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Testing the shock protection performance of Type I construction helmets using impactors of different masses

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Abstract.
BACKGROUND: Wearing protective helmets is an important prevention strategy to reduce work-related traumatic brain injuries. The existing standardized testing systems are used for quality control and do not provide a quantitative measure of the helmet performance.
OBJECTIVE: To analyze the failure characterizations of Type I industrial helmets and develop a generalized approach to quantify the shock absorption performance of Type I industrial helmets based on the existing standardized setups.
METHODS: A representative basic Type I construction helmet model was selected for the study. Top impact tests were performed on the helmets at different drop heights using two different impactor masses (3.6 and 5.0 kg).
RESULTS: When the helmets were impacted with potential impact energies smaller than the critical potential impact energy values, there was a consistent relationship between the peak impact force and the potential impact energy. When the helmets were impacted under potential impact energies greater than the critical potential impact energy values, the peak impact forces increased steeply with increasing potential impact energy.
CONCLUSION: A concept of safety margin for construction helmets based on potential impact energy was introduced to quantify the helmets' shock absorption performance. The proposed method will help helmet manufacturers improve their product quality.

Keywords: Construction helmet, experiment, impact test, shock protection performance, safety margin

1. Introduction

Statistical data has shown that the number of claims related to work-related traumatic brain injury (WrTBI) in the United States and Canada increased nearly 250% over the past decade [1–3]. WrTBI is one of the most serious types of workplace injuries among all work-related injuries in the United States [4]. A study of workers' compensation data in Washington state found that WrTBI is one of the costliest types of workplace injuries [5]. Even a mild WrTBI case can result in cognitive, behavioral,

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and functional impairments, which may last for months, years, or even remain permanently. Therefore, injury prevention of WrTBI is the priority in our research focus. Wearing industrial helmets is one of the important prevention strategies used at construction sites to reduce WrTBI risk [6,7]. The most commonly used type of industrial helmets at construction sites are categorized as Type I helmets [8,9]. Type I helmets are mainly designed for head protection from top impacts. The top drop impacts are considered essential tests to evaluate helmet shock absorption performance in different industrial standards.

Currently, there are two commonly used test standards for testing Type I industrial helmets: ANSI/ISEA Z89.1 standard [10], which is mostly used in North America, and the European standard EN397 [11]. Different impactors are used in these two standardized test methods: a 3.6 kg impactor is used in the ANSI/ISEA Z89.1 standard test, versus a 5.0 kg impactor that is used in the EN397 standard test. The drop impact energy is applied in a different manner in these two test standards. In the ANSI/ISEA Z89.1 standard, the testing is performed at an impact velocity of 5.5 m/s. To pass the test, the maximal transmitted force must be smaller than 4.45 kN. In the European standard EN397, an impactor is dropped from a height of 1.0 m. To pass the test, the transmitted force must be less than 5.0 kN. If frictional loss of these test systems is neglected, the potential impact energy is 54.45 and 49.05, respectively, for ANSI/ISEA Z89.1 and EN397 [10,11]. The current standardized testing systems are considered as a "two-level" or "binary" grading system because test outcomes are either pass or fail [12]. To pass either of the standardized tests, the peak impact forces must be smaller than the levels specified in the testing standards. The standardized testing systems do not determine the failure of the helmets; consequently, they do not provide a quantitative measure for the performance or safety margins of the helmets if they pass the tests.

The definition and measurement of the failure of helmets differ from those of the failure analysis of most engineering structures. For testing most engineering structures, the applied loading will be increased continuously until the failures of the structures. For the helmet impact testing, the helmet samples can only be impacted once at one impact force level [10,11]. The definition of the helmet failure at a certain impact force level would mean that the helmets lost their ability to absorb the shock impacts or their shock absorption ability deteriorates at that impact force level. In a previous study [12], we proposed an approach to quantify the shock absorption performance of Type I industrial helmets that had passed the existing standardized tests. However, that approach was only applied by using the ANSI/ISEA Z89.1 standard setup. The purpose of the current study was to develop a method to analyze the failure characteristics of Type I industrial helmets using ANSI/ISEA Z89.1 and EN397 standardized setups. Furthermore, we will develop a generalized approach to quantify the shock absorption performance of Type I industrial helmets. A representative off-the-shelf model of a Type I industrial helmet was selected for the study. Top impact tests were performed on the helmets at different drop heights using two different impactor masses, 3.6 kg and 5.0 kg, as respectively specified in the ANSI/ISEA Z89.1 and EN397 standards.

