

Effects of Impactor Mass in Top Impact Tests in Evaluation of Shock Absorption Performance of Construction Helmets: A Preliminary Study

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Abstract: Helmets have been considered one of the important prevention strategies in construction to reduce work-related traumatic brain injury risk. Top impacts are considered essential tests to evaluate the shock absorption performance of commonly used industrial helmets. Currently, there are two major test standards that are widely applied in industry: the U.S. standard ANSI/ISEA Z89.1 and the European standard EN397. Since drop impacts are performed using different impactor mass and drop heights, results obtained from two different test standards are quite different. The purpose of the current study is to analyze, evaluate, and compare the test results obtained using these two frequently used helmet test standards. A representative basic Type I construction helmet model was selected for the study. A total of 23 drop impact tests were performed at different drop heights and in two groups using two different impactor masses: (a) fifteen drop impacts were performed using an impactor mass of 3.6 kg at drop heights from 0.30 m to 2.23 m and (b) eight drop impacts were performed using an impactor mass of 5.0 kg at drop heights from 0.22 m to 1.35 m. Relationships between the drop height and the maximal transmitted force for two test groups were analyzed. When test data were plotted in the peak force and peaks accelerations as a function of impact kinetic energy, all test results for groups (a) and (b) fall narrowly on the same curve. Our results showed a consistent trend for the relationship of maximal transmitted force and accelerations as a function of the impact kinetic energy, independent of the impactor mass. When the impact energy is smaller than the critical impact energy, the peak impact forces and peak accelerations increase gradually and slowly with increasing impact energy; when the impact energy is greater than the critical impact energy, the peak impact forces and peak accelerations increase steeply with increasing impact energy.

Keywords: Construction helmet, Top impact tests, Impact force

1. Introduction

Work-related traumatic brain injury is one of the most serious workplace injuries among all work-related injuries in the United States from 1998 to 2007 (Konda et al. 2015). Helmets are considered one of the important prevention strategies in construction to reduce the work-related traumatic brain injury risk (Janicak 1998). Type I helmets are the most commonly used helmets in construction sites and they are mainly designed to provide head protection from top impacts (Gilchrist and Mills 1987; Mills and Gilchrist 1993). Top impact tests are considered essential tests to evaluate the helmet shock absorption performance in different helmet test industrial standards.

Currently, there are two major test standards that are widely used to evaluate helmet performance: the ANSI/ISEA Z89.1 (ANSI 2014) standard and the European standard EN397 (BS 2012). The technical parameters used in these two test standards are summarized in Table 1, in which the highlighted parameters are derived theoretically in frictionless condition. In ANSI/ISEA Z89.1, impacts are performed by using an impactor mass of 3.6 kg, whereas in European standard EN397, the impactor mass is 5.0 kg. In ANSI/ISEA Z89.1 standard, the tests are performed at an impact velocity of 5.5 m/s and the maximal transmitted force shall be smaller than 4.45 kN to pass the test. In European standard EN397, the impactor is dropped from a height of 1.0 m and the acceptable transmitted force shall be less than 5.0 kN. Since different parameters and

different masses of the drop impactors are applied in these two different standards, obtained results are different. The purpose of the current study is to analyze and evaluate the effects of impactor mass in top impact tests on the performance evaluation of construction helmets.

Table 1. Comparison of ANSI Z89.1 standard with EN397 standard. The highlighted values are derived theoretically in frictionless condition.

