INJURY BIOMECHANICS RESEARCH
Proceedings of the Thirty-Fifth International Workshop

Predicting Motorcycle Helmet Impact Severity from Residual Crush Damage

A. L. DeMarco[1], J. C. Gardiner[1], C. C. Wilkinson[1], E. A Hassan[1], and G. P. Siegmund[1,2]

[1]*MEA Forensic Engineers & Scientists, Richmond, BC, Canada;*
[2]*School of Human Kinetics, University of British Columbia, Vancouver, BC, Canada*

ABSTRACT

Motorcycle helmets reduce the frequency and severity of head and brain injuries by attenuating head acceleration and distributing the impact force. This is achieved primarily through permanent crushing of the interior energy absorbing liner. Our goal is to characterize the relationship between residual helmet damage and impact energy. Working toward this goal, the current study measures the changes in energy absorbing liner residual thicknesses for helmets subjected to drop tests of various severities. We conducted 32 single drop tests of five different helmets on a flat anvil at impact energies of 30 to 259 J (impact speeds = 3.4 to 10 m/s). Percent maximum crush, percent crush volume and stiffness were determined for each helmet impact. For the full-face style helmets tested, linear correlations ($r^2 > 0.9$) were found showing an increase in the change in thickness measures with increasing impact severities. The shorty helmet showed this trend as well, but also showed a steep increase in percent maximum crush above about 180 J. Of the helmets tested over the range of severities, the stiffness values were found highest at the lowest severity impacts (30 J).

INTRODUCTION

Helmets reduce the frequency and severity of head and brain injuries resulting from motorcycle crashes (Hurt et al., 1981; Shankar et al., 1992; Rowland et al., 1996). They achieve this reduction by attenuating head acceleration and distributing the impact force over a larger area of the head. For helmets that comply with the standards set out by the Department of Transportation (DOT, 2001), Snell Memorial Foundation (Snell, 2005), the Economic Commission for Europe (ECE, 2002) or other comparable agencies, this impact attenuation is achieved through deformation and cracking of both the helmet's hard outer shell and interior energy absorbing liner.

The shell and liner damage sustained by motorcycle helmets following an impact potentially provide information about the impact sustained by the helmet. For example, often the location and pattern of markings to the exterior of the helmet can provide information about the location of the impact and type of object struck. Likewise, permanent crushing of the interior energy absorbing liner is the predominant method of energy absorption in motorcycle helmets (Thom, 2006), and we hypothesize that the damage sustained by the interior energy absorbing liner of the helmet can provide information about the severity of the impact to which the helmet was exposed.

Previous studies investigating energy absorbing liners of motorcycle helmets have been limited to damage replication tests (Hope and Chinn, 1990; Schuller et al., 1993; Wobrock et al., 2003), tests on ECE approved helmets (Beusenberg and Happee, 1993) and tests where the liner deflection was calculated by double integration of the acceleration result (Zellmer, 1993; Mitsuishi et al., 1994; Mellor and StClair, 2005). Currently, data quantifying the residual energy absorbing liner damage for many common helmets used in North America and tested over a wide range of impact severities do not exist.

Our goal was to characterize the relationship between motorcycle helmet damage and impact energy. This relationship could then be used to determine the impact energy for a DOT and/or Snell approved helmet following real-world impacts.

METHODS

Five helmet models were impact tested on their right side (Figure 1, Table 1). All helmets had soft foam comfort liners, expanded polystyrene (EPS) energy-absorbing foam liners and hard shells made of either fiberglass or polycarbonate. A nominally 2 × 2 cm grid was drawn over the right side of all helmets, except for one helmet, which had a nominally 1.5 × 1.5 cm grid over the entire helmet. The 2 cm grids were similar but not identical across helmets. Pilot testing of the helmet with the 1.5 cm grid showed negligible thickness changes to the left side of the helmet following the right-sided impact used in this study.