2. Materials and methods

2.1. Experimental setup

A Type I 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, Type I impact tests were performed, where a free-falling impactor impacts on the top crown of the helmet shell that is fitted on a fixed headform (Fig. 1). The experimental setup was similar to those used in our previous studies [12,13]. Helmet drop impact trials were performed using a commercial drop tower test machine (H.P. White Laboratory, MD,

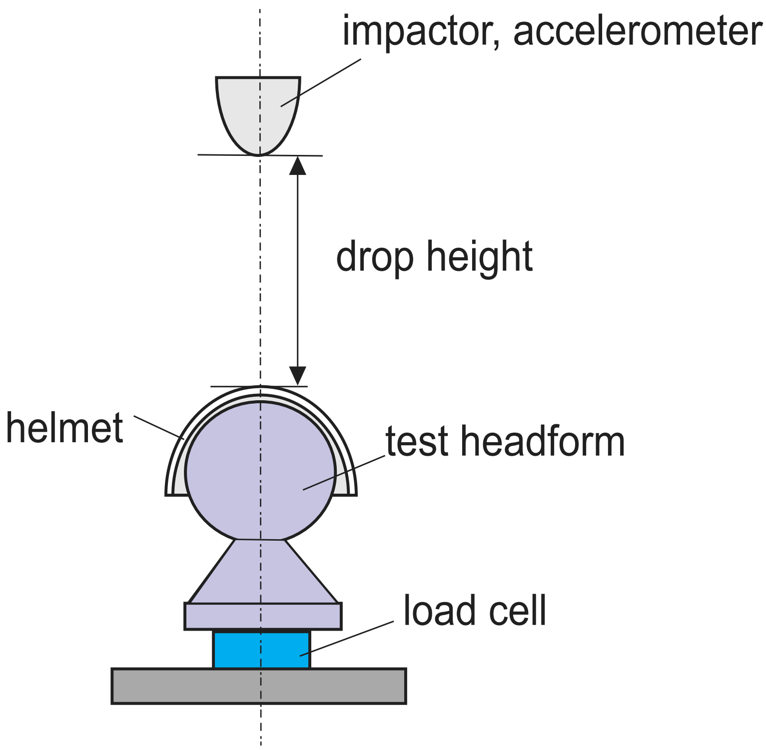


Fig. 1. Schematics of test procedure. The control parameter was the drop height, h; the reaction force at the base of the headform and the impactor velocity just before the impact were measured.

USA), which complies with the ANSI/ISEA Z89.1 standard [10]. The forces transmitted to the headform were measured using a uniaxial force sensor (Model 925M113, Kistler, Amherst, NY, USA), which had a capacity of 22.2 kN ($5 \cdot 10^3$ lbf) and an accuracy of ±2.5% full scale. The force sensor was installed between the base of the tower and the headform (Fig. 1). The velocity of the impactor in the vertical dropping direction was measured just before impact via an optical sensor built in the system. The impactor was semi-spherical with a radius of 48 mm at the striking face. In the current study, two impactor masses were used: 3.6 kg and 5.0 kg. The headform was made of aluminum and had a mass of 3.64 kg. The force data were collected at a sampling rate of 25 kHz. The force sensor was calibrated according to the recommendations in the ANSI/ISEA Standard Z89.1.

2.2. *Test procedure*

A total of 19 drop impact trials were performed in two groups, as described in Table 1. In test Group A, 10 drop impacts were performed using the 3.6 kg impactor at 10 dropping heights ranging from 0.31 m (1.0 ft) to 1.93 m (6.3 ft). In test Group B, 9 drop impacts were performed using the 5.0 kg impactor at nine dropping heights ranging from 0.22 m (0.72 ft) to 1.32 m (4.32 ft). Each of the impact trials was replicated four times. Impacted helmets were disposed of following the drop impact tests. A total of 76 ((10 + 9) × 4 (replicates)) drop impacts were performed using 76 new helmets. The recorded time-histories of impact forces were processed using a custom program developed using MATLAB software

Table 1
Description of top impact tests conducted in the study

(a) 3.6 kg impactor										
Test #	1	2	3	4	5	6	7	8	9	10
Drop height, h (m)	0.305	0.610	0.9150	1.220	1.373	1.525	1.629	1.732	1.830	1.928
(b) 5.0 kg impactor										
Test #		1	2	3	4	5	6	7	8	9
Drop height, h (m)		0.220	0.439	0.659	0.878	0.988	1.098	1.171	1.247	1.318

A total of 19 drop impact tests using a representative Type I helmet model were performed in two groups using two different impactors (3.6 kg and 5.0 kg). Group (a): tests using 3.6 kg impactor performed at 10 different drop heights (h) from 0.31 m to 1.93 m. Group (b): tests using 5.0 kg impactor performed at nine different drop heights 0.22 m to 1.32 m. Each of the impact trials was replicated four times. There were a total of 76 impact tests.

that was able to identify the maximal peaks during the impacts. The unfiltered raw data were used in the determination of the maximal peak values during the impacts.