Standard	Impactor mass	Drop height	Impact speed	Impact energy	Max. transmitted force
	m (kg)	h (m)	v (m/s)	mgh (J)	F_{\max} (kN)
ANSI Z89.1	3.60	1.54	5.50	54.45	4.45
EN397	5.00	1.00	4.43	49.05	5.00

2. Methods

2.1 Experiment set-up

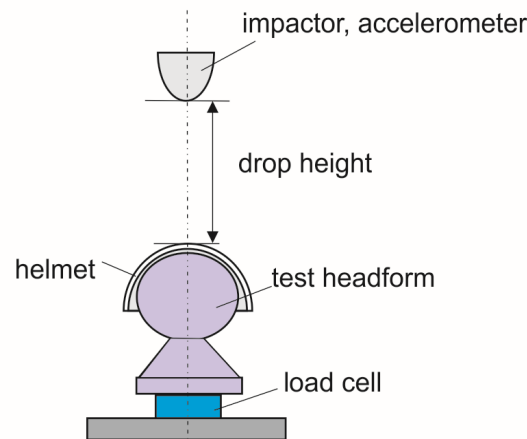


Figure 1. Schematics of test procedure. The tested helmet was placed on a fixed headform and was impacted by a free falling impactor.

One representative off the shelf Type 1 construction helmet model was used in this study. A Type 1 helmet is designed for top impact protection only and is not designed for protection from lateral impacts to the front, side, or rear of the head. In the current study, only Type 1 impact tests were performed: a free falling impactor is impacted on the top crown of the helmet shell that is fitted on a fixed headform (Fig. 1). The experimental setup is similar to that used in our previous studies (Pan et al. 2019; Wu et al. 2018). Drop impact tests were performed using a commercial drop tower test machine (H.P. White Laboratory, MD, USA) similar to that used in our previous studies (Wu et al. 2018). The drop tower system was made to comply with the ANSI Z89.1 standard (ANSI 2014). The forces transmitted to the headform are measured using a force sensor (Model 925M113, Kistler, Amherst, NY, USA), which is uniaxial and has a capacity of 22.2 kN (5k lbf) and an accuracy of $\pm 2.5\%$ full scale. The force sensor was installed between the base of the tower and the headform (Fig. 1). The acceleration was measured using a single axis accelerometer (Model 357B03, PCB Electronics, Depew, NY, USA), which was installed in the impactor in the impactor drop direction (vertical) and had a peak range of 19.6 km/s^2 (2,000 g). The velocity of the impactor just before impact was measured via an optical sensor built in the system. In the current study, two impactor masses were used: 3.6 kg and 5.0 kg. The force and acceleration data were collected at a sampling rate of 25 kHz. The force sensor and accelerometer were both calibrated according to the recommendations in the ANSI Standard Z89.1 (Appendix C2 and C3).

Table 2. A summary of top impact tests conducted in the study. (a) Fifteen (15) drop impact tests were conducted using a mass of 3.6 kg. (b) Eight (8) drop impact tests were conducted using a mass of 5 kg.

Mass 3.6 kg, Test #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Drop height, h (ft)	1.00	2.00	3.00	4.00	5.00	5.83	5.91	6.00	6.08	6.16	6.24	6.32	6.64	7.00	7.32
Drop height, h (m)	0.30	0.61	0.91	1.22	1.52	1.78	1.80	1.83	1.85	1.88	1.90	1.93	2.02	2.13	2.23
Mass 5.0 kg, Test #	1	2	3	4	5	6	7	8							
Drop height, h (ft)	0.72	1.44	2.16	2.88	3.60	4.32	4.38	4.44							
Drop height, h (m)	0.22	0.44	0.66	0.88	1.10	1.32	1.34	1.35							

