CRITERIA FOR HEAD IMPACT PROTECTION BY MOTORCYCLE HELMETS

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Abstract

The objective of this study is to establish criteria for head impact protection to be required for optimal performance of motorcycle helmets. Head injury severity sustained in real accidents was compared with test results obtained by laboratory drop-tests according to ECE-R 22, considering residual damage of protective padding as an indicator for head impact loading. 15 integral helmets were collected from real motorcycle crashes providing basic important accident data concerning head injury and head impact characteristics. For new helmets similiar to those used in the real accident sample, comparable damage was simulated in laboratory drop-tests using various anvils and impact areas and applying step by step increasing impact velocities. Comparing deceleration profiles from drop tests representing a best as possible approximation of residual accident damage with corresponding head injury severity (AIS), the following principal results and conclusions were obtained:

1) *Increasing head injury severity is not closely related to increasing residual deformation of the energy absorbing liner.*
2) *Critical head injury (AIS 5) may occur for impacts which are related to rather low translational head deceleration of approximately 150 g or lower measured in the ECE-R 22 headform. High rotational acceleration might be decisive in these particular accident cases.*
3) *Test results suggest that ECE-R 22 limits should be significantly reduced to optimize head impact protection.*

Introduction

In common practice, i.e. as required in national and international standards, the performance of protective helmets for motorcycle riders is evaluated predominantly by energy absorption test results. According to the test procedure from ECE-R 22 [1], helmets equipped with an instrumented headform have to be dropped from certain heights (2.5 m⇔7 m/s and 1.84 m⇔6 m/s) on a fixed flat or hemispherical anvil. The impact deceleration within the headform has to be recorded triaxial versus time. The resultant deceleration curve has to be evaluated with respect to peak value and duration. The ability of shock absorption and therefore the performance of helmets is considered to be the better, the less a resultant deceleration is recorded.

Test procedures established for helmet standards are designed for good reproducible measurements as well as a simple as possible experimental set-up. As a consequence, basic differences have to be considered when comparing results obtained from laboratory test procedures, e.g. according to ECE-R 22, and real accident conditions. In particular, these are the following aspects:

1. The headform is similar to the human head only in shape and weight, but cannot simulate the complex biological structure of the human head.

2. The impact energy transfer in drop-tests is determined only by the mass of the headform and the helmet, and not influenced by the riders whole body mass which in real accidents possibly is creating a different specific effective head mass.
3. Real accident biomechanical effects concerning the head-neck junction (e.g. damping and oscillations) cannot be simulated in the drop-test.
4. Loading of the cervical spine and base of the skull cannot be measured.
5. The fixed anvils to be used represent only a limited number of the great variety of possible impacted structures in real accidents.

Therefore, it is evident that headform decelerations obtained from ECE-R 22 drop-tests are not necessarily equivalent to head decelerations occuring for identical impact velocities in real accidents. Thus, drop-tests are representing predominantly comparative testing of material and construction properties for different helmets under dynamic loading conditions.

Objective of the Study

Being aware of these limitations concerning laboratory drop-tests, nevertheless, it is assumed that residual deformation of the protective padding could be at least to a certain extent an indicator for dissipated impact energy both in reality and in laboratory drop-tests. Then, headform deceleration measured for that particular drop-test which is simulating the real accident residual deformation of the protective padding should be a suitable physical parameter to estimate head impact loading (cf. [2], [3]).

Therfore, the study consisted of two parts:

1. Helmets collected from a well documented real accident sample were examined for damage, in particular for residual deformation of the protective padding. From accident files and accident reconstruction for each case characteristic accident parameters were determined, such as rider kinematics, impact situation etc., and related to head injury type and severity.

2. For new helmets selected as far as possible to be of the same kind as accident helmets, drop-tests were carried out applying various impact velocities and anvil types, in order to determine the relationship between impact energy, resultant headform deceleration and residual deformation of protective padding.

If the residual deformation of the protective padding produced in a defined laboratory test is assumed to estimate the biomechanical head loading for the accident case, the laboratory test results may be applicated to predict head injury risk and to establish criteria for head impact protection to be required for optimal performance of motorcycle helmets. Furthermore, these findings may also suggest improvements or changes for test procedures and performance requirements in standards.

Accident Helmets and Injury

From accident cases investigated at the Munich Institute for Legal Medicine, 15 integral helmets were selected for this investigation. The motorcycle riders wearing these helmets sustained head injury of severity AIS 0 to AIS 6. External damage of helmets indicated impacts against various structures characterized by various impact areas and impact directions.

Table 1 summarizes relevant data for the real accident sample, i.e. helmet type, head injury type and severity, impacted structure, impact area, impact direction and helmet damage. Altogether, the accident cases are covering a wide range of the real motorcycle accident scene.

