Experimental Study on Impact Absorbing Performance of Motorcycle Helmets

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The regulation regarding motorcycle helmets to protect the head from impacts has been amended recently. In Europe, the Head Injury Criteria (HIC), which is more relevant to indicate the probability of death than the limitation of maximum acceleration, has been adopted. An experimental study has been conducted following the procedure of the new European regulation, by changing various helmet structural parameters such as the lamination and the bulk density of the shell, and the liner, to investigate the ability of the helmet to protect the head from injuries. The maximum acceleration and HIC were measured. Experimental data have been analyzed with respect to varying lamination of shells and weight of liners. The HIC was found to be improved by reducing the bulk density of the liner and the number of laminations of a shell, and by increasing the loading area of the headform.

Key Words: Europen Regulation, Head Injury Criteria (HIC), Headform, Impact, Lamination, Liner, Motorcycle Helmet, Shell

1. Introduction

The protection from injury caused by a blow to the head has been always a matter of great concern. Damage to the brain and the scalp, and the outer covering of the head, can be inflicted through varying mechanisms. To protect from various kinds of injuries such as lacerations, abrasions, fractures, and other forms of tissue disruption a variety of approaches may be required. However, the fundamental principles are to place padding in order to reduce the severe effect of impact and to uniformly distribute the impact load.

A helmet is the most popular form of head protection. The purpose of wearing a helmet is to reduce the severity or probability of injury caused by an inadvertent impact to the head. An outer shell and an energy absorbing liner are two primary elements for the usual helmet. A shell provides a hard, strong, outer surface that serves to distribute the impact load over a large area. It also provides a penetration shield against high-speed objects and serves to protect both the wearer and the underlying liner of the helmet from abrasion of the impacting surface. It should have a high strength-to-weight ratio, and usually a smooth exterior finish. The interior of a shell is the liner of the helmet. It absorbs a lot of impact energy through its partial destruction. In order to enhance its performance it should be deformed by a force less than that causing head injury. The strength of a liner should be insensitive to the impact velocity. Furthermore, to maximize the ability of energy absorption, it should have slow recovery (rebound) characteristics.

The regulations for the impact absorbing performance of motorcycle helmets are established in many countries. In Europe, the Head Injury Criteria (HIC) which is more relevant to indicate the probability of death than the limitation of maximum acceleration, has been adopted recently to improve the standard of motorcycle helmets.

In this study, the ability of head protection by

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a helmet has been investigated by using an experimental procedure of the new European regulation, by changing helmet structural parameters such as the lamination and the bulk density of the shell and the liner. The accelerations of helmets were measured, and the deformation, rebound velocity and HIC were estimated with the help of the measured values. The experimental data have been analyzed with respect to varying lamination of shells and weight of liners. In addition, the effect of installation of polyethylene pads on the improvement of helmet performance has been estimated.

2. Background

The impact attenuation of motorcycle helmets requires that the maximum acceleration (of a helmet when it is dropped on an impact surface) shall not exceed a certain level. The requirements are specified at ECE R22.03 in Europe and at FMVSS No. 218 Part 571 49CFR in USA. In the USA, there is another standard of SNELL M90 which is established by the Consumer Protection Agency. These standards listed in Table 1 show a little difference in the requirements and test methods such as impact speed, type of anvil, etc (Backaitis, 1992 ; Federal, 1992).

Various investigations were set up to improve the understanding of the tolerance of human head injury in Europe during late 1980s. Information on fatal and non-fatal motorcycle accidents except penetration by a sharp object was collected. Information on brain scans of fatalities and the helmets was also included. Drop tests were made at different energy levels by using an instrumented solid wooden headform with helmets analogous to the real accident. The acceleration of the headform was measured to estimate the HIC and peak acceleration. These values were assumed as those experienced in real accident.

The helmets used in this study were found to withstand an impact equivalent to HIC 2000 without producing discernable damage. Considering that the resilience of a helmet was typically on the order of 0.6, we concluded that the HIC was a more relevant indicator representing the probability of death than the peak acceleration for the criteria of assessment (Newman, 1980). Although helmets having the characteristics of resilience satisfied the regulation of ECE R22.03, it was noted that the HIC level could indicate very high probability of death.