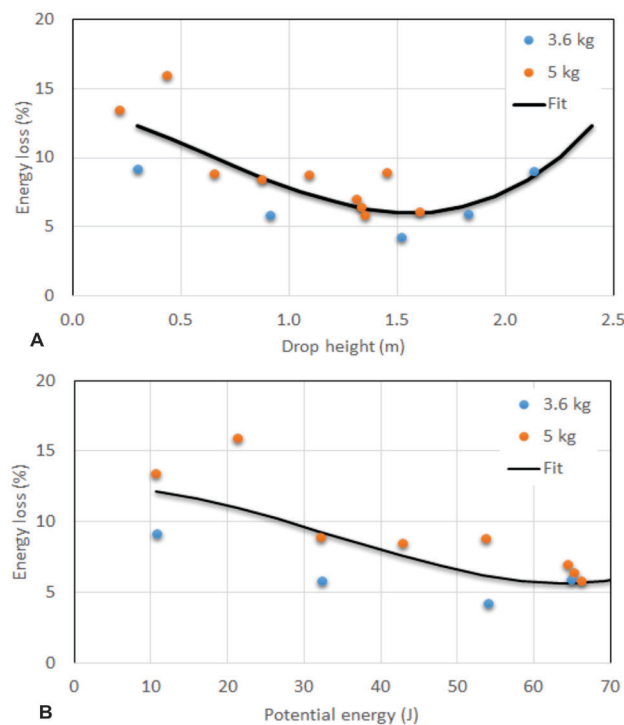


Figure 2. The energy loss in the system during impact tests as a function of drop height (A) and potential energy (B). Tests were conducted using impactor masses 3.6 kg and 5.0 kg.

2.2 Test procedure

Before data collection, we performed a benchmark tests to evaluate the performance uniformity of the helmet. The helmets were impacted at drop height of 0.30 m, 0.91 m, 1.52 m, and 1.83 m, with an impactor mass of 3.6 kg. Four trials were performed at each of the drop heights. Each drop impact trial was performed using a new helmet sample, which was disposed of following the trial.

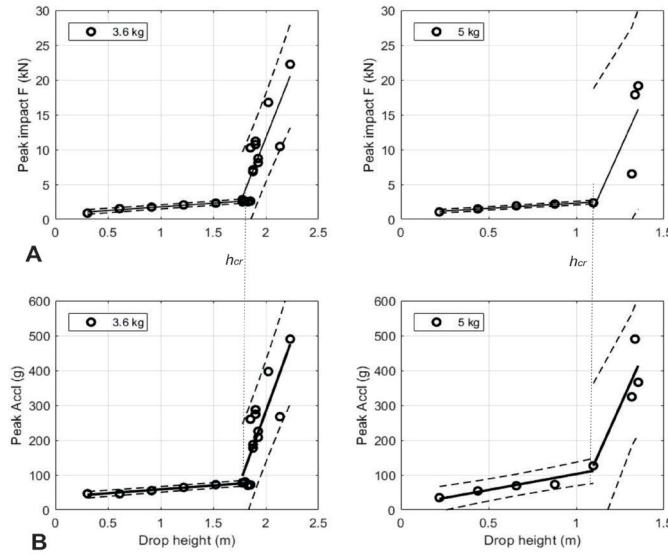


Figure 3. The peak impact forces (A) and peak accelerations (B) as a function of drop height. The Left and Right plots are the results obtained using impactor mass of 3.6 kg and 5 kg, respectively. The test results were fitted using separate lines (solid lines). The dashed lines are the 95% confidence intervals for the linear regressions.

A total of 23 drop impact trials were performed in two groups, as described in Table 2. In the first test group, 15 drop impacts were performed using an impactor mass of 3.6 kg at drop heights from 0.30 m (1 ft) to 2.23 m (7 ft). In the second test group, eight drop impacts were performed using an impactor mass of 5.0 kg at drop heights from 0.22 m (0.72 ft) to 1.35 m (4.44 ft). In order to examine the data variations, we performed benchmark tests with a impactor mass of 3.6 kg with four repeats at each of four different drop heights: 0.30 m (1 ft), 0.91 m (3 ft), 1.52 m (5 ft), and 1.83 m (6 ft). Each drop impact trial was performed using a new helmet sample, which was disposed of following the trial. The recorded time-histories of forces and accelerations were processed using a custom program developed using MATLAB software to find the maximal peaks, which occurred in the initial impact. The unfiltered raw data were used in the determination of the peak impact forces and accelerations.

