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Motorcycle Helmet Impact Behavior Depends on Impact Surface Shape

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ABSTRACT

Motorcycle helmets attenuate head accelerations through cracking and deformation of the outer shell and inner energy absorbing liner. Impacts with non-planar surfaces have been shown to result in more helmet damage and to be associated with an increased risk and severity of head and brain injury. Our goal was to determine the effect of impact surface shape on helmet damage and the resulting head acceleration response. Previously, we characterized the relationship between residual helmet damage and impact energy onto a flat impact surface (DeMarco et al., 2007). Here we continued this research by conducting helmet impacts onto a curbstone anvil. A total of nineteen drop tests were performed with identical motorcycle helmets impacting a flat (n=10 from DeMarco et al., 2007) or curbstone anvil (n=9) at impact speeds of 0.9-10.1 m/s (energy=2-260J). Residual crush was defined as the maximum percent change in helmet thickness, measured from the interior of the inner liner to the exterior of the outer shell, between the pre- and post-impact conditions. A linear relationship (r^2=0.90) between maximum crush and impact energy was observed across all impact energies for flat anvil impacts. For curbstone anvil impacts, a bilinear relationship was observed, with one linear region up to 150J (r^2=0.99) and another at 180J and above (r^2=0.79). Between 150J and 180J, the residual crush decreased about 40% because of hidden deformation at the liner/shell interface related to penetration of the curbstone anvil. The peak linear head accelerations from the curbstone impacts were significantly less than those from the flat anvil impacts ($p<0.02$). Based on these tests, the relationship between residual helmet liner deformation and impact energy depends on the shape of the object being struck by the helmet. These data suggest that incident specific tests using a similar helmet and struck object may be needed to estimate the impact severity of a motorcycle helmet from its post-impact residual crush.

INTRODUCTION

Standard-approved motorcycle helmets reduce the frequency and severity of head and brain injuries in motorcycle crashes (MacLeod et al., 2010; Rowland et al., 1996; Hurt and Thom, 1992). This reduction is achieved by distributing the impact force over a larger area of the head and by attenuating the head acceleration exposure. Impact attenuation is accomplished through deformation and cracking of the helmet's hard outer shell and its interior energy absorbing liner.

The impact damage sustained by a motorcycle helmet in a crash may provide useful information about the severity of the impact, which in turn may be helpful in understanding injury causation and tolerance (Hope and Chinn, 1990). Hope and Chinn (1990) reported that damage to motorcycle helmets is closely related to impact energy; however, the level of damage in their study was only assessed visually. In later work (Chinn et al., 2001), residual liner deformation was reportedly related to impact velocity, however the details of this relationship were not given. In oblique helmet impact tests, peak deformation of the polystyrene foam liner was reported to increase linearly with impact severity expressed as impact velocity normal to the anvil (Mills, 2010; Ghajari et al., 2013). Preliminary work in our laboratory showed linear correlations (r^2>0.9) between impact energy and residual helmet deformation for several helmets impacted against a flat anvil (DeMarco et al. 2007). These data demonstrate that residual crush may be a useful measure from which to estimate the impact energy in real world motorcycle crashes.

In contrast to these studies, McIntosh and Patton (2012) performed flat anvil impacts and found no correlation between drop height and residual deformation for the pooled data from three motorcycle helmets. They concluded that this approach was not valid for reconstructing helmeted motorcycle head impacts. Their contrary findings may be related to pooling different helmets certified to different standards and their thickness/deformation measurement protocol. Interestingly, McIntosh and Patton (2012) did find a significant correlation between drop height and residual deformation for bicycle helmets. These studies highlight the potential effect of different helmet structure and material properties on the relationship between helmet damage and impact energy. While the helmet clearly plays a role in the damage sustained, so may the impact surface. The studies listed above only tested against a flat surface and thus do not considered the potential effect of impact surface shape on the damage profile/impact severity relationship.

