Present and Future Performance Levels of Head Injury Protection for Motorcycle Helmets

An Attempt to Search for Better Impact Energy Absorption Property of Helmets

H. Mitsuishi[1)], K. Ono[1)], T. Nishimoto[1)] and N. Nakamura[2)]
1) Japan Automobile Research Institute, Inc., 2530 Karima, Tsukuba City, Ibaraki Pref., Japan 305
2) The Jikei University School of Medicine, 3-25-8 Nishi-shinbashi, Minato-ku, Tokyo, Japan

ABSTRACT

In an attempt to observe the impact absorption of current helmets, this study was conducted to test actual helmet characteristics and to consider the requirements and potential for improving head protection. For the helmet characteristics tests, three types of helmets were placed on the head of the Hybrid III Dummy which was dropped from certain heights. The parameters used included head acceleration, absorbed energy and head injury criteria (HIC), in addition to the shape of the objects struck (two variations) and impact velocity (four variations).

The potential for increasing head protection was tested by preparing and drop-testing three types of helmets—Base-line, Type-1 and Type-2 were drop tested with some combination of shell materials (FRP and Aluminum), thickness and densities of styrene-foam liners. The results indicated different impact levels in terms of HIC, according to the drop test conditions among various helmets standards applied: roughly 750-4,000 (JIS T-8133, ECE-R.22, SNELL M90). On the other hand, helmets designed for each standards used in this study showed similar impact energy absorption characteristics. The results show that there is a possibility to improve the impact absorption characteristics of current helmets by selecting more appropriate helmet materials.

INTRODUCTION

Because damaging impacts to the head and neck presently account for about 60% of two-wheeler accident fatalities(1), the role of head protection in reducing fatalities cannot be taken for granted. In addition to being easy and comfortable to wear(2), the design of helmets have been enhanced as "protectors"(3) whereby they disperse impacts to the head so as to prevent severe damage, such as skull fracture, to certain areas of the head. Attempts have been made to improve helmet testing methods in such a way that actual accident mechanisms are more precisely reflected such as with regard to the two-time-impacts test routine, perforation, the shape of struck objects, impact velocity, protected range, etc.(4).

Medical experts have reported on a possible correlation between helmet stiffness and head damage, and between head rotational acceleration and diffuse brain injury(5). This has led researchers into looking at the impact absorption characteristics of helmets and at parameters for head injury protection(6).

This study was conducted by focusing impact absorption property out of various required characteristics for helmet. In the first part of this study, a helmet drop-test was carried out to understand the basic characteristics of current helmets. In the second part, a basic characteristics test of various helmet materials was conducted to examine the possibility of improving helmet characteristics.

TWO-WHEELER ACCIDENTS IN JAPAN

Total traffic accident fatalities and fatalities among two-wheeler riders in Japan are shown in Figure 1. Two-wheeler riders who die in traffic accidents number about 2,000 a year, or roughly 20% of all traffic accident fatalities. Figure 2 shows the number of fatalities of motorcyclists and moped (50cc) riders. The ratio of fatal accidents among motorcyclists and moped riders is

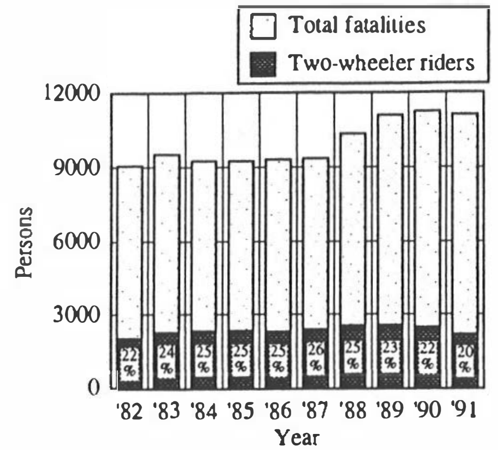


Fig. 1 Total traffic accident fatalities and two-wheeler rider fatalities.

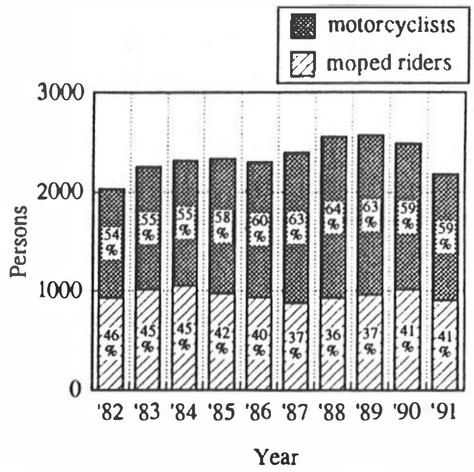


Fig. 2 The number of fatalities among motorcyclists and moped riders.