2.3. Determination of the system frictional energy loss

The frictional energy loss in the system during the impacts was evaluated using both the 3.6 kg and 5.0 kg impactors. When an impactor is dropped at a height (h) and the impact velocity (v) just before the impact is measured, the frictional energy loss of the system during the impact is estimated by:

$$\delta = \frac{gh - \frac{1}{2}v^2}{gh} \times 100\%, \quad (1)$$

where g is the gravitational acceleration.

3. Results

To evaluate the system's frictional energy loss, the impact velocities of both 3.6 kg and 5.0 kg impactors as a function of drop height were recorded (Fig. 2A). The frictional energy loss for the drop tower test system as a function of drop height and potential impact energy was calculated and is shown in Figs 2B and 2C, respectively. In a drop height range from 0.5 m to 2.0 m (Fig. 2B), the range of potential impact energy was 20–70 J (Fig. 2C), which covers the range for drop impacts required in the ANSI/ISEA Z89.1 and EN395 standards. The frictional loss of the system was around 12%. Our results show that the frictional energy losses obtained using 5.0 kg impactor are comparable to those obtained using 3.6 kg impactor.

In each of the drop impacts, the time histories of the impact forces were recorded. Representative time histories of the impact forces for impact tests at different drop heights tested for the 3.6 kg and 5.0 kg impactors are shown in Figs 3 and 4, respectively. The general characteristics of the impact force patterns (Figs 3 and 4) are consistent with our previous observations [12]. In general, the impact forces gradually increased with increasing drop height when the drop height was smaller than a critical height (h_{cr}). When the drop height was greater than that critical value, narrow spikes were observed on the top of the base impact force impulse. These sharp force spikes were very narrow and had a duration of less than 1 ms.