In real world crashes, helmet impacts involve both planar and non-planar surfaces. Non-planar surfaces have been suggested to cause more helmet damage and to be associated with an increased risk and severity of head and brain injury. While planar impacts, by nature of their greater occurrence, cause more AIS>3 head injuries overall, corner type impacts have a higher risk of AIS>3 head injury per impact (Vallée et al., 1981). Additionally, Wobrock et al., (2003) demonstrated that the geometry of the object struck by the head was a better overall predictor of injury outcome than was impact severity. Despite the increased head injury risk in non-planar impacts, a detailed investigation into the association between non-planar impacts, motorcycle helmet damage and head acceleration response has not been performed.

Our goal here was to characterize the relationship between motorcycle helmet damage and impact energy in a specific non-planar impact, i.e., into a curbstone anvil. Peak linear headform accelerations were analyzed in order to assess potential differences in helmeted head injury exposure in curbstone versus previously reported flat-anvil impacts (DeMarco et al. 2007).

METHODS

Nine certified (DOT and Snell M95) full-face helmets of the same model (L·H Comet C3-FS) were tested (Figure 1). Each helmet had a soft foam comfort liner, an expanded polystyrene (EPS) energy absorbing foam liner, and a hard outer shell composed of fiberglass. All helmets were medium size and tested on an ISO J magnesium alloy headform (Half Magnesium K1A, Cadex Inc., Quebec, Canada). To ensure consistent helmet positioning, the helmet positioning index was measured before each impact (Snell, 2005).

Each helmet was dropped along a 6 m tall monorail onto the edge of a curbstone anvil (Figure 2) (Cadex Inc., Quebec, Canada). The anvil edge had a radius of 15 ± 0.5 mm and was formed by the junction of two surfaces having an included angle of 105 ± 0.5° (Figure 2). The linear acceleration of the headform was measured using a ±2000g accelerometer (7264B-2000T, Endevco, San Juan Capistrano, CA). Each helmet was dropped once on its right side (Figure 2) at impact severities ranging from about 30 to 256 J (3.4 to 10 m/s).

Figure 1: Helmet model (L·H Comet C3-FS) used in tests was certified to DOT and Snell M95 standards. The visors of the helmets were cut prior to testing to accommodate the ball arm of the monorail and trolley assembly.

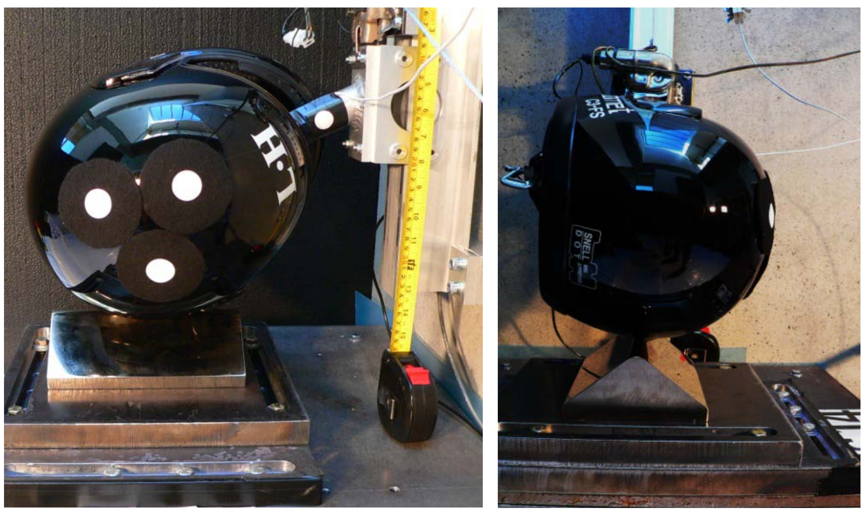

Figure 2: Test set-up showing engagement of right side of helmet with curbstone anvil. Left photograph shows a view of the top of helmet and the side of the anvil. Right photograph shows view of back of helmet and an end view of the anvil.