3. Head Injury Criteria

The HIC was originated from the pioneering work of Gurdjian and co-workers in 1932. They developed the "Wayne State University Cerebral Concussion Tolerance Curve" as shown in Fig. 1. The relationship between effective acceleration and duration was then constructed, and a boundary to separate the "skull fracture" zone from the "no skull fracture" zone was established (Nahum, 1993: Melvin, 1993). Gadd introduced the concept of a Severity Index to provide a rational and

Table 1 Regulations of impact attenuation for motorcycle helmet (g=gravity).

Regulation	U.S.A.		Europe	
	FMVSS No. 218	SNELL M90	ECE R22.03	ECE R22.04
Impact Velocity and Type of Anvil	6.0m/s at flat 5.2m/s at hemispherical	7.5m/s at flat, hemispherical and edge	7.0m/s at flat 6.0m/s at hemispherical	7.5m/s at flat and kerbstone
Peak Acceleration	400g	300g	300g	275g
Max. Cumulative Duration	2msec at 200g, 4msec at 150g	-	5msec at 150g	-
HIC (max.)	-	-	-	2,400

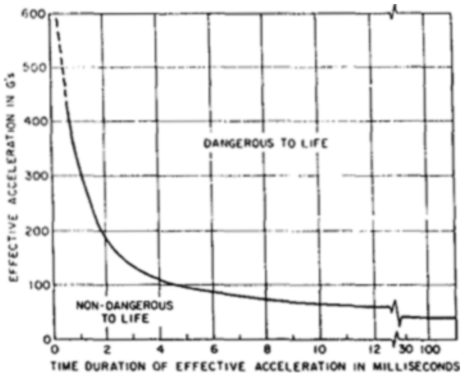


Fig. 1 Wayne state tolerance curve.

consistent basis for comparing the severity of various head impacts in 1966 (Pike, 1990). The Wayne State Curve was approximated by an empirical expression:

$$SI=\int_{t_1}^{t_2} \tilde{a}^{2.5} dt \quad (1)$$

where ã is the effective acceleration and t is the time duration of the acceleration pulse.

Abundant analyses and experiments were carried out after the Severity Index was published. Versace analyzed the relationship between the Wayne state Tolerance Curve and Severity Index based on HIC in 1971. The HIC has been revised several times so far. The present definition of HIC may be expressed as

$$(t_2-t_1)[1/(t_2-t_1)\int_{t_1}^{t_2} a(t)\,dt]^{2.5} \quad (2)$$

where a is the resultant acceleration as a multiple of 'g', and t_1 and t_2 are taken as any two points on the time axis during the impact so as to maximize Eq. (2) (Proposl, 1994).

A HIC value of 1000 is an arbitrary accepted number for the non-fatal to fatal threshold. This does not take into account variations in human tolerance. The HIC is based on the assumption that the brain is a visco-elastic medium. The synergistic effect of both acceleration and duration is taken into account. This approach claims that two parameters (acceleration and duration) rather than a single parameter (peak acceleration) are suitable for the definition of the limitation.

4. Specimens and Experimental Method

The performance of impact attenuation of motorcycle helmets is affected by the outer shell and the inner liner. The material of the shell was fiber-reinforced plastic (FRP), which has been widely used and is known to be strong against impact. The shell was made by a hand lay-up process. Three types of shells (2-ply, 3-ply and 4-ply) have been chosen as specimens to investigate the characteristics according to the difference in number of FRP mats. The expanded polystyrene (EPS) bead foam with desirable stress-strain properties was used for liner material.

Table 2 Test data for motorcycle helmets at UTAC.