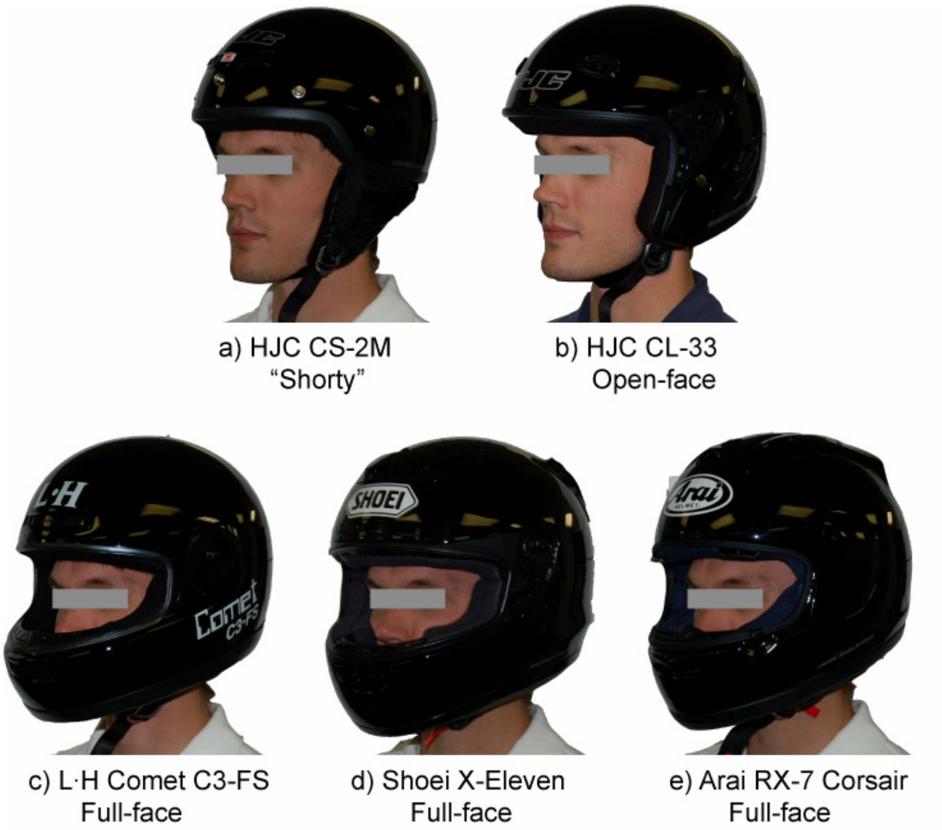
At each point on the grid, the helmet thickness (distance between the shell exterior and the energy absorbing liner interior) was measured before the test and at least 24 hours after the test using a digital height gage (Series 192, 600 mm, 6 digit, Mitutoyo, Japan). All thickness measurements were taken by one individual (CCW). Repeatability testing indicated an RMS error in thickness measurements of ± 0.15 mm.

All helmets were medium size and fit the magnesium alloy headform (ISO J, Half Magnesium K1A, Cadex Inc., Quebec, Canada). The shorty helmets were tested without their snap-on visors, and the visors for the open- and full-face helmets were cut to accommodate the ball arm (Figure 2a). The removable ear flaps of the shorty helmets remained installed for the tests (Figure 1b).

A 6 m tall monorail and trolley assembly guided the helmets during the drop tests (Figure 2a). The headform was fastened to the trolley via a ball arm angled downwards at 25º. The helmet's chin strap was clamped to a surrogate chin. A uni-axial ± 2000g accelerometer (7264B-2000T, Endevco, San Juan Capistrano, CA) was fixed into the ball arm where it fastened to the headform. The total mass of this moving assembly was 5.09 kg.

Impact speed was measured with a speed trap located within 40 mm of impact and impact speed accuracy was better than ± 0.5 percent at 10 m/s. Speed trap signals were acquired at 100 kHz. Impact energy was calculated using the moving assembly mass and impact speed. Helmet mass was not included in the energy calculation.

The test setup and equipment used for these tests were based on but did not strictly comply with the requirements stipulated by the Snell standard. Each helmet was dropped once onto a flat steel anvil. The flat anvil was perpendicular to the headform trajectory and measured 30 cm x 30 cm. To ensure consistent helmet positioning, the helmet positioning index was measured before each impact (Snell, 2005).


a) HJC CS-2M
"Shorty"

b) HJC CL-33
Open-face

c) L·H Comet C3-FS
Full-face

d) Shoei X-Eleven
Full-face

e) Arai RX-7 Corsair
Full-face

Figure 1: The helmets used in this study and the standards they meet.