Helmet thickness, defined as the distance between interior surface of the energy absorbing liner and the exterior surface of the shell, was measured across the impact side of each helmet on a nominal 2x2cm grid using a digital height gage (Series 192, 600 mm, 6 digit, Mitutoyo, Japan) **(**Figure 3**)**. Post-impact helmet thickness was measured at least 2 days after impact in all helmets and pre-impact thickness was measured in one helmet. Thickness measurements had an RMS error of ± 0.15mm. Maximum crush was defined as the maximum difference between the pre- and post-impact thickness values measured at a single point on the grid and was expressed as a percentage of pre-impact thickness. Peak headform acceleration and maximum crush from the curbstone impact tests were then compared to the results of ten previous tests of the same helmet model onto a flat anvil across similar impact energies (DeMarco et al., 2007).

Linear regressions were used to evaluate correlations between residual helmet deformation and impact energy for both the curbstone and flat anvil impacts. Coefficients of determination were calculated for each regression. Additionally, a paired t-test was performed between peak headform accelerations from the curbstone and flat anvil impacts at similar impact energies. Statistical significance was set at $p<0.05$.

Figure 3: Left: General arrangement of grid and helmet thickness measurement locations. Right: Height gage apparatus used to measure helmet thickness over each grid location.

RESULTS

Curbstone impacts resulted in oblong contact regions to the shell and caused shell surface damage at impact energies of 60J and above. This damage typically consisted of paint crazing, cracking and flaking. The flat anvil impacts produced circular contact regions and only light scuffing of the shell surface, even at higher energies. In contrast to the exterior shell damage, the inner surface of the energy absorbing liner had deeper and larger cracking patterns after flat anvil impacts than after curbstone impacts.

The relationship between impact energy and maximum residual crush was linear for the flat-anvil impacts (r^2=0.96, Figure 4) but not for the curbstone impacts (r^2=0.47). For the curbstone impacts, the relationship appear to be bilinear with an ~40% decrease in maximum crush between 150J and 180J. A repeated drop at 180J yielded similar results. At low energy levels, the coefficient of determination between impact energy and maximum crush was r^2=0.99 and maximum crush from the curbstone impacts generally exceeded that for the flat anvil impacts. At high energies, the coefficient of determination was r^2=0.79 and maximum crush from the curbstone impacts was generally less than for the flat anvil impacts.

To further investigate the drop in maximum residual crush at 180J, one of the curbstone helmets tested at 180J was dismantled. This revealed localized deformation of the outer surface of the energy absorbing liner immediately below the shell damage due to dynamic penetration of the curbstone anvil into the shell and liner (Figure 5). The liner deformation covered an oblong area 11cm long, 5cm wide and a maximum depth of about 3.2mm. This deformation was hidden by the exterior shell and was therefore missed by our measurement technique.

Headform acceleration for the curbstone impacts increased with impact energy up to 180J and then leveled off (Figure 6). At similar impact energies, peak headform accelerations for the curbstone impacts were significantly lower than for the flat anvil impacts ($p<0.02$).

DISCUSSION

In this study, we investigated the relationship between residual motorcycle helmet damage and impact energy following curbstone anvil impacts. We observed a bilinear response with a large drop in apparent residual helmet deformation above 150J. This response was very different from the previous flat-anvil data that exhibited a monotonic increase in residual deformation with increasing energy, and indicates that the shape of the object struck by the helmet can have a large effect on the amount of residual damage present after an impact.

The decrease in maximum crush we observed between 150J and 180J was unexpected. Subsequent dismantling of one of the helmets exposed to 180J showed hidden focal deformation of the impact liner at the foam/shell interface. This deformation was not captured by our residual crush measurement technique. Combining the peak deformation (~3.2 mm) at the outer surface of the liner to the residual crush measurement from the inner surface of the liner in this helmet yielded a total maximum crush near the value