Riders who sustained critical and fatal head injury (AIS 5 and AIS 6) predominantly were exposed to lateral impacts in the temporal region and occipital impacts. Those impacts occured against various structures, but for 5 out of the total of 6 cases linear impact signs were observed on helmets.
A strong correlation between external damage of helmets and injury severity is not evident. Certainly, in general, helmet damage tends to increase along with injury severity, but, for example, in case No. 2, critical AIS 5 head injury occured, although no significant helmet damage could be observed.

Dynamic Tests for New Helmets

Laboratory investigations of the MPA Stuttgart were carried out on five helmet types (integral helmets), testing 20 helmets for each type (cf. Table 2). The test helmets were selected to be as best as possible similar to the corresponding accident helmets, i.e. with respect to size, construction, material of the shell and the protective padding.

The new helmets were tested for impact velocities ranging from 4.4 m/s up to 10 m/s and using the following anvil types: flat, hemisperical, rail, kerbstone, semicylindrical. Impact areas on helmets are illustrated in Fig. 1: frontal (B), lateral (X), parietal (P), and occipital (R). For each drop-test headform deceleration was recorded triaxial against time and residual deformation produced in the protective padding was measured.

Fig. 2 shows two characteristic resultant deceleration-time curves recorded which are to be interpreted as follows: The helmet tested provides good performance for an impact against a flat anvil with a velocity of 4.4 m/s (resultant headform peak deceleration 74 g) and almost no performance, i.e. failure of the shock absorbing liner, for an impact against a hemispherical anvil with 8.8 m/s (resultant headform peak deceleration 1350 g).

Figs. 3 - 6 are presenting diagrams of resultant headform peak deceleration versus impact velocity measured for new helmets which were impacted to various anvils and impact-areas. Failure of the protective padding, i.e. a steep increase of deceleration, occured for crown impacts (impact area P) against flat anvils at higher impact velocities as compared to circumference impacts (impact areas B, X, R) and to impacts against more punctate anvils.

Residual deformations of protective padding measured in laboratory tests were analyzed with respect to headform peak decelerations. As an example, for impact area B (frontal) and for flat and hemispherical anvil types the variation ranges for these data are demonstrated in Fig. 7. Fig. 8 presents the corresponding percentage residual deformation of the protective padding related to the inertial thickness.

On practical application of the diagrams from Fig. 7 and Fig. 8 sometimes difficulties may arise, because for steep curve segments small inaccuracies concerning the measurement of residual deformation will result in rather high variations for the related peak headform decelerations. Nevertheless, the following estimation is considered to be possible: Residual deformations of the protective padding lower than 5 mm (15 %) are correlated to peak headform decelerations lower than 150 g, independant of anvil types used. Up to 10 mm residual deformations (27 %), headform decelerations of 300 g will not be exceeded. Therefore, the local residual deformation of protective padding can be considered as an indicator, whether the accident conditions have been stronger or milder than ECE-R 22 test conditions.

If residual deformation of the protective padding is exceeding 10 mm (27 %) the corresponding head-form decelerations cannot be obtained reliable from the overall presentation in Figs. 7 and 8.

But, for these cases a special analysis may be successfull, if the specific accident parameters are considered, such as helmet construction, impact area and the impacted structure.

This procedure was carried out for accident case No. 9 (cf. Table 1): Accident files reported a collision of the motorcycle with an oncoming passenger car. The 20 years old female passenger of the motorcycle was thrown on the road surface without any vehicle contact. External helmet damage indicated an occipital impact. The young women sustained critical head injury (skull fractures and brain contusion) and died 5 days after the accident. The residual deformation of the protective padding (10 mm) appeared not to be produced by a flat structure rather than by a rounded or edged structure of linear extension, such as a kerbstone to be found at the accident location.

Applying diagrams from Fig. 7 and Fig. 8, the residual deformation of 10 mm would be related to a peak deceleration of 180 g to 300 g (flat anvil) and 80 g to 180 g (hemispherical anvil).

In order to reproduce the residual deformation for helmet No. 9 as best as possible, drop tests were carried out using a flat and rail type anvil, in order to simulate impacts on the road surface and the kerbstone. Best aproximation for the residual deformation of the accident helmet could be achieved under following conditions:

Anvil type	rail.
Impact area	occipital.
Impact velocity	7 m/s.
Peak deceleration	129 g.
Residual deformation	8 - 9 mm.
HIC	671.
5 ms deceleration	85 g.

These data are located in the center of the variation range for the hemispherical anvil in Fig. 7 and Fig. 8. The experiments applying a flat anvil did not produce such a good aproximation of real accident residual deformation of the protective padding. A 8 - 9 mm residual deformation could be achieved for higher impact velocties and higher peak decelerations, i.e. 170 g and 260 g resp..