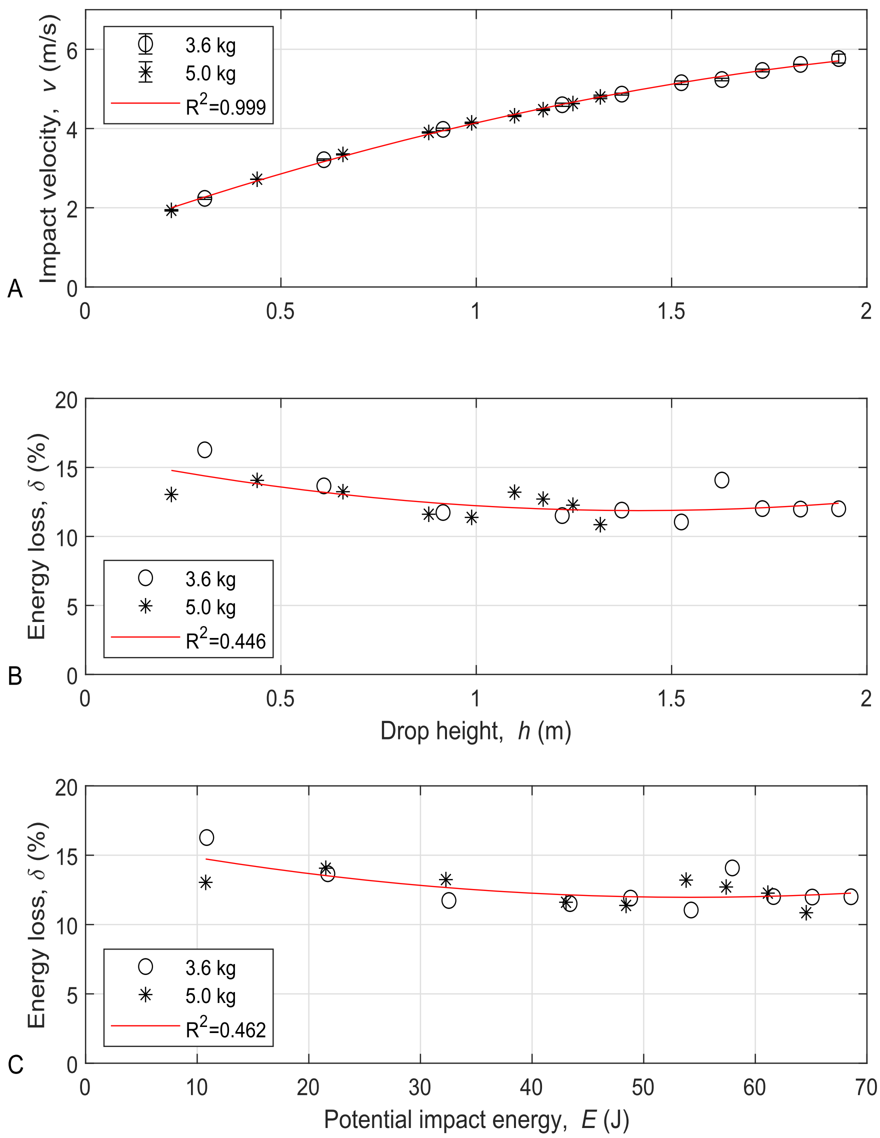


Fig. 2. Analysis of the frictional energy loss in the system during drop impact tests performed with 3.6 kg and 5.0 kg impactors. A: Impact velocity (v) as a function of drop height. B: Fictional energy loss (δ) as a function of drop height. C: Frictional energy loss (δ) as a function of potential impact energy.

Typical patterns for impact forces for impacts under the critical drop height ($h < h_{cr}$) are compared with those above the critical drop height ($h > h_{cr}$) in Figs 5A and 5B for tests with 3.6 kg and 5.0 kg impactor, respectively.

The peak impact forces as a function of drop height using 3.6 kg and 5.0 kg impactors are shown in Fig. 6A. For $h < h_{cr}$, the peak impact forces increased gradually with increasing drop height; for $h > h_{cr}$, the peak impact forces increased steeply with even a small increase of the drop height. The critical drop height, h_{cr}, was approximately 1.78 m for impact tests with the 3.6 kg impactor and approximately 1.13 m for impact tests with the 5.0 kg impactor.

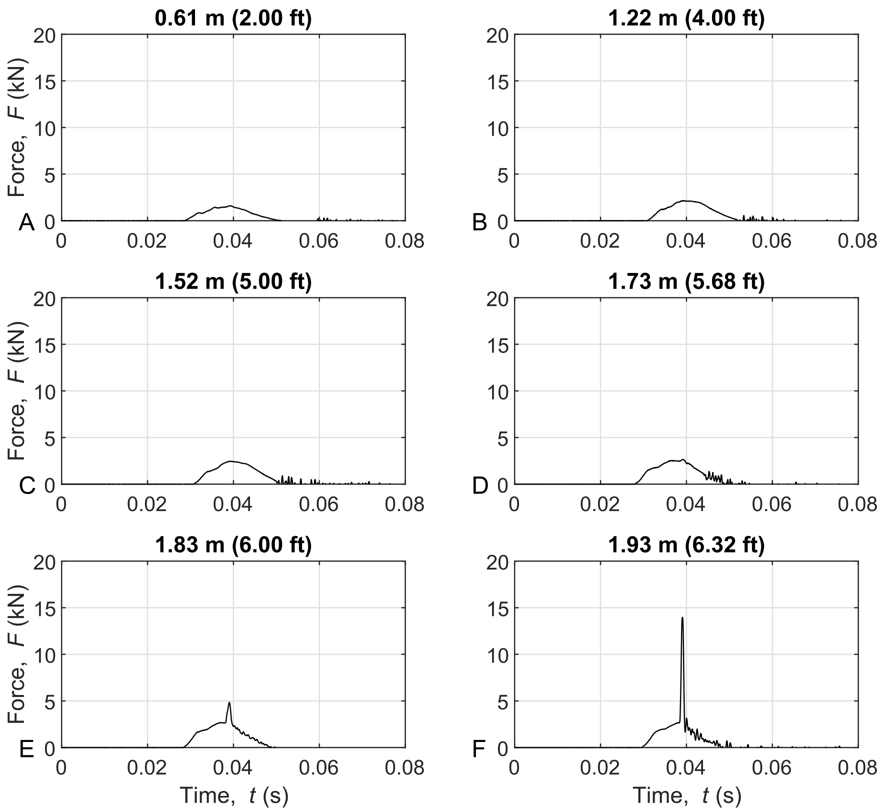


Fig. 3. The representative raw data for the time-histories of the impact forces around the impact for tests using 3.6 kg impactor at six different drop heights. A: 0.61 m. B: 1.22 m. C: 1.52 m. D: 1.73 m. E: 1.83 m. F: 1.93 m.

The peak impact forces are shown as a function of potential impact energy ($E = mgh$, with m being the impactor mass) in Fig. 6B. Since the potential impact energy (E) includes combined effects of mass and drop height, the results obtained using the 3.6 kg impactor can be compared with those obtained using the 5.0 kg impactor. The general trends of the relationship between the peak impact forces and the potential impact energy, obtained with both the 3.6 kg and 5.0 kg impactors, are consistent.