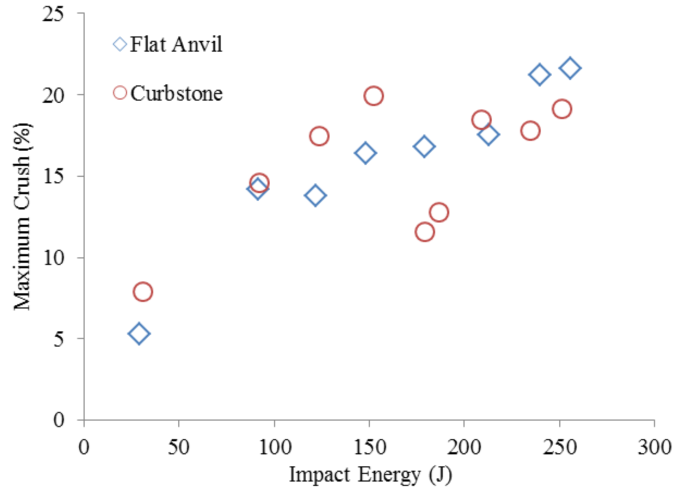

Figure 4: Percent maximum residual helmet crush in flat and curbstone anvil impacts as function of impact energy. Two curbstone impacts were performed at about 180J to confirm crush results.

Figure 5: Views of exterior surface of energy absorbing liner following 180J test with curbstone anvil. Left: Overall view of impact side (helmet cut in half). Right: Close-up of the localized liner deformation due to penetration of the curbstone anvil into the shell and liner.

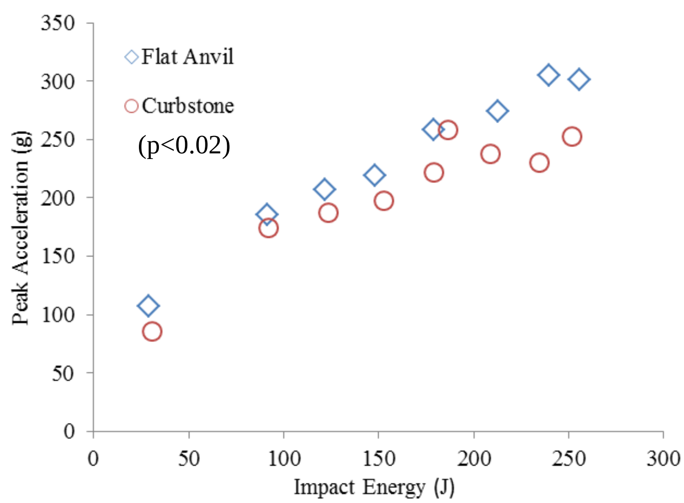

Figure 6: Peak headform acceleration for the curbstone anvil impacts was significantly lower ($p<0.02$) than for the flat anvil impacts at similar energies.

measured for the 150J helmet. This suggests that consideration of the liner crush on both the inner and outer surfaces may improve the correlation of residual crush with impact energy over the entire impact energy range in curbstone impacts. Since it is not always possible to dismantle a helmet to inspect for hidden liner crush, computed tomography (CT) scans may be an effective non-destructive way to assess total helmet liner deformation (Cooter, 1990).

The helmet damage we observed suggests that damage type and pattern may be useful in distinguishing planar from non-planar impacts. This relationship was previously reported in Chinn et al., (2001) who observed that surface scratches, scuffs, and paint chips often relate to impact speed, angle, and target shape. The findings of our study, while only considering two different impact surface shapes, suggest that the damage to the shell surface may grossly indicate the shape of surface impacted. Paint crazing, cracking and chipping of the helmet shells was only observed following curbstone impacts. Light scuffing was observed on the shell following flat anvil impacts. Additionally, although only two helmets have been cut in half, the deformation profile at the outer surface of the energy absorbing foam liner appears to mimic the anvil shapes used in our study and may help determine impact surface shape.

Previous studies have suggested that helmet impacts with non-planar objects result in more helmet damage and more severe injuries (Wobrock et al., 2003; Chinn et al., 2001; Vallée et al., 1981). Our tests, however, showed a reduction in peak linear headform acceleration in curbstone impacts compared to flat anvil impacts. The lower accelerations in the curbstone impacts are likely due to increased penetration and damage of the shell and outer liner surface caused by the narrow profile of the curbstone anvil. Others have also reported lower head accelerations in non-planar (edge, hemispherical, and cylindrical) motorcycle helmet impacts compared to planar impacts (Thom, 2006; Mitsuishi et al., 1994; Mills, 1990). Decreased linear head accelerations in non-planar impacts are at odds with epidemiological data that show an increased incidence of severe head injuries with non-planar impacts compared to planar impacts. Several reasons for this apparent contradiction may exist, including i) linear acceleration is only one of several head injury measures and may not be the most important measure in non-planar impacts, ii) the thick energy absorbing liners (40mm) in the helmets we tested did not densify and helmets with thinner energy absorbing liners may bottom out during the type of focal crush we observed from the curbstone impacts.