Table 1. Description of helmets tested. All helmets acquired in 2006, except the L·H Comets, which were acquired in 1995.

Make and Model	Type	Mass (g)	Shell Material	Approved by
HJC CS-2M	Shorty	980	polycarbonate	DOT
HJC CL-33	Open-face	1074	polycarbonate	DOT
L·H Comet C3-FS	Full-face	1613	fiberglass	DOT, Snell
Shoei X-Eleven	Full-face	1424	fiberglass	DOT, Snell
Arai RX-7 Corsair	Full-face	1423	fiberglass	DOT, Snell

Table 2. Test matrix showing thirty right sided impacts (●), one vertex impact (○), and one right sided pilot impact (Δ).

Helmet	Impact Energy (J)									
	30	90	120	140	150	180	210	225	240	256
HJC Shorty	●	●	●		●	●	●●●	●	●	
HJC Open-face								●		●
L·H	●	●	●	Δ	●	●	●		●	●
Shoei	●	●	●		● ○	●	●		●	●
Arai					●					●

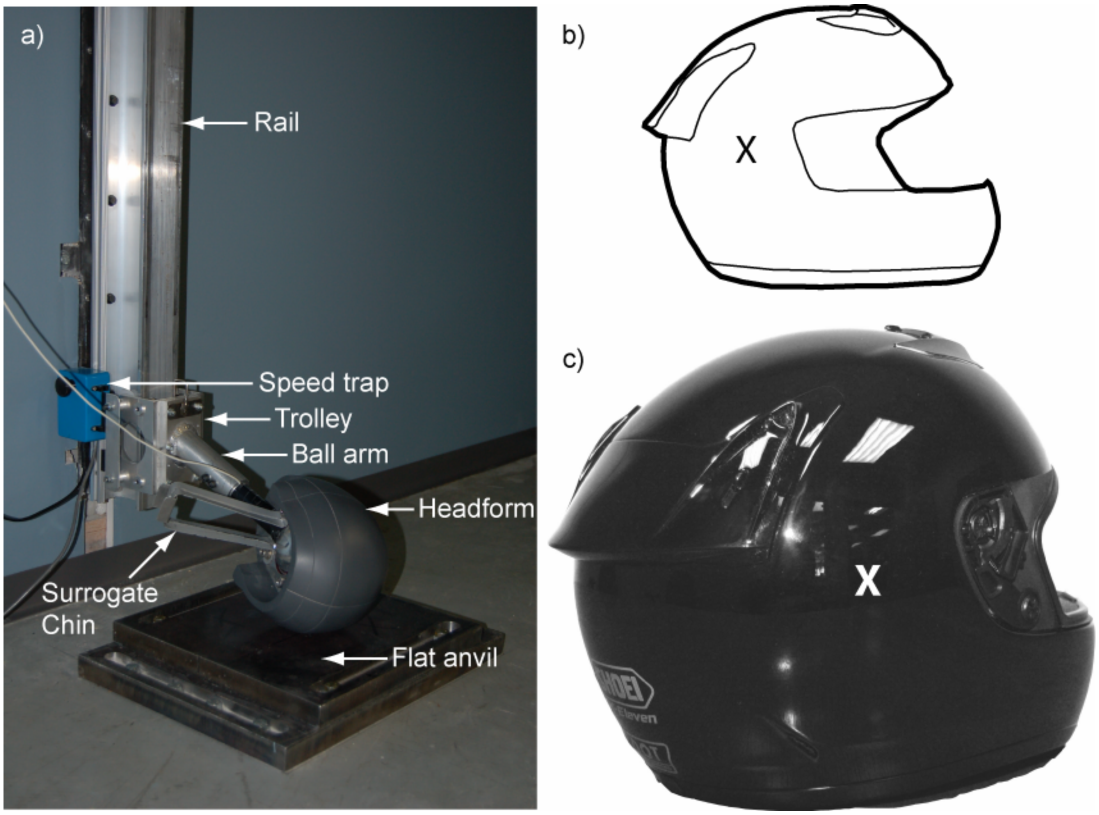


Figure 2: a) Test setup, b) lateral schematic of the Shoei helmet and c) ¾ view of the Shoei helmet. The **X**'s depict the right side impact location used for tests marked with a ● in Table 2.