4. Discussion

In the current study, we developed a method to analyze the failure of Type I industrial helmets using the standardized testing setups and applied the proposed method to quantitatively evaluate the shock absorption performance of Type I industrial helmets. Although the proposed methodology was applied to one representative Type I helmet model, as illustrated in the study, the method can be generally be applicable to all Type I industrial helmets. The current study generalized our previously proposed approach [12] to quantify the shock absorption performance of industrial helmets for top impacts based on different standards. The proposed approach would conceptually change the conventional standardized helmet testing methods. If the proposed method is generally adopted in the helmet industry, it will not only help helmet manufacturers improve their product quality, but also provide supplementary information for consumers to make more knowledgeable decisions when selecting construction helmets.

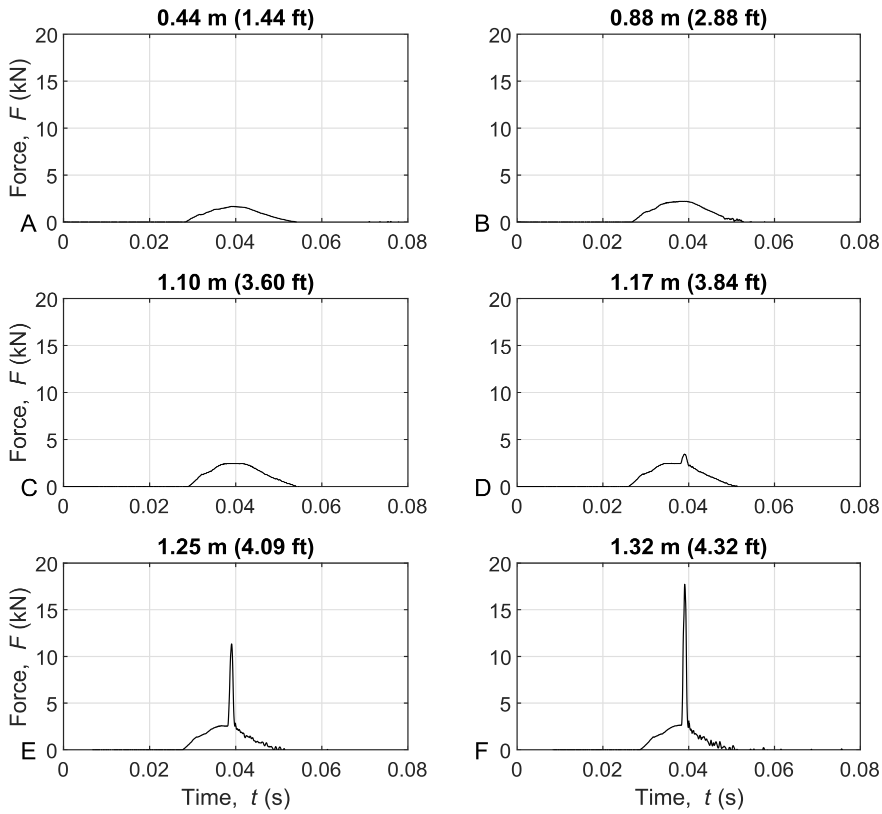
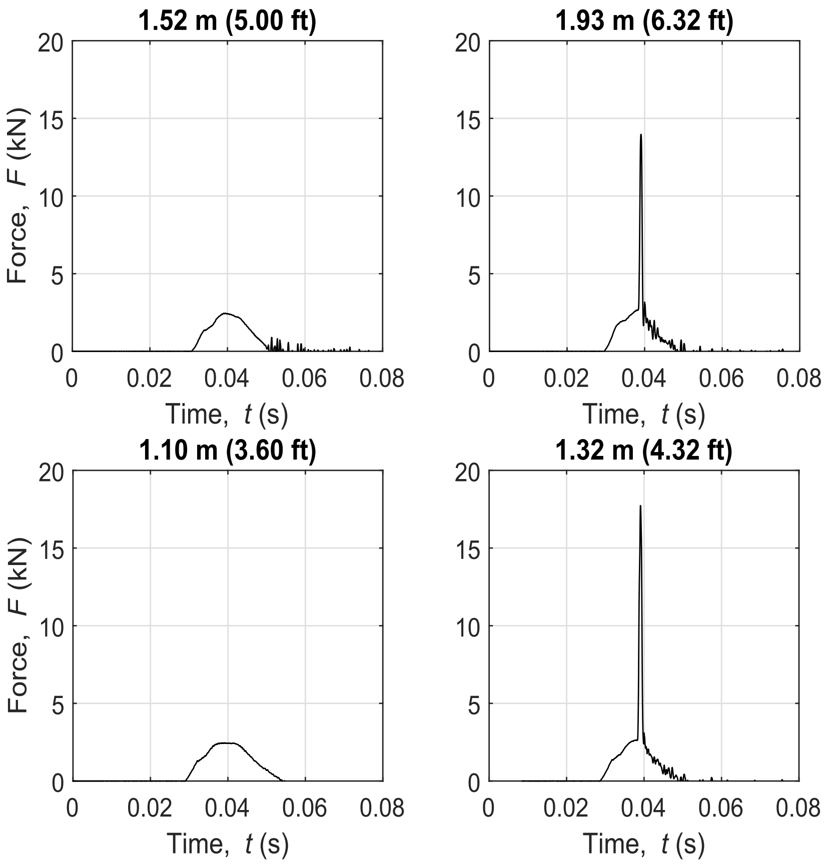