No. of Lamination	Weight of EPS[gm.]	Impact Position	Acceleration		HIC	Remark
			a[g]	t_{150}[ms]		
2 Ply	108	B	153	0.93	1058	Anvil:Kerbstone Condition:+50℃
		X	188	2.13	1164	
		P	167	3.99	1671	
		R	179	1.79	1247	
		B	191	2.53	1375	Anvil: Flat Condition : −20℃
		X	221	2.86	1649	
		P	254	4.24	2586	
		R	223	3.52	1989	

Three types of liners (100 gram, 130 gram and 170 gram) have been selected as specimens to analyze the characteristics of absorption of impact energy according to the difference of bulk density to determine the crushing properties.

The headforms to simulate a human head are divided into five sizes corresponding to the size of a person's head. A mid-sized headform has been used. Impact surfaces on which helmets are dropped are divided into two types, a flat anvil and a kerbstone anvil. Eight tests with the different types of anvil and various position of impact were conducted at UTAC (Union Technique De L' Automobile Du Cycle ET Du Motocycle). The helmets used in this study were identical to the models used at UTAC. They had a 2-ply shell and a liner weighted at 108 gram. The test results are shown in Table 2. The highest value of the HIC was 2586 at impact point P of the helmet on a flat anvil. Note that the requirement of ECE R22.04 is 2400. We used the flat anvil instead of the kerbstone anvil as an impact surface because the helmets were met the reguirement at severer condition. The top (point P), which yielded the highest value of HIC, was chosen as an impact location (Recommendations, 1991).

The height of the front and side of the helmet after the helmet was adjusted to the normal position at the 1st experiment was measured to keep the experimental condition consistent. The height measured at the first experiment has been used for the standard value to set the helmet through out the experiments.

5. Test Equipment

5.1 Drop test device for motorcycle helmets

The test device for motorcycle helmets which was manufactured according to the European drop test equipment in this study is shown in Fig. 2. The seating plate is a place to set up the helmet at the impact position. The headform support dolly, a single body with the plate, is designed to eliminate the rotation or shaking of the seating plate by a 3-wire guide cable passed through holes at the end of the dolly when it is dropped. The test helmet with headform, the seating plate,

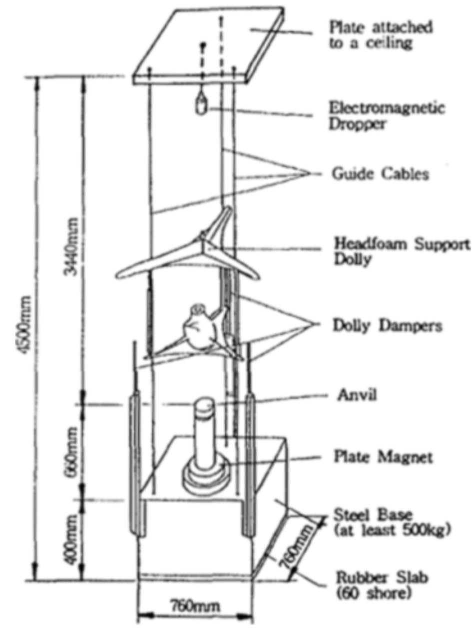


Fig. 2 European drop test equipment for motorcycle helmet.

and headform support dolly are dropped at a height corresponding to the impact speed. At first the helmet impacted the top of the flat anvil which rested on a steel base, and then the seating plate with the dolly hit a dolly damper to absorb the impact energy

5.2 Data acquisition and reduction system

Three piezoresistive type accelerometers (Model 7264-2000) with maximum capacity 2000g were installed on the mounting bracket in the x, y and z directions, and the bracket was fixed at the installation position inside the headform. The analog signals produced from the accelerometer were amplified at a signal conditioner (Model MDS32) and filtered at the class 1000 channel frequency, and stored in the memory inside the amplifier. The analog signals were then converted to digital data by an A/D converter at sampling frequency of 10kHz and with 12 bit resolution.

HIC was calculated from the acceleration by a data analysis program PIAS (V3.0 MTE), and also the relationship between the velocity and force-deflection were estimated.

6. Discussion

6.1 Original specimens

The resultant data for 9 tests are shown in Table 3. The typical comparison between HICs are shown in Figs. 3 and 4. The maximum resultant acceleration, (a(max)), duration, (t_{150}), at 150g, HIC, time interval of two point to maximize HIC, (t_2-t_1), deflection, (X_d), and rebound velocity, (V_e), were measured.

