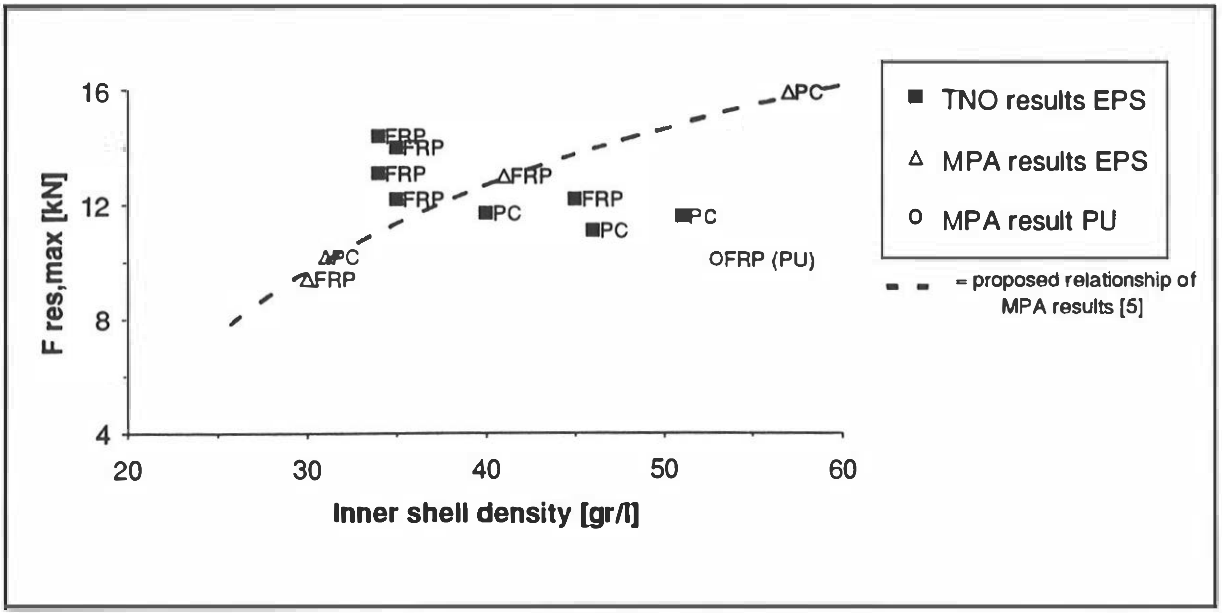

Figure 5: Maximum headform force vs. inner shell density; comparison of TNO (this study) and MPA [5] results.

The relationship found by Rentschler cannot be substantiated by the current study. Furthermore, in Figure 5 Rentschler does not account for differences in outer shell material and thus in differences in deformation mode. Figure 5 shows no clear relationship between the maximum load on the head and inner shell density for either FRP shelled helmets or PC shelled helmets.

Figure 3 and Table 1 show that the maximum displacement of the headform nearly equals the thickness of the inner shell for PC helmets. Figure 3 also shows that an initial displacement of the headform occurs without considerable force acting upon the headform. This initial displacement is probably due to the compression of the comfort padding and nearly equal for all helmets. This shows that at the current impact test on a flat anvil according to R.22, PC shelled helmets almost bottom-out. The effect of bottoming-out is illustrated in Annex 2, Figure A3 in which tests are shown on a sheet of EPS foam with a density of 30 gr/l and a thickness of 32 mm. In these tests a spherical mass with diameter 165 mm and a mass of 4.7 kg is dropped onto the foam with an initial velocity increasing from 1.0 m/s to 7.0 m/s (with increments of 1.0 m/s). In these tests, bottoming-out occurs at approximately 85% compression, which is only achieved at impact velocities above approximately 6.0 m/s. These figures indicate that the deformations of PC outer shells do not significantly contribute to energy absorption in the helmet tests. Because of their limited thickness, all helmets will have a tendency to bottom-out with increasing impact energy. Stiffer outer shells tend to increase the energy level at which bottoming-out occurs because of higher load distribution capacity, however show higher initial head responses, as discussed before.