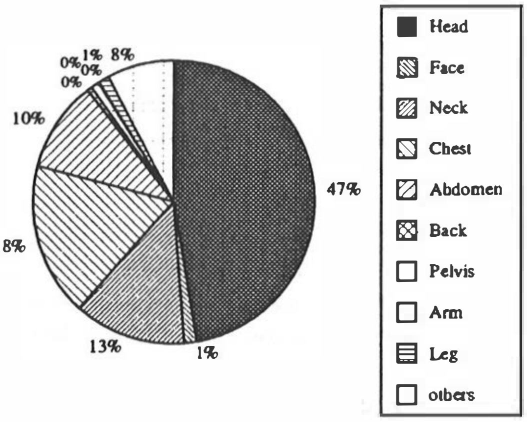


Fig. 3 Injury body region on motorcyclist fatalities.

	Minor	Serious	Fatal	Total
With	41,719 (82%)	8,076 (16%)	1,000 (2%)	50,795 (100%)
Without	625 (52%)	418 (35%)	153 (13%)	1,196 (100%)

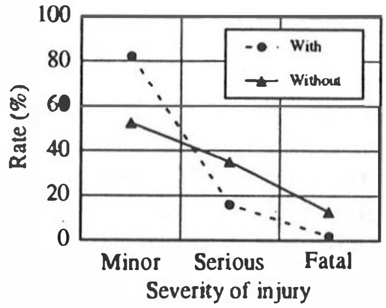


Fig. 4 Comparison of injury severity of motorcyclists, with or without helmet.

approximately 6 to 4. Since both motorcyclist and moped riders use helmets, they are classified together here under "motorcycles" which is the focus of this paper.

Figure 3 shows motorcycle fatalities and regions of body injury. Roughly 50% of motorcycle fatalities result from injury to the head, and another 10% to the neck. Reports by Otte(7) and the other indicated that head and facial injuries accounted for 70% of all fatal body injuries to motorcyclists. It is, therefore, important to reduce head and neck injuries in order to reduce motorcyclists fatalities.

Figure 4 compares motorcyclists who wore and did not wear a helmet in terms of fatalities, the severity of injury, and the helmet-wearing rate. Fatalities for helmeted riders show about 2% while 13% for non-helmeted riders, indicating wearing helmet reduces the severity of head injuries. However, about 600 of the 1,000 helmeted deaths are resulted from fatal injuries to the head and neck.

HELMET DROP TEST

In the first part, a helmet drop test was conducted to review the basic characteristics of current helmets in terms of such parameters as maximum acceleration, energy absorption and HIC. Although impacts could be applied to various areas of the head, including frontal, lateral and occipital, the parietal area was selected to facilitate the measurement of impact absorption by the helmet's shell and liner. Furthermore, in addition to maximum acceleration and impact duration, (see Figure 5) used in existing helmet standards, 3ms acceleration, impact energy absorption and HIC are used in the analysis.

		Anvil shape	Drop Height(m)		Peak G(G)	Duration
			1st Impact	2nd Impact		
JIS T 8133: (Japan Industry Standard)						
	-C:	Flat	1.83	1.83	300	150G/4msec
		Hemi.	1.38	1.38	300	150G/4msec
	-A:	Flat	1.60	non	400	150G/4msec 200G/2msec
		Hemi.	non	non		
SNELL M90: (Standard for protective headgear, SNELL Memorial Foundation)						
		Flat	3.06	2.25	300	non
		Hemi.	3.06	2.05	300	non
DOT FMVSS 218: (Federal Motor Vehicle Safety Standard)						
		Flat	1.83	1.83	400	150G/4msec 200G/2msec
		Hemi.	1.38	1.38	400	150G/4msec 200G/2msec
ECE R.22-03: (ECE-Regulations)						
		Flat	2.50	non	300	150G/5msec
		Hemi.	non	1.83	300	150G/5msec

Fig. 5 Test Standards of motorcycle helmets.

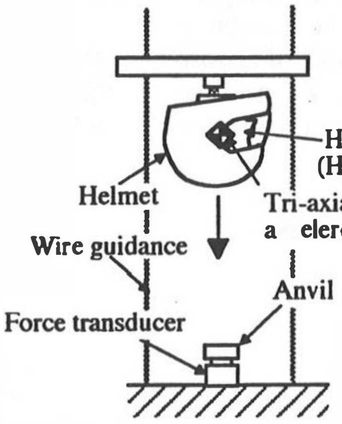


Fig. 6 Test set up for helmet drop test.

Table1 Sample helmets

Sample-A	JIS T8133[8]-A	: for the riders of two-wheelers not larger than 125cc
Sample-B	JIS T8133 -C	: for the riders of two-wheelers
Sample-C	JIS T8133-C-SNELL	: for the riders of two-wheelers

Experiment

The experiment conditions for this first-step test are shown in Figure 6. While standards use magnesium headforms for a human head model, the head of the Hybrid III Dummy was used in this experiment in order to better simulate human head characteristics. Although impact could be applied to various areas of the head, including frontal, lateral and occipital, the parietal area was selected to facilitate the measurement of impact absorption by the helmet's shell and liner. The dummy head was furnished with three types of helmets (Sample-A, B, C ; see table 1).