The residual deformation pattern of helmet No. 9 could be simulated under conditions, which meet the requirements from ECE-R 22. If it is considered to be true, that headform peak deceleration measured in drop tests and real head impact loading, i.e. translational head deceleration, are almost of the same order, a test result meeting the standards does not guarantee that critical head injury of AIS 5 will be avoided, even when impact conditions are significantly milder than the required 300 g in the ECE-Regulation.

Discussion

The investigation of helmets impacted in real accidents and corresponding experimental laboratory impact tests simulating the residual deformation of the protective padding suggest, that headform decelerations measured in drop-tests indicate real accident head loading, i.e. at least translational head deceleration.

The corresponding relationship evaluated in this study is presented in Fig. 9. For accident cases head injury severity (AIS) is plotted versus actual residual deformation of the protective padding, distinguishing helmet shells made of Polycarbonate (PC) and Glass-Reinforced-Plastic (GFRP). In the same way, the upper limit of the variation range for headform peak decelerations shown in Fig. 7 is plotted versus residual deformation of protective padding of new helmets produced experimentally. Applying laboratory test results to accident helmets leads to the result, that half of the accident cases representing critical and fatal head injury (AIS 5 and AIS 6) occured under impact conditions which are related to headform peak decelerations lower than 150 g measured in laboratory drop-tests. The accident sample includes not a single case related to headform peak decelerations more than 300 g.

Fig. 9 also indicates that there exists no strong correlation between head injury severity and residual deformation of protective padding observed for accident helmets (e.g. 2-7 mm is related to AIS 3-6), and, as a consequence, no close relationship between head injury severity and headform peak deceleration (e.g. AIS 3 - 6 for decelerations < 150 g).

For specific accident situations, e.g. for case No. 9., it is evident, that high rotational head acceleration may have been occured as a consequence of an occipital impact. This could be an explanation that, in fact, rather low translational head deceleration did occur, as indicated by the corresponding laboratory test, and a high rotational head acceleration, not measured in the falling headform, was additionally responsible for the AIS 5 head injury sustained in the real accident. A review of biomechanical head impact tolerance data from the literature [4] presented in Fig. 10 indicates that severe head injury is to be expected either for high translational or for high rotational accelerations (c.f. solid marks in Fig. 10). Because of the head neck anatomy both components appear not to be independant from each other. According to Fig. 10 head injury severity AIS > 2 could be expected even for rather low translational acceleration (< 150 g), if rotational acceleration exceeds 10 krad/s^2. However, as far as rotational and translational components are considered not to be independent, translational accelerations < 120 g would not cause rotational accelerations $>$ 20 krad/s^2 which appear not be critical according to Fig. 10.

Conclusion

The results of the study suggest that rotational head acceleration could be important in real accident impact situations. To include this as a performance criterium in a test procedure for standards would be very difficult and probably not necessary, because, as demonstrated above, a significant reduction of limit for the translational headform deceleration, e.g. up to 120 g, would exclude critical rotational head acceleration in real impact situations.

References

[1] ECE-Regulation 22: Uniform Provisions Concerning the Approval of Protective Helmets for Drivers and Passengers of Motorcycles.

[2] Otte D., P. Jessl, and E.G. Suren: Impact Points and Resultant Injuries of Motor-Cyclists Involved in Accidents, with and without Helmets. Proc. of the 1984 IRCOBI Conference.

[3] Hope P.D. and B.P. Chinn: The Correlation of Damage to Crash-Helmets with Injury, and the Implications for Injury Tolerance Criteria. Proc. of the 1990 IRCOBI Conference.

[4] Data collected in particular from: a) Proceedings of the Stapp Car Crash Conference, annually published since 1966 (10th, 11th etc.) by SAE (Society of Automotive Engineers), Warrendale, Pennsylvania, USA, b) Proceedings of the IRCOBI Conference (International Research Committee on Biokinetics of Impacts), annually published since 1973 (1st, 2nd etc.) by IRCOBI Secretariat, 109 Rue Salvador Allende, 69500 Bron, France.

[5] Newman J.A.: A Generalized Acceleration Model for Brain Injury Threshold (GAMBIT). Proc. of the 1986 IRCOBI Conference.