SUMMARY AND CONCLUSIONS

In this study, 8 helmet types are subjected to standard impact tests. On the basis of headform and anvil responses, the helmets are evaluated with respect to general phenomena related to head injury risk: the maximum load on the head, load distribution, rate of onset of loading and several criteria which include time dependency of the acceleration response. Particularly the characteristics of outer and inner shells are discussed in terms of helmet effectiveness. The helmets effectiveness is considered in terms of linear response, showing:

* All helmets tested comply with proposed tolerance limits for the mechanical phenomena discussed.

* Linear regression analyses show a high correlation between the maximum resultant acceleration of the headform on one hand and HIC or SI on the other hand. This indicates that, for the particular set of helmets used in this programme, no substantial difference in evaluation is apparent using $a_{res,max}$, HIC or SI; they all show similar trends.

* The maximum load experienced by the head is not a function of inner shell characteristics only. A stiff outer shell tends to show this maximum load rather early during the impact, while a less stiff outer shell shows the maximum load at maximum deformation.

* The deformation mode of FRP shelled helmets differs from that of PC shelled helmets particularly with respect to load distribution. FRP shelled helmets tend to absorb energy by inner shell deformation predominantly at the inside, while PC shelled helmets absorb energy predominantly from the outside. As a consequence, this puts higher requirements on helmet fit for FRP shelled helmets compared to PC shelled helmets. Furthermore, PC shelled helmets tend to bottom-out sooner compared to FRP shelled helmets.

* The deformation modes observed in this study are related to the recti-linear deformation of EPS. A better load distribution, particularly with PC shelled helmets, may also be achieved using a non-linearly deforming inner shell, either by construction or choice of a new material.

* In standard impact tests, FRP shelled helmet show higher maximum load and rate of onset while force distribution is more favorable compared to PC shelled helmets. The total energy absorbed by helmet deformation is quite similar for all helmets.

* Helmet shell fracture does not show a significant effect on the amount of energy absorbed by the helmet but is likely to result in poorer load distribution with a possible increase in risk of severe head injuries.

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REFERENCES

1. Schuller, E., G. Beier, W. Spann: "Assessment of the Effectiveness of Safety measures - Conclusions Drawn from the Munich Area Seat Belt and Motorcycle Study."
SAE paper no. 850091; Proc. of Field Acc. Data Collection, Anal., Methodologies and Crash Inj. Reconstr. SAE P.159, pp. 39 - 49; 1985.

2. Otte, D., P.Jessl, E.G. Suren: "Impact Points and Resultant Injuries to the Head of Motor-Cyclists Involved in Accidents, With and Without Crash Helmets."
Proc. of the 1984 Int. IRCOBI Conf. on the Biomechanics of Impact, Delft, Netherlands; IRCOBI Secr., 109 Av. Salvador Allende - 69500 Bron, France; 1984.

3. Newman, J.A.: "On the Use of the Head Injury Criterion (HIC) in Protective Headgear Evaluation."
SAE paper no. 751162, Proc. of the 19th Stapp Car Crash Conference, pp. 615-640; 1975.

4. Beusenberg, M.C.: "Modules for the Inclusion of Safety Requirements in (Sport) Helmet Standards - Vol. 1 and 2."
TNO Crash-Safety Research Centre, Delft, the Netherlands; published by the Consumer Safety Institute, report 105a/b; ISBN 90-6788-122-8; Amsterdam, the Netherlands; 1991.

5. Rentschler, K.: "Verbesserung der Prüfverfahren für Kraftfahrer-Schutzhelme im Hinblick auf verbesserte Stoßdämpfung."
MPA-Suttgart; VDI Verlag Heft 295; ISSN 0070-4210; 1985.

6. ECE Regulation 22: "Uniform Provisions Concerning the Approval of Protective Helmets and of Their Visors for Drivers and Passengers of Motor Cycles and Mopeds"; United Nations, Geneva, SUI; including 03 series of amendments (including various corrections, addenda, etc.); 1992.