Thirty-two drop tests were conducted (Table 2). Thirty-one sustained impacts to the right side of the helmet (**X** in Figures 2b,c) at impact energies between 30 and 259 J. In one right-sided impact test (L·H helmet; 140 J, 1.5 cm grid), the impact location was generally similar, but not exactly the same as the others. In another test (Shoei; 150 J) the impact was to the vertex. Three shorty helmets were tested at the same impact energy (210 J).

Residual helmet deformation was quantified using three dependent variables: maximum crush, crushed volume and implied stiffness. Maximum crush was the maximum difference between the pre- and post-impact thickness measurements measured at a single point on the grid and then expressed as a percentage of that point's pre-impact thickness. Crushed volume was the difference between the pre- and post-impact liner volumes, again expressed as a percentage of pre-impact volume. Volumes were computed assuming planar deformation between groups of three nodes on the grid. A single stiffness value (k) was calculated for each test assuming a relationship between impact energy (E) and residual crush (x) of the form $E = \frac{1}{2}kx^2$. The implied stiffness was computed by summing of the energy absorbed by each three-node element (weighted by the area of each element) and equating this sum to the impact energy.

Linear regressions were used to evaluate correlations between the three measures of residual helmet deformation and impact energy separately for the shorty, L·H and Shoei helmets. Coefficients of determination were calculated for each regression and statistical significance was set at the $p<0.05$ level.

RESULTS

The pre-impact measurements showed the Arai and L·H helmets are the thickest and the shorty helmets are the thinnest of the helmets evaluated here (Table 3). The three shorty helmets tested at one impact energy had similar liner deformation results (Table 4) and indicated good repeatability.

All of the helmets exhibited residual deformation after every impact. In addition, all of the helmet models except the HJC open-face helmet exhibited increasing deformation with increasing impact energy (Figure 3a,b). For the three helmets with more than two impact tests, the correlations between the crush variables (maximum crush and crushed volume) and impact energy were strong ($r^2 > 0.90$, $p < 0.0002$; Table 3). The HJC open-face helmet was only tested at 225 and 256 J, and had a slightly smaller maximum crush and crushed volume at the higher impact energy. Additional tests of this helmet are needed to determine whether this simply represents scatter within this helmet's performance or some other phenomenon.

The HJC Shorty helmets sustained the largest percent maximum crush—consistent with having the lowest pre-impact thickness. The Shorty helmet also appeared to exhibit a steeper increase in maximum crush than the other helmets at impact energies above 180 J (Figure 3a). The L·H helmets consistently had a larger crushed volume and a lower stiffness than the other helmets (Figure 3b,c).

The vertex impact to the Shoei helmet (at 149 J in Figure 3) fits well with the right-sided impact data and was therefore pooled with the right-sided Shoei data.

Of the three helmets tested below 100 J (HJC Shorty, L·H and Shoei), the Shorty and Shoei exhibited increasingly higher stiffness values at decreasing impact energy levels (Figure 3c). For the Shorty helmet in particular, the stiffness at 30 J was more than triple the stiffness at impact energies of about 100 J (Figure 3c). The L·H helmet, on the other hand, maintained a relatively uniform stiffness over the entire range of impact energies.

Table 3. Pre-impact thickness measurements and coefficients of determination of maximum crush and crushed volume versus impact energy.

		Coefficients of Determination (r^2)	
Helmet	Thickness[1] (mm)	Maximum crush	Crushed volume
HJC Shorty	29.70 ± 1.09	0.939	0.957
HJC Open	36.58 ± 0.43	-	-
L·H[2]	43.13 ± 0.58	0.909	0.955
Shoei	40.74 ± 1.82	0.962	0.961
Arai	46.36 ± 0.45	-	-

1. Pre-test thickness at the point of maximum crush during the impact tests.
2. The pilot test of the L·H helmet is excluded from these data.

Table 4. Results from the three HJC Shorty helmets tested at 210 J.