Two types of objects were used: a flat steel anvil and a hemispherical steel anvil. The head was dropped onto these anvils from four different heights: 0.8, 1.5, 1.8, and 3.0m. Although standard procedures require two-time-impact testing as shown in Figure 5, the head was dropped only once from each height in this study. The measurements included tri-axial acceleration of the dummy head (4.35kg), load on the object, impact velocity, and behavior/ displacement as recorded by high-speed cine and video cameras.

Results

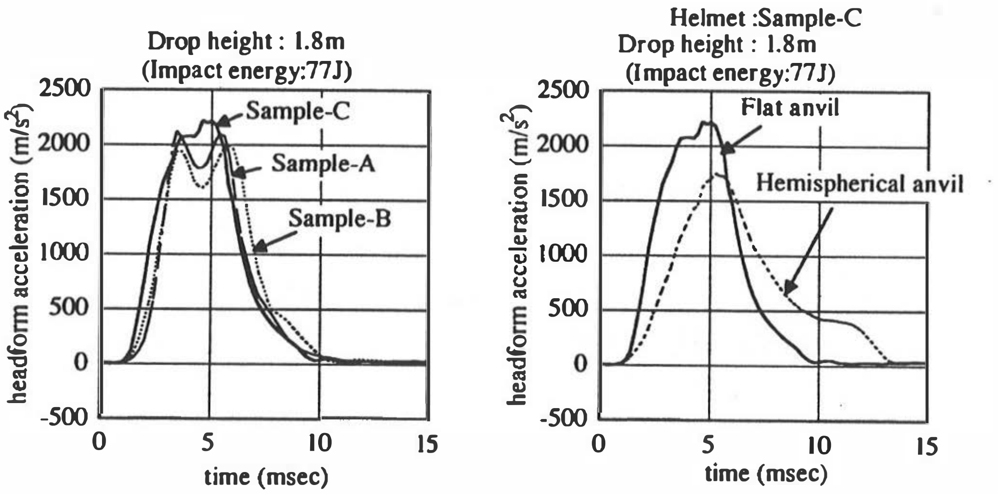
Figure 7a shows typical acceleration waveforms for the three helmets (covering a headform), dropped from a 1.8m height on two types of anvils. The helmets indicated similar acceleration waveforms when dropped on an identical anvil, but their maximum acceleration values differed in response to the subtle differences in the deformation of their shells and others (Figure 7a). A comparison of the same model of helmet dropped on the flat anvil and the hemispherical anvil showed a lower maximum acceleration value and an increased duration time with hemispherical anvil, indicating greater shell deformation (Figure 7b).

Figure 8 shows the relation between impact energy (i.e., drop height) and maximum head acceleration. Maximum head acceleration was practically equal between the three types of helmets when dropped on the same anvil, but was higher when dropped on the flat anvil than on the hemispherical anvil. This was because the shell deformation was less against the flat anvil, which was equivalent to greater shell stiffness.

Figure 9 shows the relation between a 3ms acceleration and impact energy. The 3ms acceleration became saturated by approximately 100J in the Sample-A helmet; in other words, a short spike-shaped acceleration was generated by around 100J in the Sample-A helmet. This is possibly attributable to the "bottoming" phenomenon of the shell and liner.

Figure 10 shows relations between impact energy and the energy absorbed by the helmet. There was virtually no difference in the amount of absorbed energy with regard to Samples except Sample-A. Absorbed energy for Sample-A became saturated above 100J impact energy, showing greater absorbed energy than Sample-B and C for all tested impact energy levels. With the moderate exception of the Sample-A helmet dropped onto a flat anvil, there was virtually no difference in the amounts of absorbed energy with regard to anvil type.

Figure 11 shows the relation between impact energy and HIC. The HIC for the flat anvil showed about two times higher than the HIC for the hemispherical anvil.



a : Flat anvil

b : Flat and hemispherical anvils

Fig. 7 Acceleration - time profiles.

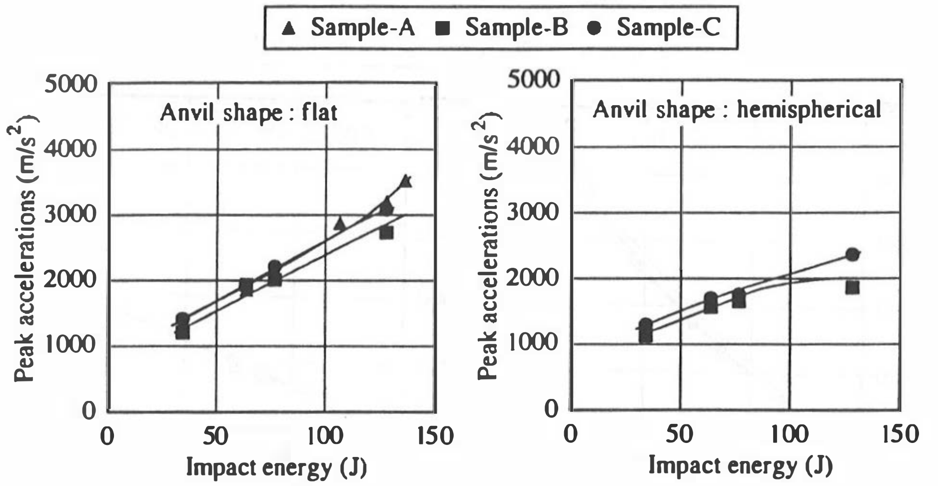


Fig. 8 Relationship between peak acceleration and impact energy on helmet drop tests.