Acknowledgements

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TABLE 1: Description of the Real Accident Sample

Accident Helmet #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Shell Material	PC	PC	PC	PC	GFK	GFK	GFK	GFK	GFK	PC	PC	PC	GFK	GFK/PC	GFK
Protective Padding	PS	PS	PS	PS	PS	PS	PS	PU	PS	PS	PS/PU	PS	PS	PU	PS
Injury															
Brain	X	X		X	X	X	X	X	X			X			
Skull	X								X			X	X		
AIS Head	5f	5	0	5f	3	5f	3	2	5f	2	2	6	2	2	1
other body segments	X		X	X			6	X	X	X	X			X	X
ISS	38	27	6	43	11	27	11	9	35	17	12	75	6	6	6
Impacted Structure															
solid	X		X		X	X	X	X	X	X	X				X
deformable		X		X				(X)		X	(X)	X	X	X	(X)
fixed	X		X		X	X	X	X	X	X	X				X
movable		X		X							(X)	X	X	X	(X)
flat	X		X				X	X	X		X		(X)		
vaulted		X		X	X	X		(X)		X	(X)	X	X	X	X
plane	X	(X)	X			(X)	X	X	X	X	X			X	
linear		X		X	X	X		(X)				X	X	X	X
Impact Area															
frontal			X										X	X	X
occipital	X		X					X	X						
parietal					X	X	X								
lateral	X	X		X		X				X					X
chin							(X)	(X)		X	X	X	X		
Impact Direction															
radial		(X)			X	X		X	X		(X)	(X)	(X)	X	X
oblique	X			X	X			X							X
tangential	X		X				X	X	(X)		(X)				
Shell Damage															
laceration					X	X	X	X			X		X	X	X
breaking					X	X	X	X			X	X		X	X
destruction					X										
abrasion	X		X	X				X	X	X		X	X		X
Protective Padding Damage															
residual deformation (mm)	2-4	2-4	<1	2	9-10	7	4	2-3	10	1-2	<1	5-6	<1	<1	2-4
breaking	(X)							X					X	X	

PC Polycarbonate, PS Polystyrole, GFK Glass-Reinforced-Plastic, PU Polyurethane, f Fatal evidence, (X) estimated, no positive proof

TABLE 2: New Helmets Selected for Laboratory Drop-Tests

Helmet Type	Size	Prod. Year	Certific.	Shell Mat.	Protective Padding
A	M	1988	ECE	PC 4mm	PS 35-39mm, 38 g/l
B	M	1988	ECE	PA 3mm	PS 31-37mm, 37 g/l
C	M	1987	ECE	GFK 3mm	PS 27-32mm, 38 g/l
D	M	1988	ECE	ABS 3mm	PS 37-40mm, 45 g/l
E	M	1988	ECE	GFK4mm	PS 30-36mm, 29 g/l
T**	M	1987	ECE	GFK4mm	PS 26-32mm, 27 g/l

PS Polystyrole, PC Polycarconate, PA Polyamide, ABS Acrylnitrile-Butadiene-Styrole,