The residual crush measurement used here is based on the distance between the inner surface of the energy absorbing foam liner (adjacent to the headform at impact) and the outer surface of the shell. In addition to not capturing the hidden liner deformation, this technique does not capture any pre-impact gap between the outer surface of the liner and inner surface of the shell due to manufacturing and assembly. The variability of this gap between and within helmet types has not been quantified and the effect of this pre-impact gap on the relationship between residual crush and impact energy has not been explored. The effect of differences between a rigid metallic headform and a more compliant human skull may also affect the distribution and degree of residual crush to the helmet liner, and may vary between different helmet types and models. Further work is needed to quantify these unknowns.

CONCLUSIONS

The relationship between residual helmet liner deformation and impact energy depends on the shape of the object being struck by the helmet. In curbstone impacts, we observed focal hidden damage between the helmet shell and liner that produced an apparent drop in the residual crush with increasing energy. These data suggest that incident specific tests may be needed to estimate the impact severity of a motorcycle helmet from its post-impact residual crush.

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REFERENCES

CHINN, B. et al. (2001) COST 327: Motorcycle safety helmets, Final report of the action. European Co-operation in the Field of Scientific and Technical Research. Belgium.

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

DeMARCO, A.L., GARDINER, J.C., WILKINSON, C.C., HASSAN, E.A., SIEGMUND, G.P. (2007). Predicting motorcycle helmet impact severity from residual crush damage. 35th International Workshop on Human Subjects for Biomechanical Research.

GHAJARI, M., PELDSCHUS, S., GALVANETTO, U., IANNUCCI, L. (2013) Effects of the presence of the body in helmet oblique impacts. Accident Analysis and Prevention, 50, 263-271.

HOPE, P.D., 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 impacts. Bron (France) 319-331.

HURT, H.H., THOM, D.R. (1992) Motorcyclist head injury mechanisms—with and without helmets. 36th Annual Proceedings, Association for the Advancement of Automotive Medicine. Portland (USA) 235-250.

MacLEOD, J.B.A, DIGIACOMO, J.C, TINKOFF, G. (2010) An evidence-based review: helmet efficacy to reduce head injury and mortality in motorcycle crashes: EAST practice management guidelines. Journal of Trauma, 69 (5) 1101-1111.

McINTOSH, P.A., PATTON, D.A. (2011) Impact reconstruction from damage to pedal and motorcycle helmets. Journal of Sports Engineering and Technology 226 (3/4) 274-281.

MILLS, N.J. (1990) Protective capacity of bicycle helmets. British Journal of Sports Medicine, 24, 56-63.

MILLS, N.J. (2009) Critical evaluation of the SHARP motorcycle helmet rating. International Journal of Crashworthiness, 15 (3) 331-342.

MITSUISHI, H., ONO, K., NISHIMOTO, T., NAKAMURA, N. (1994) Present and future performance levels of head injury protection for motorcycle helmets. International IRCOBI conference on the biomechanics of impacts. Bron (France) 259-270.

ROWLAND, M.S, 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. American Journal of Public Health, 86 (1) 41- 45.

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

THOM, D.R. (2006) Comparison tests of motorcycle helmets qualified to international standards. International Motorcycle Safety Conference, 1-14.

VALLEE, H., THOMAS, C., SACRESTE, J., HENRY, C., TARRIERE, C. (1981) Characteristics of objects struck by the head of moped riders or motorcyclists. International IRCOBI conference on the biomechanics of impacts. Salon de Provence (France) 319-331.

WOBROCK, J., SMITH, T. (2003) Effectiveness of collision-involved motorcycle helmets in Thailand. 47th Annual Proceedings, Association for the Advancement of Automotive Medicine. Paramount (USA) 1-23.