For a 2-ply shell and 100 gram liner weight, the HIC achieved the lowest value of 2210, and the deformation rate at the impact point P was 67%. It was found that decreasing liner weight with the same number of laminations of the shell decreases the peak acceleration and HIC. The deformation and the time durations of (t_2-t_1) for most HIC were increased. The main reason seems to be the reduction of the strength of liner at the same volume of liner, which increases the liner deformation and the loading area. Comparisons of acceleration and force-deflection for different liner weights (100gram, 130gram, 170gram) are shown in Figs. 5 and 6. The HIC decreased, and all of the deformation except the 3-ply shell combination with 130 gram liner increased as lamination of shell at the same weight of liner decreased.

Table 3 Variation of test data for different ply-shell and liner weight of helmet.

No. of Lamination	Weight of EPS[gm.]	Ve[m/s]	Acceleration		HIC		X_d[mm]
			a(max) [g]	t_{150}[ms]	Value	t_2-t_1[ms]	
2 P	100	3.6	225	3.9	2210	5.2	24.2
	130	3.7	287	4.1	2782	4.6	20.6
	170	3.6	309	3.9	3120	4.2	19.9
3 P	100	3.7	222	4.1	2260	5.4	24.2
	130	4.0	310	3.5	3043	3.6	19.7
	170	3.8	317	3.7	3428	3.8	19.2
4 P	100	3.8	232	4.2	2653	4.8	22.0
	130	3.9	284	3.9	3076	4.2	20.1
	170	4.4	377	3.5	4580	3.4	17.0

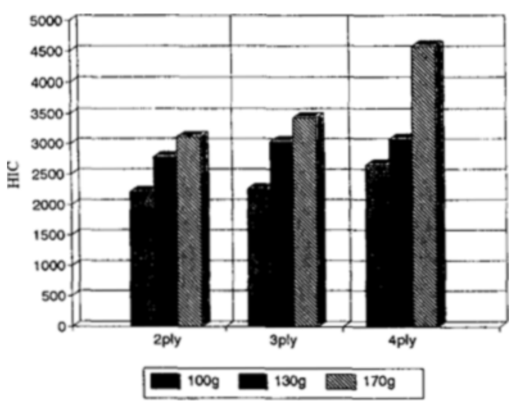


Fig. 3 Comparison of HIC for different ply shell combination with various liner weight.

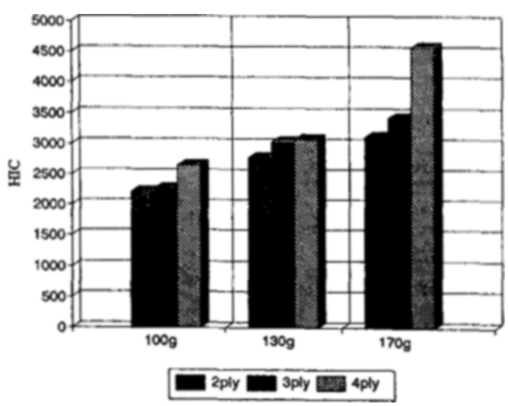


Fig. 4 Comparison of HIC for different liner weight combination with various ply shell.

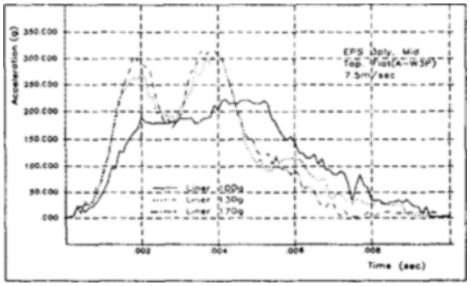


Fig. 5 Variation of acceleration for different liner weight combination with 3-ply shell.