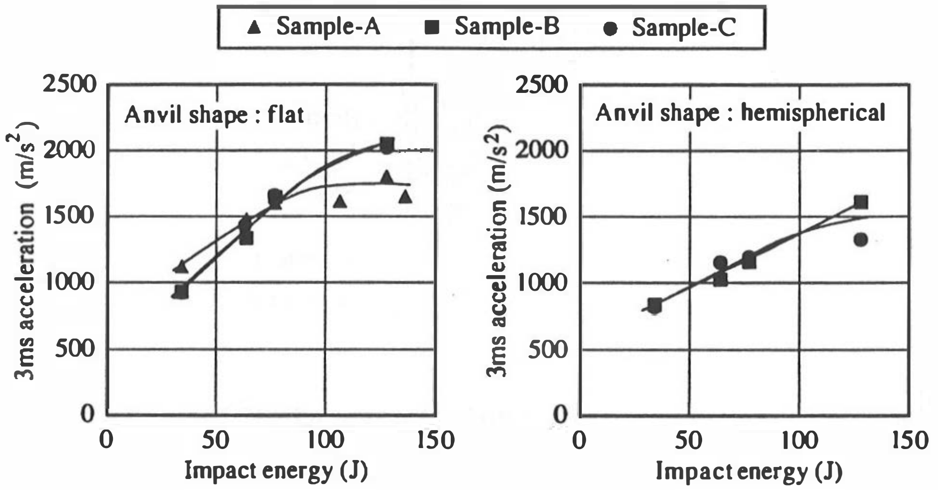


Fig. 9 Relationship between 3ms acceleration and impact energy.

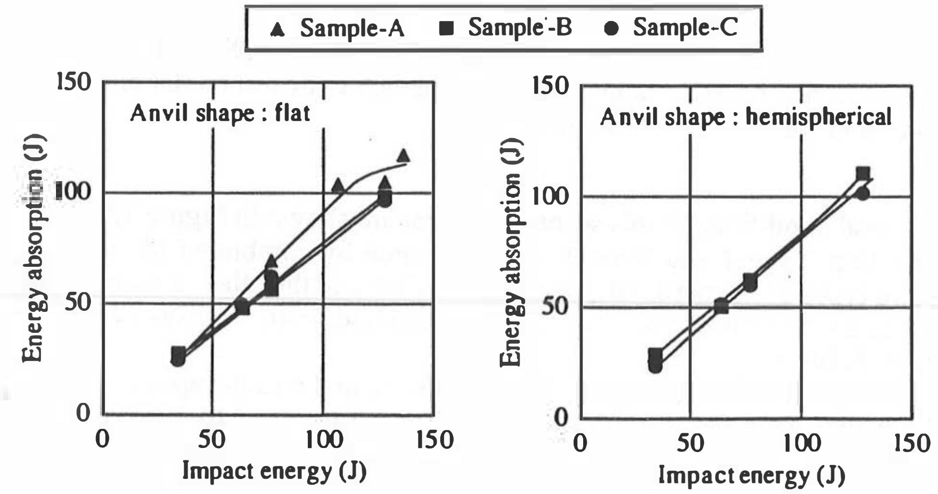


Fig. 10 Relationship between impact energy and energy absorption.

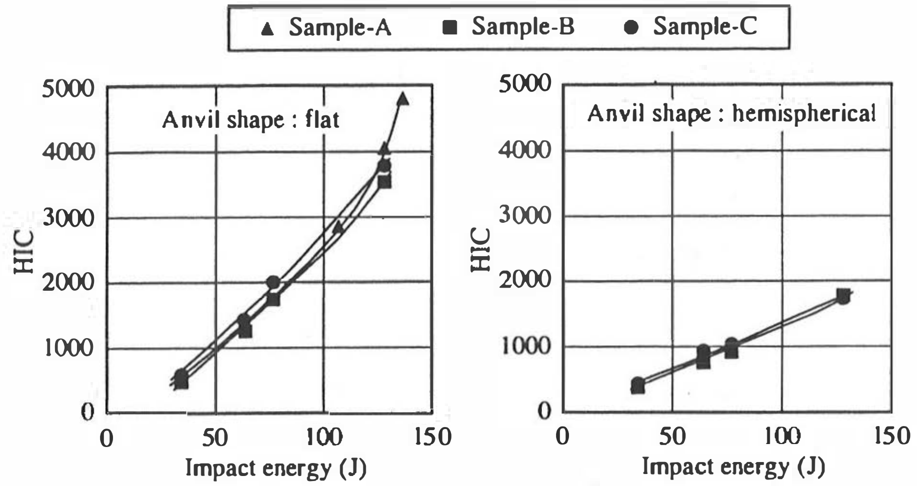


Fig. 11 Relationship between impact energy and HIC.