7. Chamouard, F., C. Tarrière, C. Got, F. Guillon, A. Patel, J. Hureau: "Relationship between some Biomechanical and Dimensional Characteristics of the Skull and the Risk of Cerebral Injuries."
Proc. of the 1986 Int. IRCOBI Conf. on the Biomechanics of Impact, Zürich, Switserland, pp. 133-152; IRCOBI Secr., 109 Av. Salvador Allende - 69500 Bron, France; 1986.

8. Chapon, A., A. Dedoyan, J.-P. Verriest: "Intra-Cranial Injuries Associated with Unconsciousness in Two-Wheeler Accidents."
Proc. of the 1984 Int. IRCOBI Conf. on the Biomechanics of Impact, Delft, the Netherlands, pp. 111-127; IRCOBI Secr., 109 Av. Salvador Allende - 69500 Bron, France; 1984.

9. Hopes, P.D., B.P. Chinn: "Helmets: A New Look at Design and Possible Protection."
Proc. of the 1989 Int. IRCOBI Conf. on the Biomechanics of Impact, Stockholm, Sweden, pp. 39-54; IRCOBI Secr., 109 Av. Salvador Allende - 69500 Bron, France; 1989.

10. Aldman, B.: "A Method for the Assessment of the Load Distribution Capacity of Protective Helmets Proposed to Replace the Current Resistance-to-Penetration Test."
CEN/TC158/WG4 Document N11; 1984.

11. Newman, J.A.: "The Influence of Time Duration as a Failure Criterion in Helmet Evaluation." SAE paper no. 821088, presented at the Int. Off-Highway Meeting & Exp., Milwaukee, Wisconsin, Sept.13-19; 1982.

12. Chou, C.C., G.W. Nyquist: "Analytical Studies of the Head Injury Criterion (HIC)." SAE paper no. 740082.; 1974.

13. Newman, J.A.: Discussion on the paper "Do Tougher Standards Lead to Better Helmets?" by S.R. Sarrailhe. Proc. of the 1984 Int. IRCOBI Conf. on the Biomechanics of Impact, Delft, the Netherlands, pp. 153-155; IRCOBI Secr., 109 Av. Salvador Allende - 69500 Bron, France; 1984.

14. Chandler, S., A. Cilchrist, N.J. Mills: "Motorcycle Helmet Load Spreading Performance for Impacts onto Rigid and Deformable Objects." Proc. of the 1991 Int. IRCOBI Conf. on the Biomechanics of Impact, Salon de Provence, France, pp. 249-261; IRCOBI Secr., 109 Av. Salvador Allende - 69500 Bron, France; 1991.

15. Vallée, H., F. Hartemann, C. Thomas, C. Tarrière, A. Patel, C. Got: "The Fracturing of Helmet Shells." Proc. of the 1984 Int. IRCOBI Conf. on the Biomechanics of Impact, Delft, the Netherlands, pp. 99-109; IRCOBI Secr., 109 Av. Salvador Allende - 69500 Bron, France; 1984.

16. Schuller, E., G. Beier: "Safety Helmets Shell Material and Head Injury Incidence in Motorcycle Accidents." Proc. of the 1981 Int. IRCOBI Conf. on the Biomechanics of Impact, Salon de Provence, France, pp. 184-192; IRCOBI Secr., 109 Av. Salvador Allende - 69500 Bron, France; 1981.