Test #	Maximum crush (mm)	Maximum crush (%)	Crushed volume (%)	k (N/mm)
H04	6.38	21.89	4.58	93.39
H06	6.78	22.82	4.49	86.16
H08	6.69	21.74	4.28	81.88

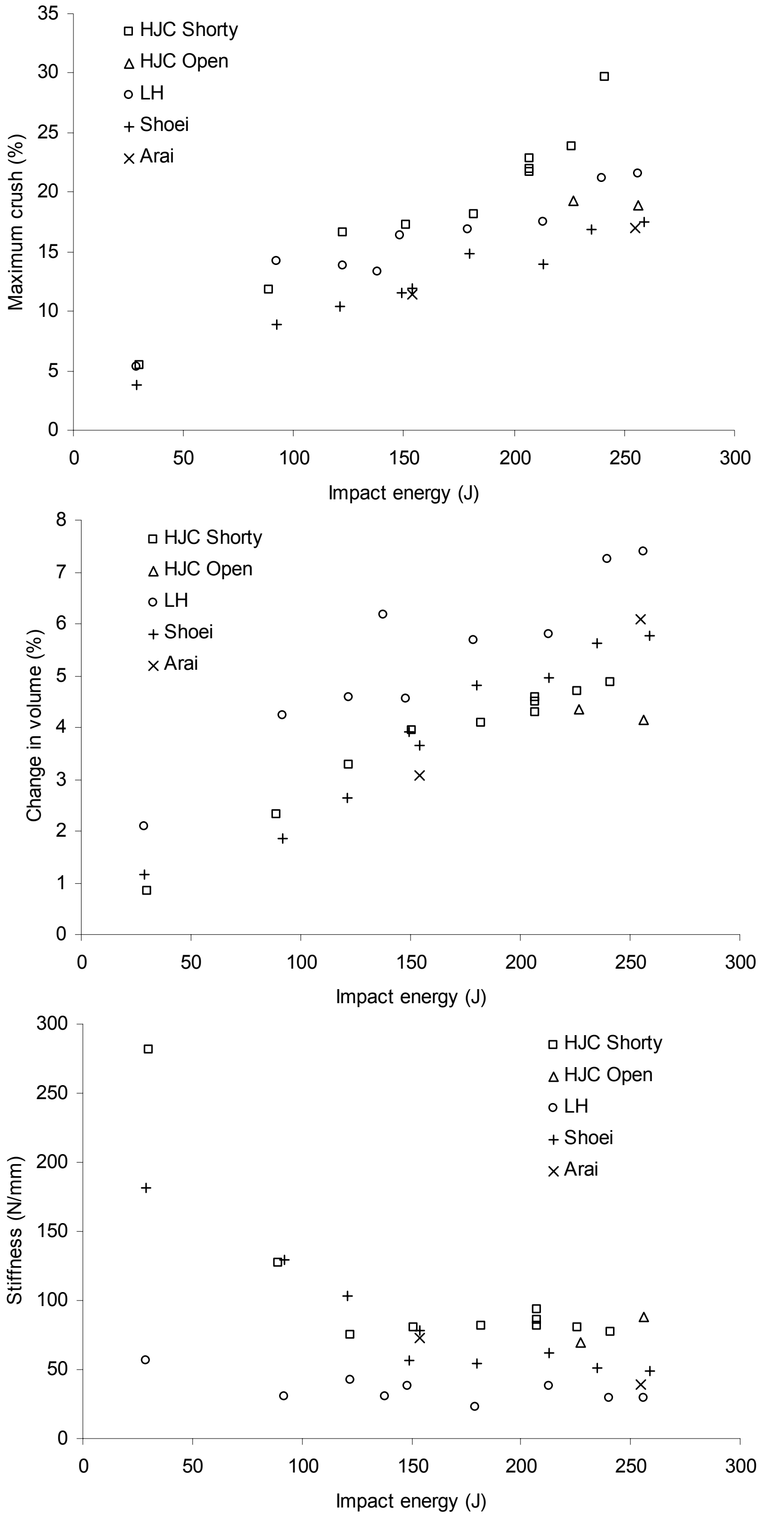


Figure 3: Graphs of the three measures of residual helmet deformation as a function of impact energy: a) maximum crush (%), b) crushed volume (%), and c) implied stiffness (N/mm).

DISCUSSION

The goal of the current study was to characterize the relationship between residual motorcycle helmet damage and impact energy. Based on the limited number of helmets tested, our results indicate that residual helmet damage—quantified here as either maximum crush or crushed volume—increases relatively linearly with increasing impact energy between 30 and 259 J. Although more tests are needed on a wider range of commonly worn helmets, the results of this study suggest that the severity of a helmet impact can be estimated from the residual crush present following an impact.