Fig. 4. The representative raw data for the time-histories of the impact forces around the impact for tests using 5.0 kg impactor at six different drop heights. A: 0.44 m. B: 0.88 m. C: 1.10 m. D: 1.17 m. E: 1.25 m. F: 1.32 m.

In our previous study [12], we found that, based on the drop impact tests using a 3.6 kg impactor, there exists a critical drop height (h_{cr}). When the drop height is less than the critical height, peak impact forces increase linearly and gradually with increasing drop height. When the drop height is greater than the critical height, the peak impact forces increase steeply with even a slight increase in drop height. This phenomenon observed in our previous study was confirmed using drop impact tests with both the 3.6 kg and 5.0 kg impactors. The critical drop height (h_{cr}) was found to be different for different impactors. It was approximately 1.78 m and 1.17 m, respectively, for the 3.6 kg and 5.0 kg impactors. The general trends in the relationships between peak impact forces and drop height observed in the current study were consistent with those in previous studies [12,13].

Our results validated our previous observation [12] that the helmets' failures start with the appearance of sharp force spikes above the top of the base force impulse (Fig. 5). Furthermore, the current results suggest that the failure mechanism of helmets under impacts with the 3.6 kg impactor is similar to that observed with the 5.0 kg impactor. The appearance of the sharp force spikes would be an indication that the helmet's suspension system loses its ability to dissipate the impact energy.

By introducing the concepts of potential impact energy (E) and critical potential impact energy ($E_{cr} = mgh_{cr}$), we demonstrated that the results obtained using the 3.6 kg and 5.0 kg impactors can be compared (Figs 6B and 7A). When the potential impact energy is below E_{cr}, the peak impact force increased linearly and gradually with increasing potential impact energy (Fig. 7A). When the potential impact energy is



A

B

Fig. 5. The representative raw data for the time-histories of the impact forces in the transition from stable to the unstable condition. A: 3.6 kg impactor. B: 5.0 kg impactor. The left column plots show the helmets are mechanically stable. The right column plots show the helmets are in mechanically unstable condition.

greater than E_{cr}, the peak forces increase steeply with even a slight increase in potential impact energy. E_{cr} values are different for different impactors. E_{cr} is approximately 62.8 J and 55.4 J, respectively, for tests using the 3.6 kg and 5.0 kg impactors. The scattering of the test data is characterized by the standard deviations of the test data and R^2 in the linear regression (Fig. 7A). Generally, in a range $E < E_{cr}$, the scattering of the test data was small. The data scattering became substantially greater when $E > E_{cr}$. Steep increase of the peak impact forces with increasing potential impact energy, together with substantially increasing scattering in the test data means that the helmets become mechanically unstable and are failing. Our results suggest that helmets would likely become mechanically unstable at a smaller potential impact energy (E) when impacted with a larger impactor (i.e., 5.0 kg).

When the helmets are tested for $E < E_{cr}$, the helmets' mechanical systems are stable and their peak impact forces (F_{max}) are linearly related to the potential impact energy (E), independent of the impact mass (Fig. 7B). A two-way analysis of variance (JPM, SAS Institute, version 16.1) indicated no difference between the slope of $F_{max} - E$ relationship for tests using 3.6 kg impactor and that using 5.0 kg impactor (p-value = 0.4001). When all testing data using 3.6 kg and 5.0 kg impactors are combined, the linear regression of the $F_{max} - E$ relationship has an excellent consistency ($R^2 = 0.98$) (Fig. 7B).