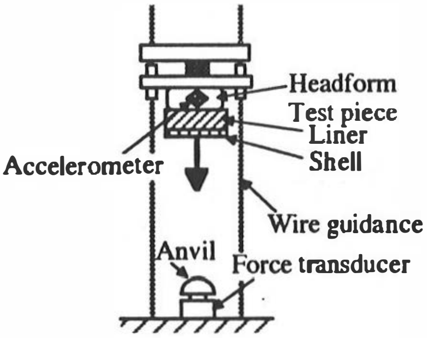


Fig. 12 Test set up for Basic Characteristic Test on shell and liner elements.

BASIC CHARACTERISTIC TEST ON FLAT PLATES CONSISTING OF HELMET ELEMENTS

In the second step of this study aimed at examining the potential for improving impact absorption characteristic of current helmets, a basic characteristic test on flat plates consisting of helmet shell and liner materials was conducted.

Experiment

The experimental conditions of this second-step test are shown in Figure 12. Three types of flat plates (Base-line, Type-1 and Type-2) were prepared by combining the following helmet materials: (1) two types of helmet shells, one made of FRP and the other of aluminum, each with a thickness of 1.2, 2.0 or 3.0mm; and (2) a styrene-foam liner with a density of 25g/liter or 34g/liter, as shown in Table 2.

Each flat plate was attached to a cylindrical headform, and was dropped on a hemispherical anvil from four different heights (0.8, 1.5, 1.8 and 3.0m). Although existing helmet performance tests require two-time-impact testing, a single impact was applied in this study. The measurement parameters included the tri-axial acceleration of the headform (4.12kg), load on the struck object, impact velocity, and behavior/displacement as recorded by cine and video cameras.

Table 2 Combinations of shell and liner materials

	Shell		Liner		
	Materials	Thickness(mm)	Material	Density (g/l)	Thickness(mm)
Base-line	FRP	3.0	EPS	34	30
Type 1	FRP	2.0	EPS	25	30
Type 2	Al	1.2	EPS	25	30

Note1: "Base-line" is equivalent to Sample-C helmet
Note2: FRP (Fiber reinforced plastic)
Al (Aluminum)
EPS (Expanded polystyrene)

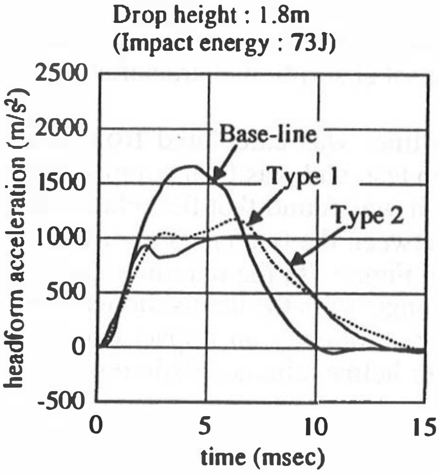


Fig. 13 Acceleration - time profiles.

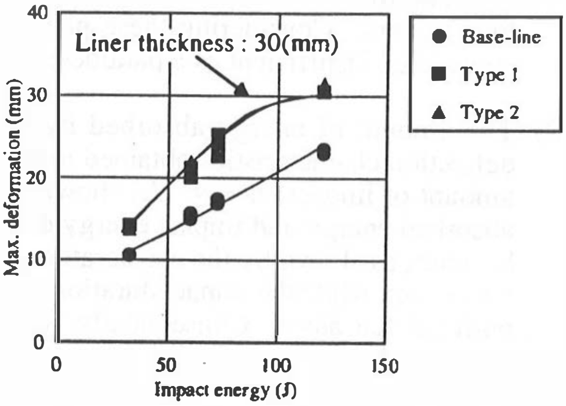


Fig. 14 Relationship between maximum deformation and Impact energy on basic characteristic test.

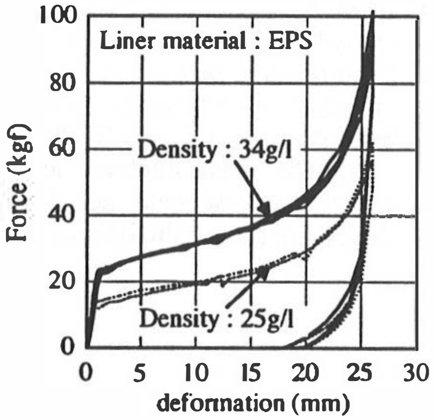


Fig. 15 Force-deformation characteristics of liner materials.

Results

Figure 13 shows typical acceleration waveforms for each of the test plates. The maximum acceleration values for the Type-1 and Type-2 plates were lower than that for the Base-line plate; correspondingly, the former's impact duration was longer than the latter's. This is attributable to differences in shell thickness, liner density, and the lower stiffness of aluminum compared to FRP shells.

Figure 14 shows the relation between impact energy and the maximum deformation. The maximum deformation values were calculated from acceleration waveforms. The Type-1 and Type-2 plates were roughly 1.5 times greater maximum deformation than that for the Base-line plate.