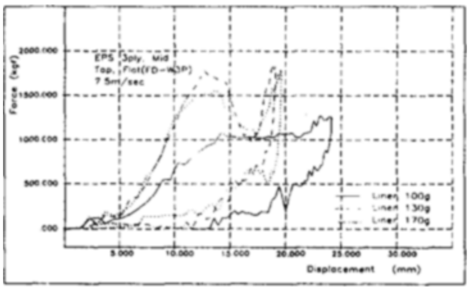
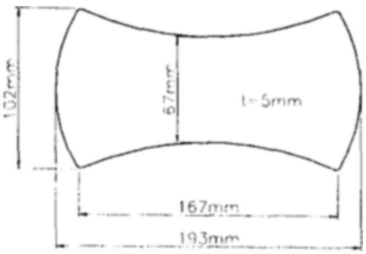


Fig. 6 Variation of force-displacement for different liner weight combination with 3-ply shell.

The resultant data for 9 experiments showed no proportional relationship between the HIC and maximum acceleration, and the liner was found to be more effective in decreasing HIC than the shell. There were two specimens, (2-ply shell combination with 100gram liner and 3-ply shell combination with 100gram liner), which meet the requirements of the amended European regulation.

6.2 Improved specimens

The actual force generated when a material is crushed depends not only on the extent of crush, but also on the inherent strength of material and the size of the loading area. The force generated when a helmeted head strikes something, or as the head strikes a padded surface, depends on the crushing characteristics of impacted material (Zellmer, 1993). Therefore one of the primary objectives of a good helmet design is to maximize the area of padding that can interact with the head during impact. Also, it was found that increasing the initial undeformed thickness of the



Material	Polyethylene	Thickness	5 mm
Weight	8.5 gram	Area	151.5 cm^2

Fig. 7 Dimension of polyethylene pad.

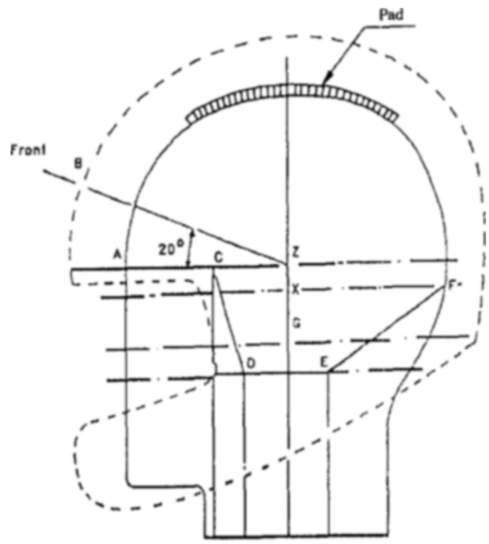


Fig. 8 Position of polyethylene pad for insertion.

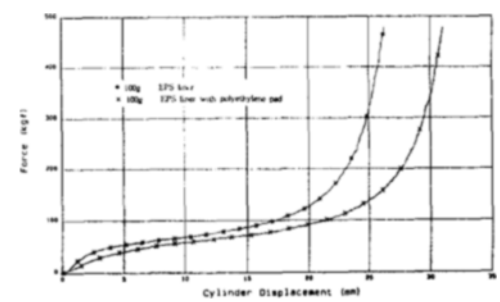


Fig. 9 Comparison of strength for 100 gram EPS liner with the EPS liner adding polyethylene pad at quasi-static compression test.

padding reduces the strain for the same deformation.

The pads shown in Fig. 7 were made of polyethlene by foaming. The configuration of the

Table 4 Test data for improved helmet with 3ply-shell.