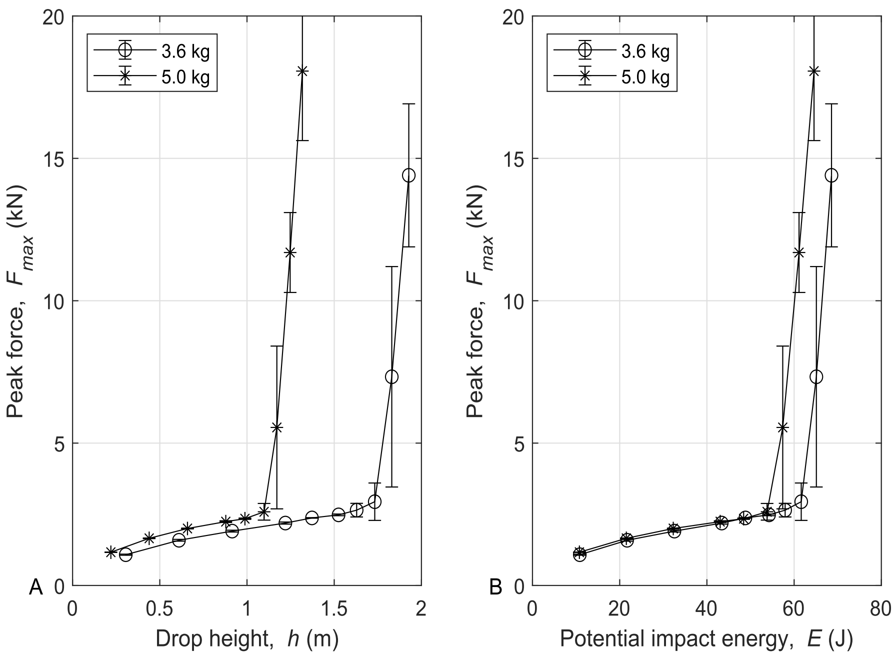


Fig. 6. Peak impact forces as a function of drop height (A) and potential impact energy (B) for impact tests using 3.6 kg and 5.0 kg impactors.

In standardized tests, construction helmets are tested below the critical potential energy E_{cr}. With the ANSI/ISEA Z89.1 standard, the helmets should be impacted at a velocity (v) of 5.5 m/s, which is equivalent to a net kinetic impact energy $E_{ANSI\ (net)}$ = 54.5 J ($J = 0.5 \cdot mv^2$, with v = 5.5 m/s and m = 3.6 kg). If including a system's frictional energy loss (approximately 12%, as in Fig. 2), the potential impact energy applied in the tests according to ANSI/Z89.1 should be: $E_{ANSI} = 1.12 \times E_{ANSI\ (net)}$ = 61.0 J. In the EN397 standard, helmets are impacted at a dropping height of 1.0 m, which is equivalent to a potential impact energy of 49.0 J ($J = mgh$, with h = 1.0 m and m = 5.0 kg). In Fig. 7B, the test conditions for Type I helmets as specified in the ANSI/Z89.1 and EN397 standards are compared with the relationship between the peak force and potential impact energy.

For the traditional standardized tests, a safety factor ρ is defined:

$$\rho_{\mathrm{std}} = \frac{F_{\max}^{\mathrm{test}}}{F_{\max}^{\mathrm{std}}}, \ \mathrm{std} = \mathrm{ANSI\ or\ EN397} \tag{2}$$

where $F_{\max}^{\mathrm{std}}$ and $F_{\max}^{\mathrm{test}}$ is the maximal peak impact force specified in the test standards and measured in the tests, respectively. It is required that $\rho_{\mathrm{std}} > 1$ to pass the standardized tests.

If helmets pass the standard tests, the safety margin of the helmet (η_{std}) is evaluated based on the potential impact energy [12]:

$$\eta_{\mathrm{std}} = \left(\frac{E_{cr}}{E_{\mathrm{std}}} - 1\right) \times 100\%, \ \ \mathrm{std} = \mathrm{ANSI\ or\ EN397} \tag{3}$$

where E_{std} is the potential impact energy required in the standards.

The safety factor for the helmet model tested in this study is ρ_{ANSI} = 1.38 and ρ_{EN397} = 1.51, respectively, for the ANSI/Z89.1 and EN397 standards. Using the current test data, E_{ANSI} = 61.0 J, E_{EN397} = 49.0 J,