The friction loss in the system during the impacts was tested using impactor masses of 3.6 kg and 5.0 kg. The energy loss in the system during impacts were estimated by dropping an impactor at a height of h :

$$\delta = \frac{\frac{1}{2}v^2 - gh}{gh} \times \% \quad (1)$$

where δ is the relative energy loss in the system, v is the measured velocity just before impact, and g is the gravitational acceleration.

3. Results

The benchmark repeat tests are summarized in Table 3. The average peak impact force at drop height of 0.30 m, 0.91 m, 1.52 m, and 1.83 m was determined at 1.05 (0.04) kN, 1.90 (0.03) kN, 2.50 (0.02) kN, and 2.71 (0.12) kN, respectively. For the range of drop heights less than h_{cr} (1.75 m) (Wu et al., 2018), the average relative standard deviation of the measurements is 1.9%, which is considered very small, suggesting that the tested helmets exhibit a uniform performance.

Table 3. Benchmark impact tests.

Test #	1	2	3	4
Drop height, h (ft)	1.00	3.00	5.00	6.00
Drop height, h (m)	0.30	0.91	1.52	1.83
Test Repeats	4	4	4	4
Impact speed, v (m/s)	2.33	4.11	5.35	5.81
Est. energy loss, δ (%)	9.2	5.7	4.2	5.8
Ave. Peak F (kN)	1.05	1.90	2.50	2.71
STD (kN)	0.04	0.03	0.02	0.12
Relative STD (%)	3.36	1.46	1.00	4.44

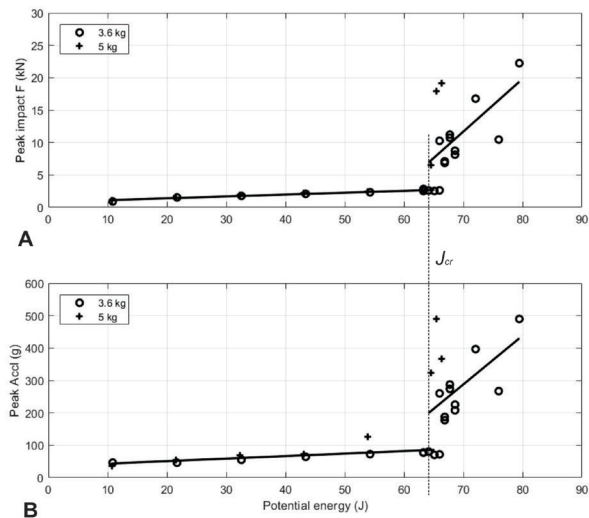


Figure 4. The peak impact force (A) and peak acceleration (B) as a function of potential energy, which is defined as $J = mgh$ with m being the impactor mass.

The friction loss in the drop tower test system as a function of the drop height and potential impact energy is shown in Fig. 2A and 2B, respectively. The energy loss in the system decreases with the increasing drop height from 0.30 m, reaches the lowest point of approximately 5 % around a drop height of 1.5 m, and then increases with increasing drop height (Fig. 2A). The test data for drop height from 0.30 m to 1.5 m are plotted as a function of potential impact energy (Fig. 2B), which is defined as mgh with m being the impactor mass. The energy loss in the system decreases with the increasing potential energy, reaches the lowest point (5 %) around 54 J, and then increases with increasing potential energy (Fig. 2B). Generally, the energy losses obtained using 5 kg impactor are slightly greater than those obtained using 3.6 kg mass.

The peak impact forces and peak accelerations as a function of drop height are shown in Fig. 3A and 3B, respectively. The results show that the peak impact forces and peak accelerations increase gradually and slowly with increasing drop height until the drop height reaches a certain level -- the critical drop height (h_{cr}), they then increase steeply with even a small increase of the drop height. The critical drop height, h_{cr} , is approximately 1.75 m for tests with the 3.6 kg impactor and approximately 1.10 m for tests with the 5 kg impactor.