Figure 15 shows the results of a static compression test on liners. The liners of both 25g/liter and 34g/liter densities indicated a tendency to harden at a shell displacement of 20mm or more. All of the liners were approximately 30mm thick.

DISCUSSIONS

1. Helmet Drop Test

1.1. Evaluation Parameters

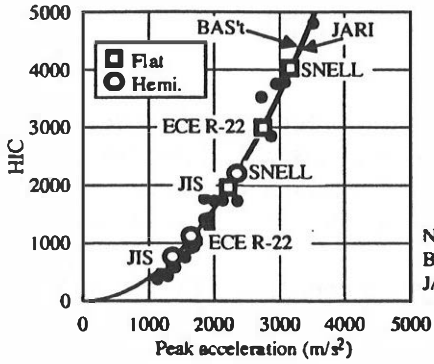
1) The maximum acceleration, which is employed as a parameter in existing helmet performance tests, was found to be more closely related to the degree of shell deformation (Figure 7a). While the maximum acceleration of the Sample-A headform rose in the impact energy range to about 100J (Figure 8) and more, its 3ms acceleration likewise began to saturate from approximately 100J (Figure 9). This suggests that a short spike-shaped acceleration is generated in the impact energy range where a "bottoming" of the shell and liner occurs. Considering these phenomena, the maximum acceleration by itself can be considered insufficient as a parameter on helmet impact absorption characteristics.

2) The amount of energy absorbed by the shell and liner was calculated from the force-deflection characteristics obtained in the helmet drop test, and was then compared with the amount of impact energy. As shown in Figure 10, it was found that the relation between absorbed energy and impact energy did not differ between the two types of anvils. This is because, as shown by the acceleration waveforms in Figure 7b, the maximum acceleration was lower, while the impact duration was 1.4 times longer with the hemispherical anvil than with the flat anvil. Consequently, a new parameter combining an impact energy and its duration should be studied as a one of view points for helmet characteristic research.

1.2. Impact Levels and Evaluation of Head Protection

HIC values were obtained for each drop height and each struck object in accordance with the respective existing helmet testing standards, and were compared with maximum acceleration (Figure 16). These HIC values were found to be 750-2,000 for the JIS, 1,100-3,000 for ECE R22, and 2,200- 4,000 for the SNELL standard.

On the other hand, it was found the helmets complying to different helmet standards showed similar characteristics when tested in same condition. Namely, the helmet made for higher impact energy test showed a similar characteristics to the helmet made for lower impact energy test when tested at lower impact energy. For further improvement of head protection of two-wheeler riders, it is important to set parameters and there levels based on head impact conditions and head injuries in actual two-wheeler accidents. It is, therefore, important to standardize indicator and it's level for the evaluation of head protection for different test standards.



Note:
BAS't (Federal Highway Research Institute, Germany)
JARI (Japan Automobile Research Institute, Inc.)

Fig. 16 Relationship between HIC and peak acceleration.

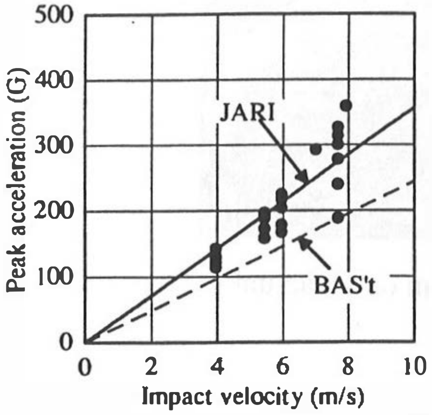


Fig. 17 Relationship between peak acceleration and impact velocity in comparison with JARI and BAS't data.

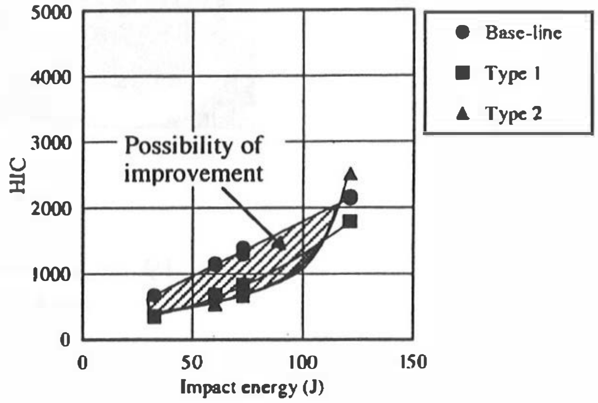


Fig. 18 Relationship between HIC and energy absorption.

1.3. Evaluation According to Shape of Struck Object

As shown in Figure 5, existing helmet performance tests set the heights from which to drop helmets on a hemispherical anvil either equal to or lower than those on a flat anvil. But the helmet drop test of this study indicated that, given an identical amount of impact energy, the maximum acceleration and HIC were lower in the case of a hemispherical anvil than a flat anvil. To consider the further improvement of the helmet impact absorption characteristics, it is necessary to take account the shape of the struck objects to which heads impact in actual accidents.