GFK Glass-Reinforced-Plastic, ** for Case No. 9 only

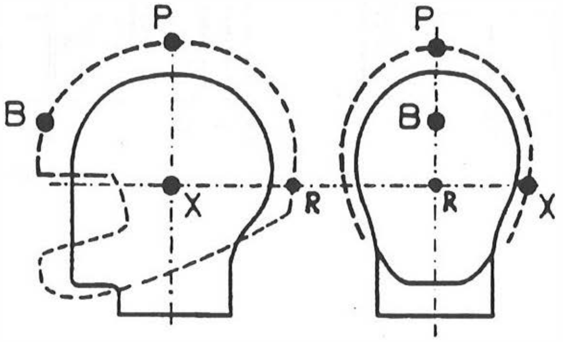

Figure 1: Impact areas

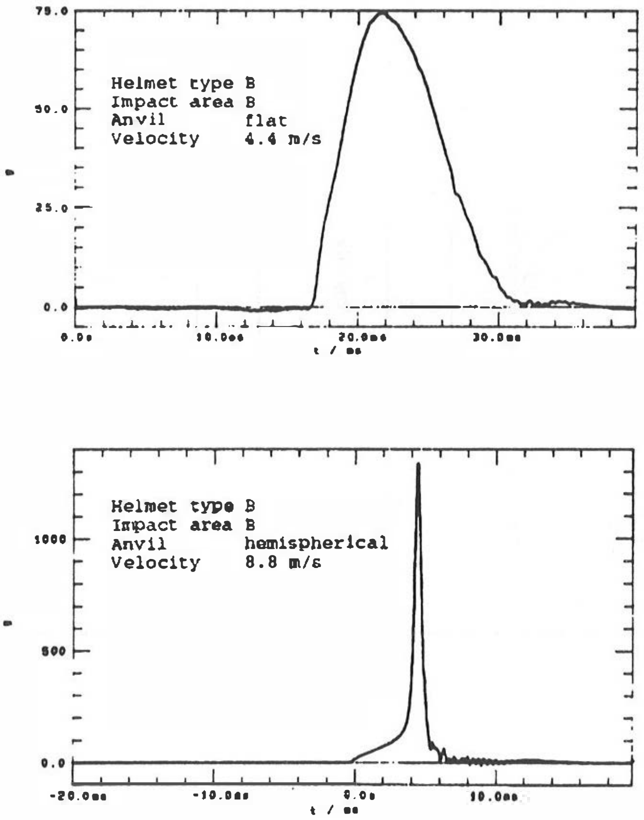

Figure 2: Characteristic deceleration-time curves

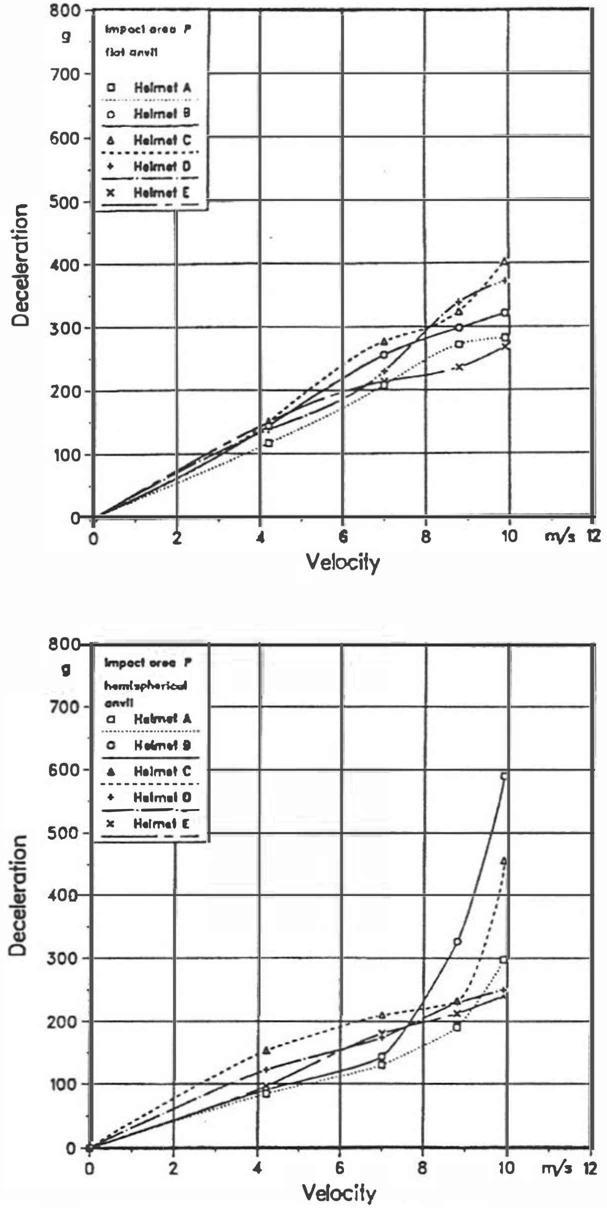

Figure 3: Falling headform tests, impact area P