ANNEX 1: LINEAR REGRESSION ANALYSES

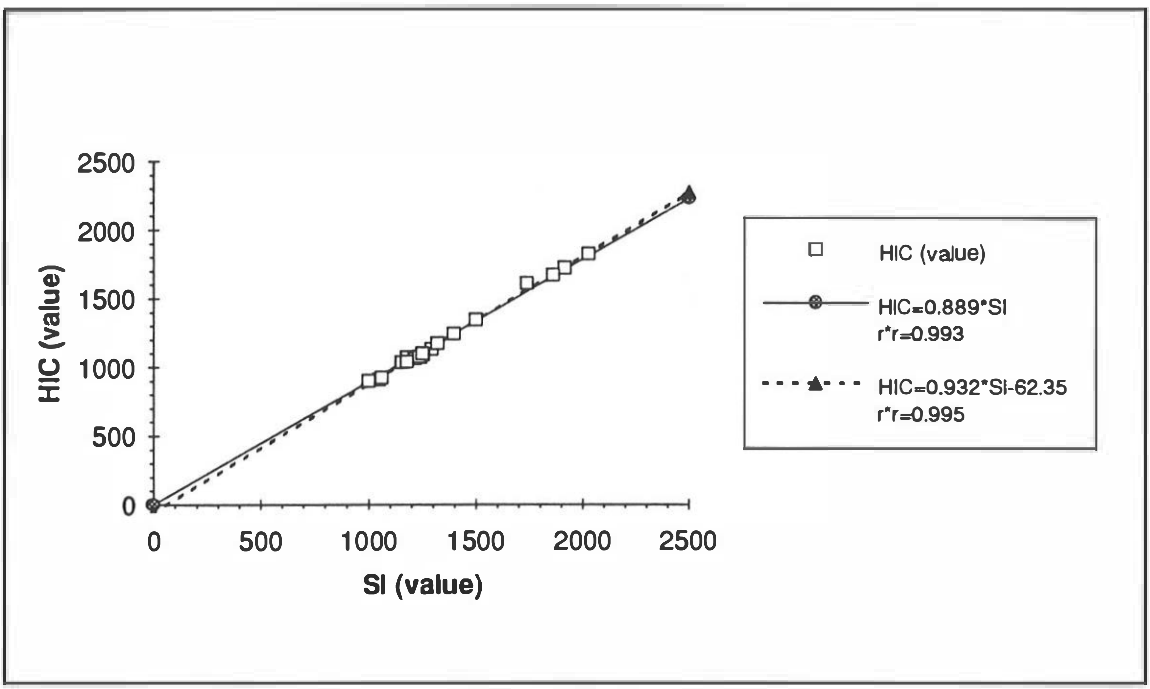

Figure A1: ***Correlation between HIC and SI (linear regression).***

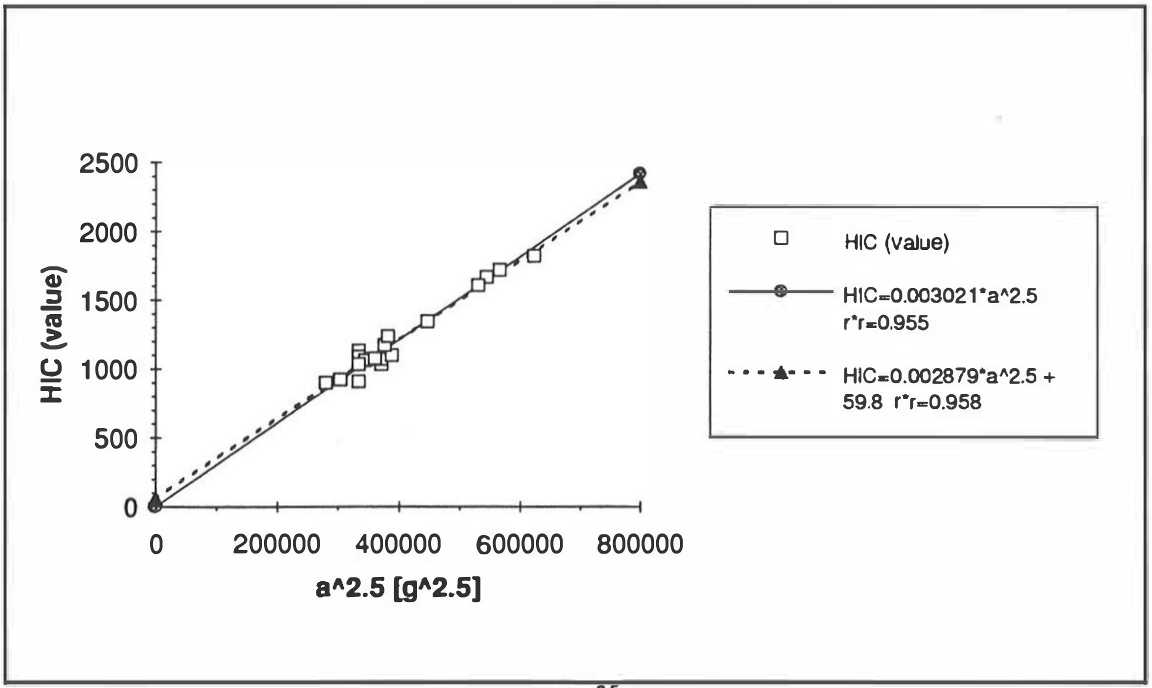

Figure A2: ***Correlation between HIC and $a^{2.5}$ (linear regression).***

ANNEX 2: BOTTOMING-OUT OF EPS FOAM

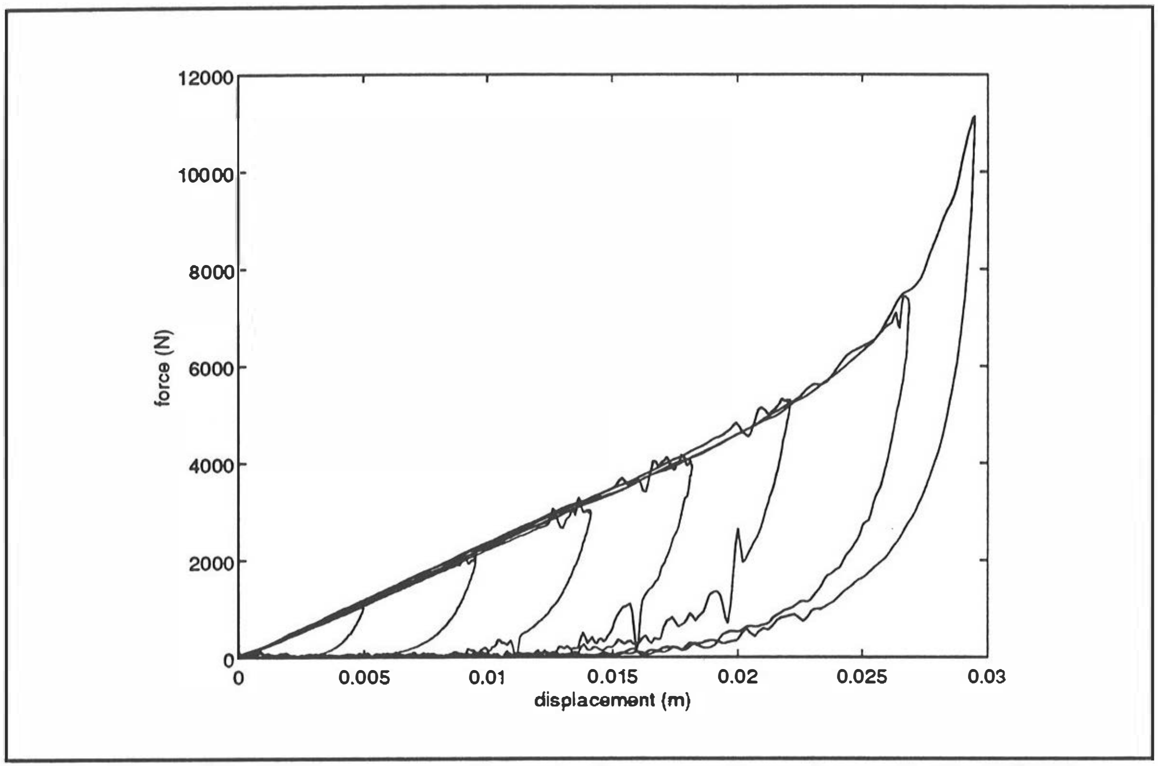

Figure A3: Force-displacement of a spherical mass impacting a sheet of EPS foam.

Foam specifications:

material:	EPS
density:	30 kg/m^3
thickness:	32 mm
length:	300 mm
width:	300 mm

Spherical mass characteristics:

material:	steel
mass:	4.7 kg
diameter:	0.165 m

Test specifications:

impact velocity: 1.0 - 7.0 m/s with increments of 1.0 m/s

The foam sheet is positioned on a rigid support without transverse support.