Weight of EPS[gm.]	Installation of Pad	Ve[m/s]	Acceleration		HIC		X_d[mm]
			a[g]	t_{150}[ms]	Value	t_2-t_1[ms]	
100	Original	3.7	222	4.1	2260	5.4	24.2
	Add	3.5	221	4.1	1985	5.2	25.0
	Insert	3.7	222	4.3	2141	5.0	24.3
170	Original	3.8	317	3.7	3428	3.8	19.2
	Add	3.8	285	3.8	2940	4.0	21.3
	Insert	4.0	316	3.5	3202	3.6	20.4

pads were determined by considering the shape of the comfort liner which contacts the head. The pads were installed at the top region of a headform using two different methods as shown in Fig. 8. One was installed at a place between the liner and the headform, the other was inserted on the liner. A portion of the liner was removed for the insertion of the pad. The strength for the EPS liner with addition or insertion of polyethylene pads was found to be lower than that of EPS liners under quasi-static compression. The comparison of strength for 100 gram EPS liner with the EPS liner with polyethylene pad was shown in Fig. 9. The adding or inserting of a pad has been applied for two different specimens, the 3-ply shell combination with 100 gram liner and 3-ply shell combination with 170 gram liner. The resultant data of 4 tests for the improved specimens of helmets are shown in Table 4, and the typical comparisons between HICs are shown in Fig. 10.

The HIC decreased for both cases and was improved from 12% to 14% for the additional pad, and also improved from 5% to 7% for the inserted cases. The increase in deformation of the liner including polyethylene pad is found to increase the contact area with headform, and consequently

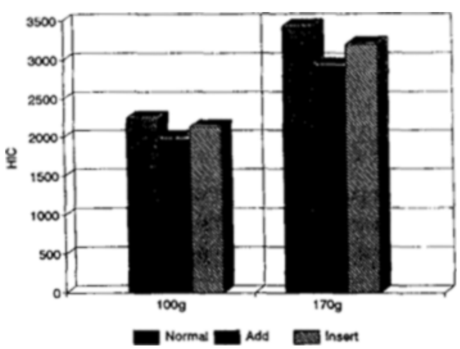


Fig. 10 Comparison of HIC for installation of polyethylene pad with 3-ply shell and various liner weight.

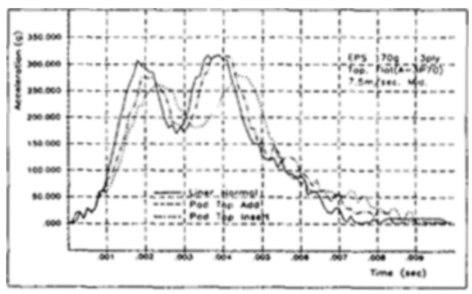


Fig. 11 Variation of acceleration for insertion of polyethylene pad with 3-ply shell and 170 gram liner.

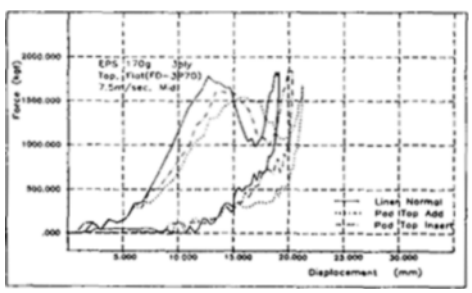


Fig. 12 Variation of force-displacement for insertion of polyethylene pad with 3-ply shell and 170 gram liner.

the energy absorbed. The decrease in the HIC, and the increase in deformation and (t_2-t_1) of the HIC for an additional pad rather than for the inserted pad implies that somewhat lower force was maintained due to the increment of total thickness of padding. Comparisons of acceleration and force-deflection for both cases of the 3-ply shell and 170 gram liner are shown in Figs. 11 and 12.

7. Conclusions

In this paper, the requirements of impact absorbing performance of motorcycle helmets for different liner weight combinations with various ply shells and installation of polyethylene pad to improve the HIC according to amended European regulation have been investigated with the aid of experimental results. The conclusions are as follows. ;

(1) The HIC is improved (by a reduction in the strength of crushing and the developing force) by decreasing the bulk density (weight per unit volume) of the liner which absorbs most of the impact energy.

(2) The HIC can be reduced further by using the bulk density of liners that are less than 100 gram due to the presense of deformation space.

(3) The HIC has been improved by decreasing the number of laminations, and it is found to be more effective to improve the absorbing ability of impact energy of liner rather than that of shell in decreasing the HIC.

(4) The HIC has been improved by increasing the loading area between the liner and headform, and by increasing the thickness of padding with the additional polyethylene pad.

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