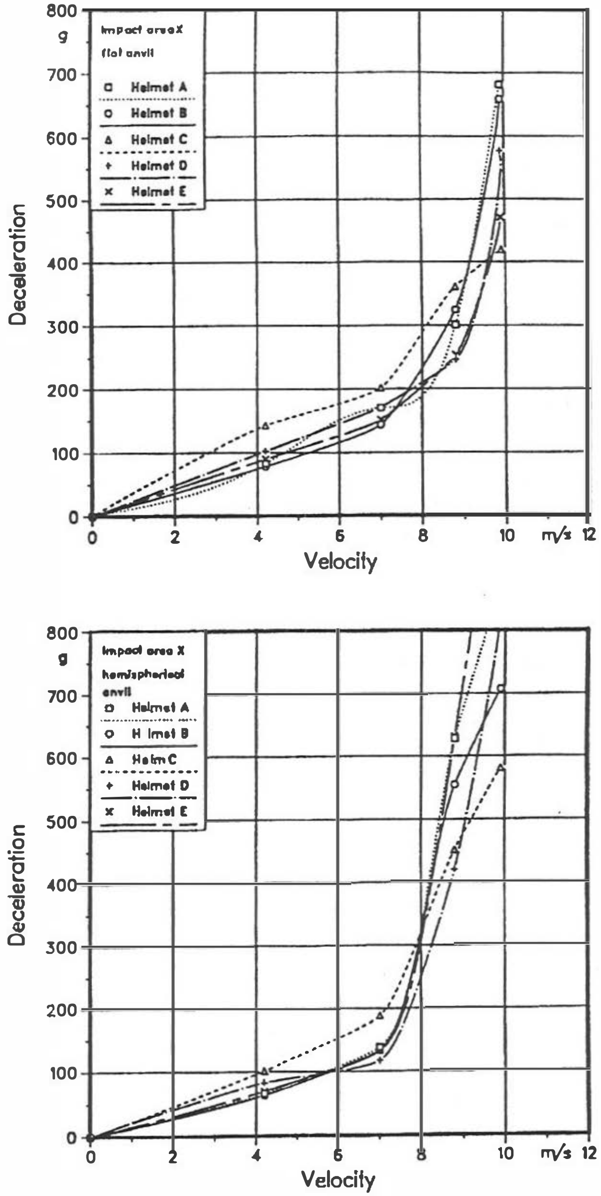

Figure 4: Falling headform tests, impact area X

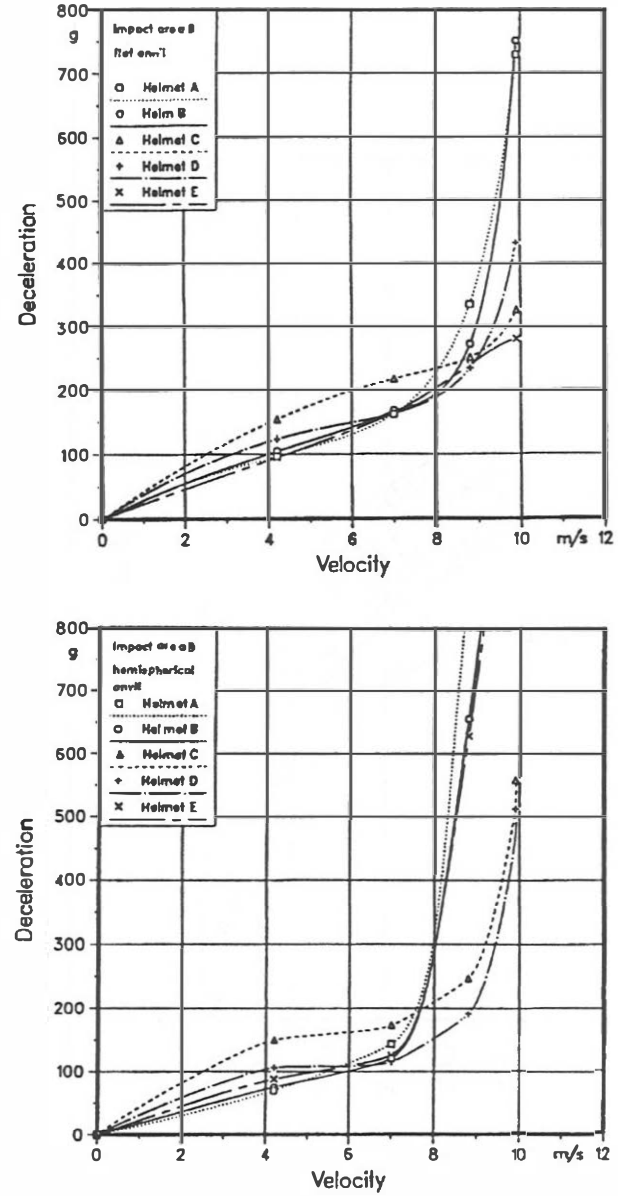

Figure 5: Falling headform tests, impact area B

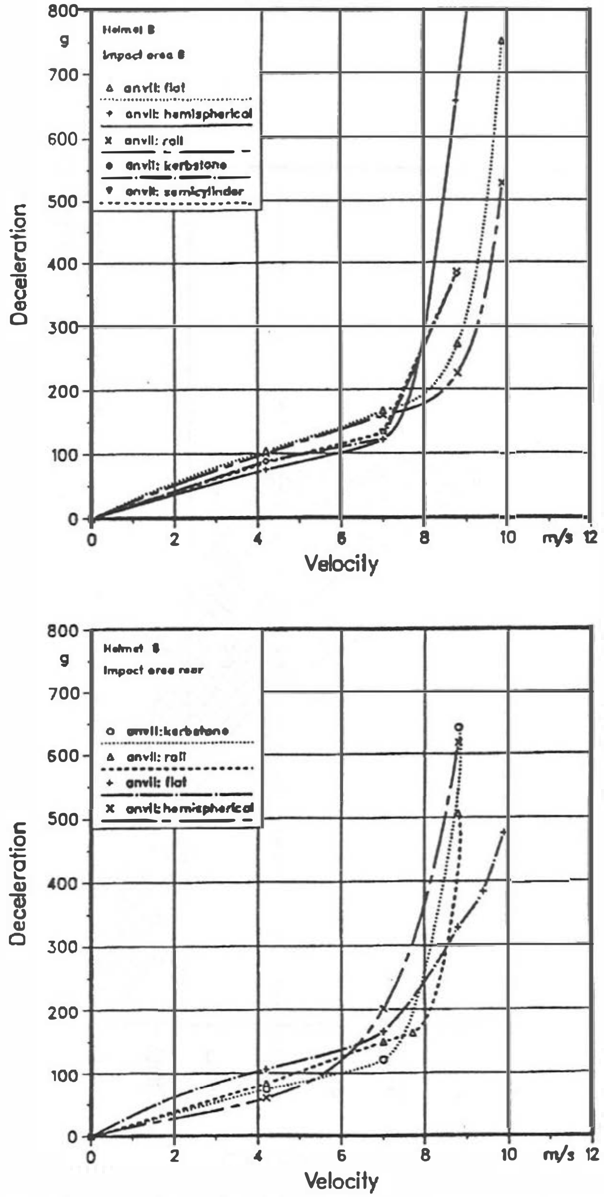