1.4. Differences in Impact Areas

A comparison of current helmet drop test results and BAS't data⁽⁹⁾ are summarized in Figure 16. It is evident that the relation between HIC and the maximum acceleration is highly comparable. In contrast, the relation between impact velocity and the maximum acceleration clearly differs from the present and past tests, as shown in Figure 17. The reason seems to be that, while the impact was applied to the parietal area of the head in the present test, it was applied to frontal and other areas in past tests. Therefore, it is advisable to examine the relation between impact areas and maximum acceleration/HIC in future studies.

2. Basic Characteristic Test on Flat Plates Consisting of Helmet Elements

2.1. Potential for Improving Impact Absorption

The relation between impact energy and HIC was examined for various test plates in order to examine the possibility of improving helmet characteristics (Figure 18). Given an identical amount of impact energy, HIC was lower for the Type-1 and Type-2 plates than for the Base-line plate. The shaded area in the figure was where HIC was actually lower in the Type-1 and 2 plates so that this area shows the possibility of improving. In the impact energy range below 100J, HIC for Type-1 and Type-2 plates was about one half of the HIC for the Base-line plate; thus, it was suggested that there is still a possibility for improving the helmet characteristics if more appropriate materials are selected for the shell and liner.

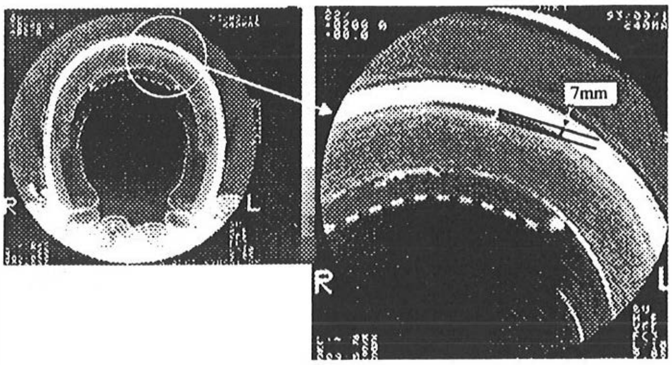


Fig. 19 A helmet CT diagram on an actual accident case.

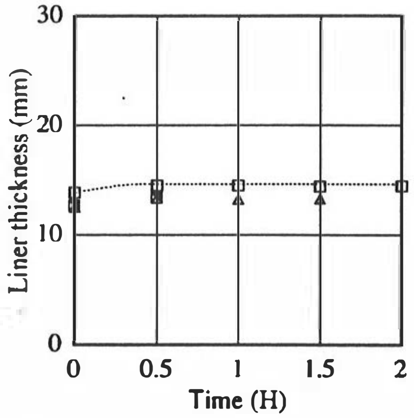


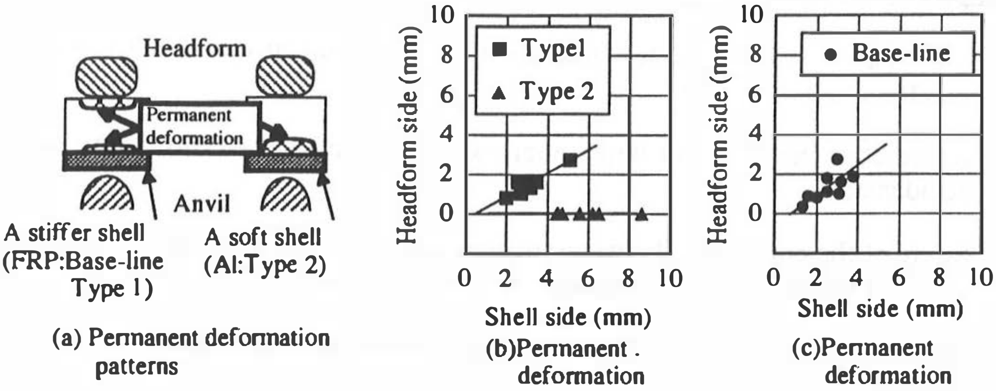
Fig. 20 Recovery of liner deformation.

2.2. Comparison with Accident Cases

The major reason why HIC for the Type-1 and Type-2 plates was lower than that for the Base-line plate (when an identical impact energy was given) seems to be the greater increase of the maximum deformation in the Type-1 and 2 plates, as shown in Figure 14. Consequently, a clue to improved helmet effectiveness lies in allowing the helmet a maximum amount of deformation. In the case of the liner, however, it tends to harden if the deformation exceeds 20mm (Figure 15).

A CT scan image of the helmet of a motorcyclist who collided with a four-wheel vehicle is shown in Figure 19. The motorcycle, running at a speed of about 60km/h, ran into the front of the four-wheel vehicle which was making a right turn at a speed of approximately 20km/h. The motorcyclist, currently alive, sustained an AIS 3 injury to his head when he was thrown down on a sidewalk curb. The permanent deformation of the liner in the Figure 19 measures 7mm.