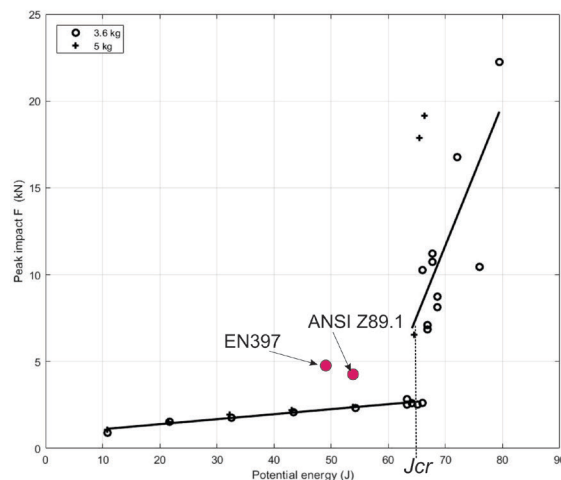


Figure 5. The peak impact force (A) as a function of potential energy in comparison with ANSI Z89.1 and EN397 standards.

The peak impact forces and peak accelerations are re-plotted as a function of potential energy in Fig. 4A and 4B, respectively. Using the potential energy as the independent variable, the results obtained using the 3.6 kg impactor can be compared with those obtained using the 5 kg impactor. Again, the peak impact forces and peak accelerations increase gradually and slowly with increasing potential energy until reaching a critical potential energy level ($J_{cr} = mgh_{cr}$), they then increase steeply with increasing potential energy. The critical impact energy J_{cr} is approximately 58 J, as determined in our study.

4. Discussion

In our previous study (Pan et al. 2019) we found that there was a critical drop height for drop impact tests using an impactor of 3.6 kg. When the drop height was less than the critical height, the peak force and peak acceleration increased gradually and slowly with increasing drop height. When the drop height was greater than the critical height, the peak force and peak acceleration increased steeply with even a slight increase in drop height. In the current study, we further confirmed this phenomenon using drop impact tests with an impactor of 5 kg. The critical drop height was approximately 1.22 m for the 5 kg impactor, compared to 1.75 m determined using an impactor of 3.6 kg (Pan et al. 2019; Wu et al. 2018). By introducing the concept of the critical potential energy ($J_{cr} = mgh_{cr}$), the results obtained using impactor masses of 3.6 kg and 5 kg can be combined (Fig. 5).

There are two test standards that are used to evaluate the performance of Type I helmets in constructions: ANSI Z89.1 and EN397. An impactor with a mass of 3.6 kg is used in ANSI Z89.1, whereas the mass of the impactor is 5 kg in EN397. Our results show that the peak impact forces and peak impact accelerations are dependent on the potential energy, indicating that the results obtained by using different impactor masses can be compared on the basis of the potential energy (Fig. 5).

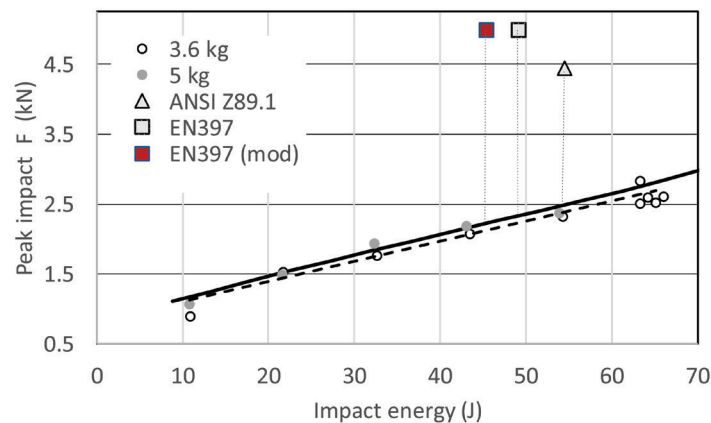


Figure 6. Effects of friction on the relationship between peak impact force and impact energy. The solid and dashed lines were fitting lines including and without including the friction loss, respectively.