Figure 6: Falling headform tests, impact area B and rear, different anvils

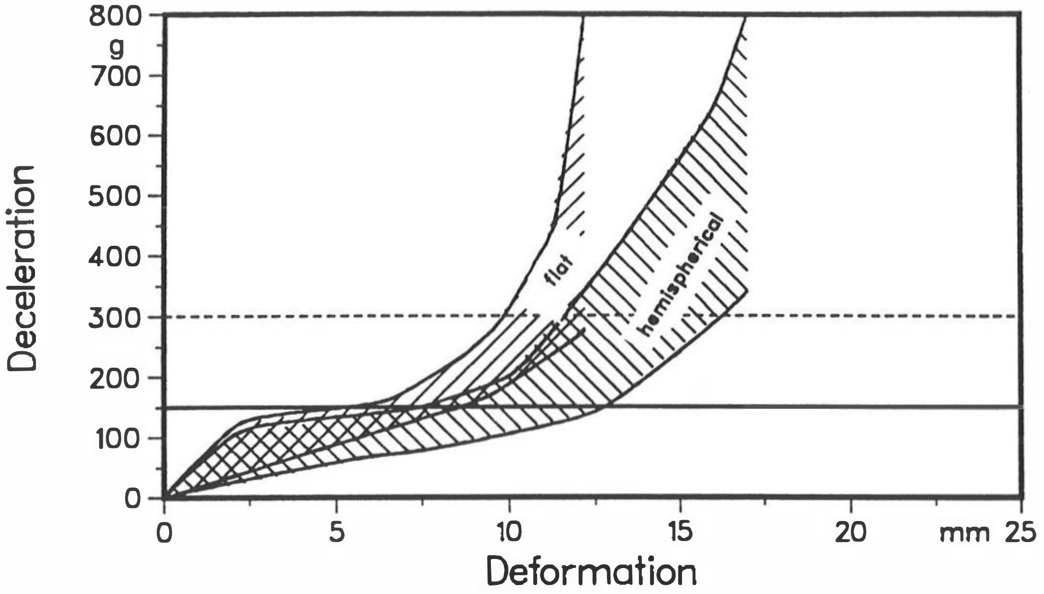

Figure 7: Deceleration-deformation scatter bands,

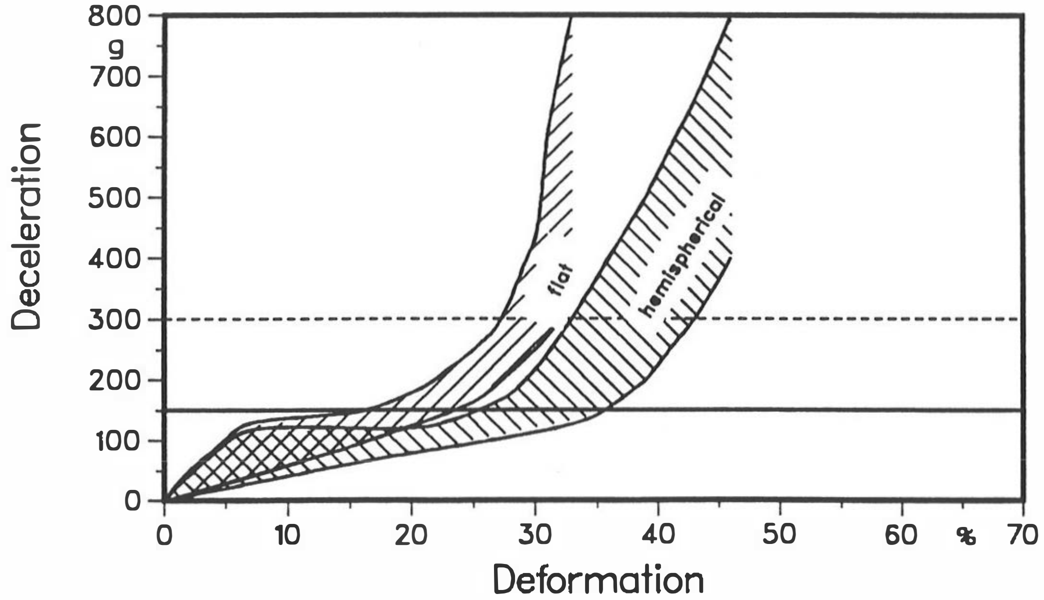

Figure 8: Deceleration-deformation scatter bands, impact area B, helmet A - E

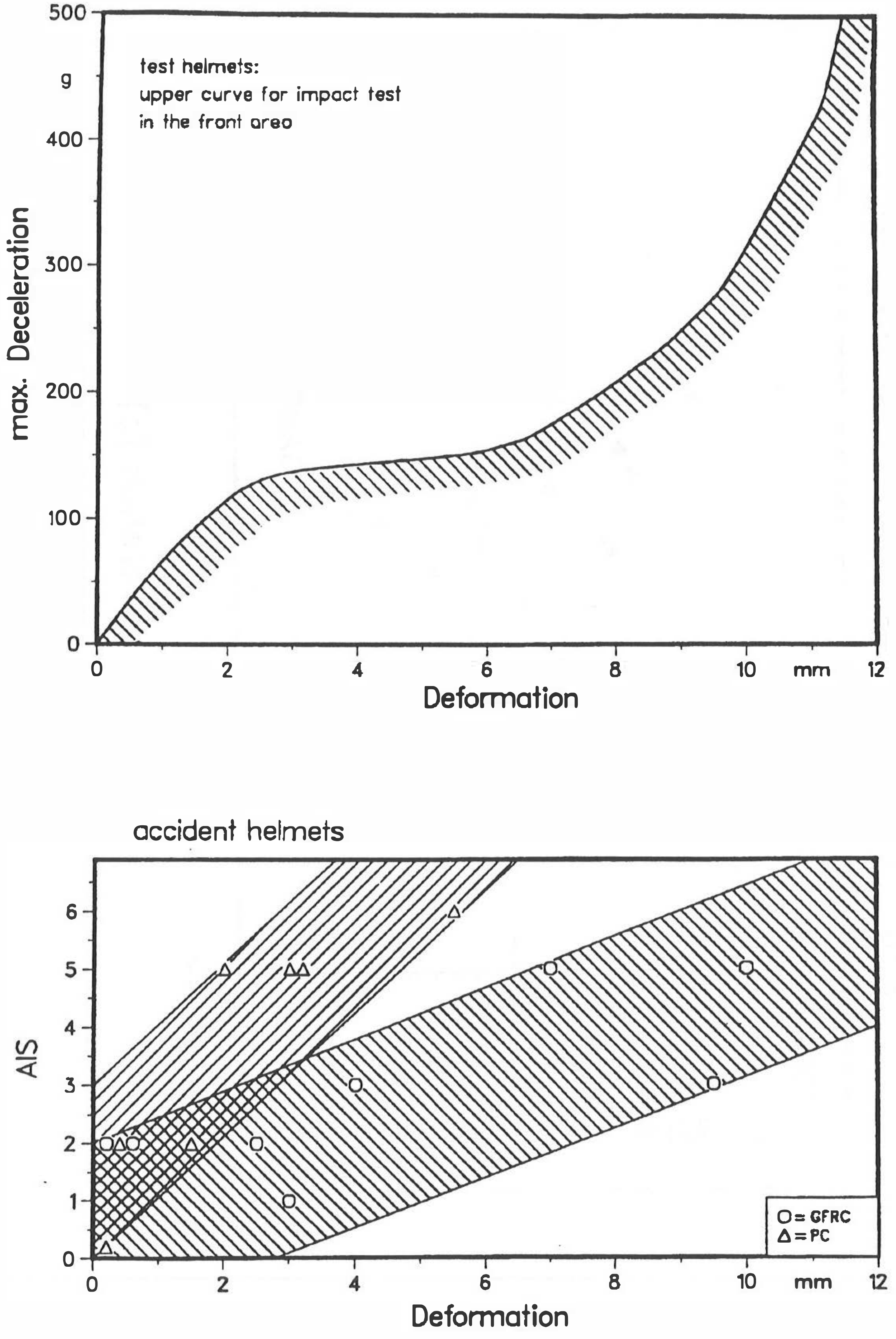

Fig. 9: Comparison of Maximum Headform Peak Deceleration and Head Injury Severity AIS Related to Residual Deformation of Test and Accident Helmets (GFRC and PC see Text)

Fig. 10: Translational and Rotational Acceleration and Head Injury Severity AIS (cf. [4], [5])