Our study was not designed to investigate differences between helmets approved by different agencies or provide data to design better helmets. Our pre-impact helmet thickness measurements, however, were thinnest (29 and 36 mm) for the DOT-only approved helmets and thickest (40 to 46 mm) for the DOT- and Snell-approved helmets. Other data from full-face style helmets have shown DOT-approved helmets to be thicker than DOT+Snell-approved helmets (Thom, 2006). Based on these combined data, helmet thickness does not appear to be consistently related to the impact standards a helmet meets.

All of our helmet impacts produced measurable residual deformation—even at impact energy levels of 30 J (impact speed = 3.4 m/s). Other previously published data from tests on BSI approved helmets show that for impacts of 5 m/s (~64 J) or less, there was no measurable residual deformation (Hope and Chinn, 1990). It is not known if this difference in the onset of residual deformation is related to the different helmets (British v. North American helmets), different standards (BSI v. DOT and Snell), or different test methods used (e.g., wood v. magnesium head form). Our results, however, suggest that even minor helmet impacts may compress the energy absorbing liner.

The HJC Shorty helmets, while showing increasing deformation with increasing impact energy like the full-face helmets, also appeared to perform somewhat differently than the full-face helmets. At impact energies above 180 J, a steep increase in maximum crush was observed. We previously reported a similarly steep increase in head form acceleration above 180 J (DeMarco et al., 2007) and postulated that the foam absorber was bottoming out at these higher energy levels. The simultaneous increase in residual crush and peak acceleration suggests that the dynamic bottoming-out of the foam is causing increased damage to the foam and altering its ability to rebound (hence the increase in residual crush). A similar phenomenon has been previously observed in the response of ECE full-face helmets (Schuller et al., 1993).

The three full-face helmets tested in this study perform similarly. Although only two Arai helmets were tested, they appeared to perform much like the Shoei helmet. Previous data for eight types of ECE full-face helmets tested at a single impact energy (174 J) showed a wider range of residual crush values than we observed (Beusenberg and Happee, 1993; see Figure 4). The wide inter-helmet variation suggested by these earlier data suggest that helmet specific data may be necessary to accurately estimate impact energy from residual crush measurements.

There is some debate in the popular and scientific literature regarding helmet stiffness (Ford, 2005; Thom, 2006). For this study we determined the effective stiffness for each helmet at several impact severities based on residual crush. Because dynamic crush exceeds residual crush, the stiffness values we calculated overestimate the actual stiffness of the helmet. Since all of the helmets we tested had similar peak head form accelerations at each of the impact energies we tested, the stiffness difference we observed between helmets may be related as much to the rebound characteristics of the energy absorbing liner as its compressive characteristics during the impact. Additional work is needed to characterize the material properties of the energy absorbing liners used in our helmets and to then relate these material properties to the observed dynamic responses.

We defined helmet thickness as the distance between the exterior surface of the shell and the interior surface of the energy absorbing liner. We chose this definition because it can be readily measured on helmets following real collisions without destroying or altering the helmet. This definition, however, does not account for any air gaps present between the liner and the shell before or after the impact. CT scans of the helmets can be used to refine the current analysis (Cooter, 1990; Mitsuishi et al., 1994; see Figure 5), and in particular limit the deformation to the interior liner as well as improve the resolution of the crushed volume calculation.

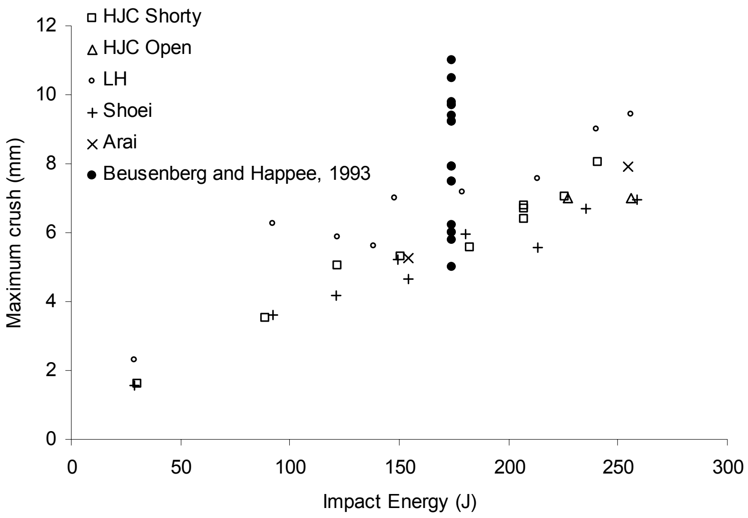


Figure 4: Maximum crush v. impact energy for our helmets compared to ECE full-face helmet data (Beusenberg and Happee, 1993).