In these two standardized tests (ANSI/Z89.1 and EN397), construction helmets are tested at impact intensities well below the critical potential energy J_{cr} , as identified in the current study. When the potential energy is below J_{cr} , the peak impact force increases linearly and slowly with increasing impact energy (Fig. 6), which is a range that helmet manufacturers are especially interested in. Considering frictional loss of the system, as depicted in Fig. 2, the original relationship (dashed line) between the peak impact force and impact energy has been slightly modified (solid line), as the net kinetic energy involved in the impact is smaller than the potential energy due to frictional loss. The required test conditions as designated in ANSI/Z89.1 and EN397 are compared with the helmet's peak force-impact energy relationship (Fig. 6). The parameter required in EN397 needs to be modified to account for the energy loss (approximately 7.5 %). Although the helmet passes both ANSI Z89.1 and EN397 standardized tests, it has different safety margins. The helmet's peak impact force is approximately 57% of the maximal allowed peak force by ANSI/Z89.1, whereas it is approximately 44% of the maximal allowed peak force in the modified EN397. Our results indicate that the helmet has a lower safety margin based on ANSI Z89.1 than that based on EN397, suggesting that ANSI Z89.1 is a more stringent standard.

The major difference between ANSI/Z89.1 and EN397 is that an impact velocity is designated in ANSI/Z89.1, whereas a drop height is designated in EN397. Principally, ANSI/Z89.1 designates a net kinetic energy involved in the impact, whereas EN397 designates a potential energy applied to the impactor. During a drop impact test, the potential energy of the impactor is converted into kinetic energy via the drop tower system that induces inevitable energy loss. These two approaches would be equivalent if frictional loss during the impact of the system is negligible. In realistic test conditions, the friction in the drop tower system is not negligible. Based on the current results, the drop tower system will introduce a friction loss of approximately 7.5% at a drop height of 1.0 m as designated in the EN397 standard. According to the EN397 standard, the kinetic energy would be 49.05 J in a frictionless condition, and it would be reduced to approximately 45.37 J, if friction loss is included. In contrast, there is no concern about frictional loss in ANSI/Z89.1, because it designates the impact velocity, which is measured just before the impact in the tests; the impact velocity is associated with the kinetic energy actually involved in the impact. The advantage of the ANSI/Z89.1 over EN397 standard is that it provides a more precise description of the test conditions, producing consistent test results independent of the drop tower systems used. However, before conducting tests based on the ANSI/Z89.1 standard, the drop tower system must first be calibrated to determine the friction loss, whereas helmet performance evaluation tests based on the EN397 standard can be conducted immediately without calibration.

A limitation of the current study is that helmets from only one representative model have been tested. For the proposed method to be accepted by industries, further validations need to be conducted with more repeat tests and using samples of different helmet models and from different helmet manufacturers. Helmets of different models may have different performance characterizations if tested using the proposed approach. Different shell materials and different suspension systems in helmets would likely result in different shock absorption characteristics. Generally, Type 2 helmets may have higher critical potential energy, provide greater safety margins, and have different characteristics of shock absorption performance. The principle of the proposed approach should be applicable for all types of construction helmets.

5. Conclusion

In the current study, the relationships among the peak impact force, peak accelerations, and impact energy of the helmet have been determined based on the impact tests using two different impactor masses: 3.6 kg and 5 kg. Our results show that the relationships between the peak force and impact energy as well as between the peak acceleration and impact energy are independent of the impactor mass. We found that when the impact energy is smaller than the critical impact energy, the peak transmitted forces and peak accelerations increase gradually and slowly with increasing impact energy; when the impact energy is greater than the critical impact energy, the peak transmitted forces and peak accelerations increase steeply with increasing impact energy. Our analysis indicated that the frictional loss of a representative drop tower system is between 4.8% and 15%, which is not negligible in the drop impact tests. We compared two commonly-used test standards (ANSI/Z89.1 and EN397) in the helmet impact absorption performance evaluations and found that, based on the analysis of the peak transmitted forces, ANSI Z89.1 is a more stringent standard.

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7. Disclaimer

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