Figure 20 shows the recovery in time of the liner shown in Figure 15 after compression of its original thickness of 30mm to a 5mm thickness and the subsequent release of the compressive load. The liner thickness instantaneously recovered to 13mm, and by another 2mm during the first 30 minutes, after which recovery was nil. From this, it can be assumed that the liner in Figure 19 had a permanent deformation of 9mm immediately after the accident. Its maximum deformation can be estimated between 18 and 23mm from the above permanent deformation value and from the results of current helmet drop test. Similarly, its HIC is estimated at 2,000. Thus, the deformation approached the maximum beyond which the liner would have hardened, and it is reasonable to believe that the helmet had high head-protection effectiveness.



(a) Permanent deformation patterns
(b)Permanent . deformation
(c)Permanent deformation

Fig. 21 Permanent deformation of liners in relation to the shell stiffness.

To improve head protection by helmets, a large number of these accident cases should be analyzed and characteristics of the shells and liners that allow maximum deformation within the limited usable space should be studied.

2.3. Differences in Dispersion of Impact

Permanent deformation patterns of liners in relation to the shell stiffness of the Type-1 and Type-2 helmets are shown in Figure 21(a). The liner of the Type-1 helmet, with a stiffer FRP shell, indicated a deformation on both its shell and headform side. But the liner of the Type-2 helmet, with a less stiffer aluminum shell, showed a deformation only on the shell side. The amount of permanent deformations for Type-1 and Type-2 helmets are shown in Figure 21(b), and the amount for the Base-line helmet is shown in Figure 21(c), in terms of the headform and shell side. Deformations on the liner vary according to the types of shells and liners combined. Deformations give a clue on how impact to the head was dispersed; therefore, it is necessary to analyze in detail the deformation of the shell and liner resulting from an impact.

CONCLUSION

1) Maximum acceleration was found to vary widely in relation to shell deformation. Consequently, it is not sufficient to use maximum acceleration by itself as a parameter for evaluating helmet characteristics.

2) When a flat anvil and a hemispherical anvil were reviewed by HIC, it was found that, given the same amount of impact energy, the HIC with the flat anvil was greater than that with the hemispherical anvil.

3) When HIC was examined in the context of various helmet performance standards, it became apparent that these standards deal with different levels of HIC. On the other hand, helmets designed for each standards used in this study showed similar impact energy absorption characteristics.

4) The HIC for the shells and liners of the Type-1 and Type- 2 helmets was lower than that for the Base-line helmet in the impact energy range by no more than 100J. This indicates a good potential for improvement of the impact absorbing characteristic of helmets by selecting materials specification for the shell and liner.

5) The deformation of liners differed according to the combination of different shells and liners. Thus, the shell and liner composition seems to affect the manner through which impact to the head is dispersed.

It is advisable that future research for the improvement of helmet characteristics must addresses the following tasks:

- Review of the flat and hemispherical anvils and penetration tests based on actual accidents;
- Study of the correlation between magnesium headforms and Hybrid III Dummy heads in terms of which can better simulate the human head;
- Clarification of the relation between impact velocity, impact area, maximum acceleration, and HIC;
- Examination of two-time-impact situations in actual accidents;
- Clarification of head injury types (especially brain damage) and the influence of head rotational acceleration impact, on the basis of actual accidents.

This study was begun with focusing on the impact energy absorption characteristics. To further improve helmets, it is necessary to proceed the research considering all related factors on the head protection such as helmet penetration characteristics, protectable areas, and medical aspects on details of head injuries in actual accidents. In addition, in-depth case studies on actual accidents must be done for analyzing the head impact conditions, as well as considerations on merchantability such as comfortableness, easiness of putting on and off, etc..

REFERENCES

1. WG4 Report of Traffic Accident Research Committee :The Statistical Analysis of Vehicle and Two-Wheeler Accidents, Japan Automobile Research Institute Inc., 1993 (In Japanese).
2. N. Nakamura, Medical Study in Motorcycle Helmets, The Jikei University School of Medicine, 1991 (In Japanese).
3. P. D. Hope, B. P. Chinn, Helmets: A New Look Design and Possible Protection, IRCOBI Conference, pp. 39-54; September 1989.
4. Proposal for Draft Amendments to Reguration No. 22, TRANS/SC.1/WP.29/GRSP/R.78/ Amend.2, September 1993.
5. J. Lane, Crash Helmet Effectiveness Over 50 Years, Crash Injury Biomechanics, July 1992.
6. M. C. Beusenberg, R. Happee, An Experimental of Crash Helmet Design and Effectiveness in Standard Impact Tests, IRCOBI Conference, pp. 308-323; September 1993.
7. D. Otte, P. Jessl, E. G. Suren, Impact Points and Resultant Injuries to the Head of Motorcyclists Involved in Accidents, With and Without Crash Helmets, IRCOBI Conference, pp.47-64; September 1984.
8. Protective Helmets for Vehicular Users, JIS T 8133, 1982.
9. H. Zellmer, Investigation of the Performance of Motorcycle Helmets Under Impact Conditions, 37th Stapp Car Crash Conference, pp. 59-68; November 1993.