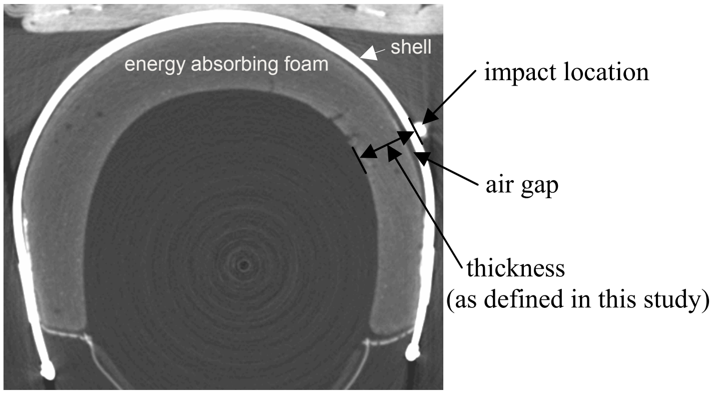


Figure 5: CT scan image of an L·H helmet following a drop test. A plastic bead placed on the helmet shell exterior identifies the impact location.

CONCLUSIONS

The residual deformation of some motorcycle helmets is linearly related to the impact energy. In particular, the maximum residual crush and the residual crushed volume correlate strongly with impact energy and may be useful measures from which to estimate the impact energy in real motorcycle crashes.

ACKNOWLEDGEMENTS

The authors thank Mr. Dennis D. Chimich, Mr. Mircea Oala-Florescu and Mr. Jeff Nickel for their help conducting the tests.

REFERENCES

BEUSENBERG, M.C. and HAPPEE, R. (1993). An experimental evaluation of crash helmet design and effectiveness in standard impact tests. International IRCOBI Conference on the Biomechanics of Impact. IRCOBI Secretariat Bron, France. 307-23.

COOTER, R.D. (1990). Computed tomography in the assessment of protective helmet deformation. J Trauma 30(1):55-68.

DEMARCO, A.L., CHIMICH, D.D., GARDINER, J.C., NIGHTENGALE, R.W., and SIEGMUND, G.P. (2007). Motorcycle helmet impact response: Comparison of helmet type and impact severity. 34th International Workshop on Human Subjects for Biomechanical Research.

DEPARTMENT OF TRANSPORTATION (2001). Laboratory Test Procedure for FMVSS No. 218 Motorcycle Helmets. TP-218-05. U.S. Department of Transportation, National Highway Traffic Safety Administration Washington, DC.

HOPE, P.D. and CHINN, B.P. (1990). The correlation of damage to crash helmets with injury and the implications for injury tolerance criteria. International IRCOBI Conference on the Biomechanics of Impact. IRCOBI Secretariat Bron, France. 319-31.

HURT, H.H., JR., OUELLET, J.V., and THOM, D.R (1981). Motorcycle accident cause factors and identification of countermeasures final report. U.S. Department of Transportation, National Highway Traffic Safety Administration Washington, DC.

ECONOMIC COMMISSION FOR EUROPE (2002). Uniform provisions concerning the approval of protective helmets and of their visors for drivers and passengers of motor cycles and mopeds. Regulation No. 22, Revision 4. September 24, 2002.

FORD, D. (2005). Motorcycle helmet performance: blowing the lid off. Motorcyclist, June 2005 issue.

MELLOR, A. and StCLAIR, V. (2005). Advanced motorcycle helmets. 19th International Technical Conference of the Enhanced Safety of Vehicles Proceedings. Washington, D.C. 1-13.

MITSUISHI, H., ONO, K., NISHIMOTO, T., NAKAMURA, N. (1994). Present and future performance levels of head injury absorption property of helmets. International IRCOBI Conference on the Biomechanics of Impact. IRCOBI Secretariat Bron, France. 259-70.

ROWLAND, J., RIVARA, F., SALZBERG, P., SODERBERG, R., MAIER, R., and KOEPSELL, T. (1996). Motorcycle helmet use and injury outcome and hospitalization costs from crashes in Washington State. Am J Public Health 86(1):41-5.

SCHULLER, E., KÖNIG, W., and BEIER, G. (1993). Criteria for head impact protection by motorcycle helmets. International IRCOBI Conference on the Biomechanics of Impact. IRCOBI Secretariat Bron, France. 283-94.

SHANKAR, B.S., RAMZY, A.I., SODERSTROM, C.A., DISCHINGER, P.C., and CLARK, C.C. (1992). Helmet use, patterns of injury, medical outcome, and costs among motorcycle drivers in Maryland. Accid Anal Prev 24(4):385-96.

SNELL MEMORIAL FOUNDATION (2005). Standard for protective head gear for use with motorcycles and other motorized vehicles. North Highlands, CA.

THOM, D.R. (2006). Comparison testing of motorcycle helmets qualified to international standards. Proc. of 2006 International Motorcycle Safety Conference, The Human Element. Long Beach, CA, March 28-30. Irvine CA: Motorcycle Safety Foundation.

WOBROCK, J., SMITH, T., KASANTIKUL, V., and WHITING, W. (2003). Effectiveness of collision-involved motorcycle helmets in Thailand. 47th Annual Proceedings of the Association for the Advancement of Automotive Medicine, pp. 443-461.

ZELLMER, H. (1993). Investigation of the performance of motorcycle helmets under impact conditions. Society of Automotive Engineers Paper No. 933113. Warrendale, PA. 59-68.

DISCUSSION

PAPER: **Predicting Motorcycle Helmet Impact Severity from Residual Crush Damage**

PRESENTER: ***Alisa DeMarco, MEA Forensic Engineers & Scientists***

QUESTION: *Erik Takhounts, NHTSA*
I have, actually, a couple of questions. Why did you decide to use ISO head form versus DOT head form?

ANSWER: We looked at both standards: the DOT and the Snell, and we based most of our setup on the Snell and that's the one that they use in the Snell standard.

Q: For now, I'm just trying to understand what you are getting at because I still don't see the relationship between the crush and some sort of injury criteria.

A: We're not there yet. So far, we can look at the crush and the head form acceleration, but there certainly are many steps to get to a head injury risk criterion. We have to test cadaver heads, for one, in order to understand the difference between having an actual human head in the helmet and a head form. And then, we also have to look into possibly doing some brain modeling and things like that in order to get there, but we are quite a ways from that.

Q: *Stephen Duma, Virginia Tech*
Kind of following up on what Erik's saying and kind of projecting into the future: As I understand it, you're going to have a technique where you can look at a helmet and correlate that impact to what kind of injury a person has, ideally.

A: Ideally, yes.

Q: I was wondering if you had kind of done an internal kind of a blind study where you do some of these tests and you don't tell the person, and they take these measurements and see how close you could actually get from your control tests.

A: No, we haven't done that yet.

Q: It might be an easy way just to run some tests.

A: Yeah. Thank you.

Q: *Voyko Banjac, Banjac Scientific Associates*
Just a quick question; actually more of a suggestion than a question: Really interesting work you're presenting here. Did you, by any chance, look at the *Motorcyclist Magazine* data? I believe about a year, year and a half ago, they did a two-part article, did a lot of their testing over at HPRL measuring primarily the impact energy correlation to the stiffness and the resulting g-forces using head forms. They did a lot of really good work and I think got around to some pretty controversial conclusions regarding the effectiveness of the Snell standard versus DOT. I think a lot of that raw data would be of interest to you folks. Did you guys consider that as part of this work or forum?

A: Absolutely. We've compared our results to that study. They were looking at head form accelerations. It's more equivalent to what I presented last year. They looked at a couple different impact severities and recorded head force accelerations. They actually impacted a chunk of asphalt as opposed to a flat, steel plate and so their impacting surface was a bit softer than ours, but our results are quite comparable to what they did find. One of the big political things with that study was that they were saying that helmets were too stiff at the lower impact severities. What I've presented here does show that some of the helmets do have quite a higher stiffness at the lower impact severities, so that would add to what they were speculating in that study.

Q: Great. Thank you.