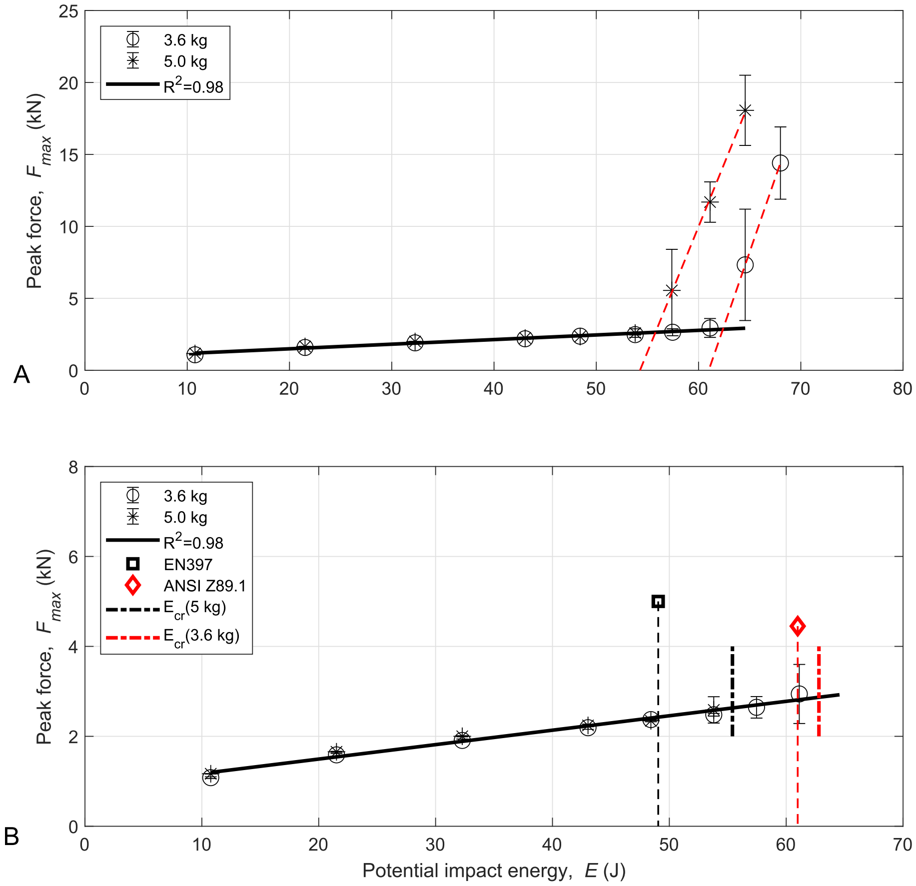


Fig. 7. Test data for peak impact forces as a function of potential impact energy with liner regressions. A: Test data for the entire range of potential impact energy with linear regressions. B: Comparison of the test results with helmet test standards ANSI/ISEA Z89.1 and EN397. In ANSI/Z89.1 standard, the potential impact energy should be E_{ANSI} = 61.0 J to consider the system's frictional energy loss. In EN397 standard, the potential impact energy should be E_{EN397} = 49.0 J. The allowable peak force is 4.45 kN and 5.00 kN, respectively, for ANSI/ISEA Z89.1 and EN397 standard. The critical potential impact energy for 3.6 kg and 5.0 kg impactor is 62.8 J and 55.4 J, respectively.

E_{cr} (3.6 kg) = 62.8 J, and E_{cr} (5.0 kg) = 55.4 J, the energy-based safety margins of the helmets are estimated to be approximately $\eta_{\text{ANSI}} = 3\%$ and $\eta_{\text{EN397}} = 13\%$, respectively, for the ANSI/Z89.1 and EN397 standards. The analysis of the test data is summarized in Table 2. For this helmet model, the peak impact forces are well below those specified in the test standards, indicating this helmet model easily passed both the ANSI/Z89.1 and EN397 standards. However, this helmet model has a very small safety margin. By increasing the potential impact energy by a mere 3% more than that required in the ANSI/Z89.1 standardized test, the helmets tend to collapse in the impact tests. Our results suggest that the peak impact force would not be a reliable parameter to evaluate the helmets' safety margin.

The essential difference between the existing standardized tests and the proposed approach is that the former evaluates helmets based on the peak impact force tested at a fixed impact load whereas the latter evaluates helmets based on the variations of the peak impact force as a function of the applied potential impact energy. Our results suggested the peak impact force value would not be a reliable parameter to

Table 2
Comparison of the ANSI/ISEA Z89.1 standard with the EN397 standard for Type I industrial helmet tests

Standards		ANSI/ISEA Z89.1	EN397
Impactor Mass, M	kg	3.6	5.0
Drop height, h	m	<u>1.73</u>	1.00
Impact velocity, v	m/s	5.50	<u>4.15</u>
Max. allowable peak force in standard, $F_{\max}^{\text{std}}$	kN	4.45	5.00
Max. impact force in tests, F_{max}^{test}	kN	2.78	2.44
Force-based safety factor, ρ	–	1.38	1.51
Potential impact energy in standards, E_{std}	J	61.0	49.0
Critical drop height, h_{cr}	m	1.78	1.13
Critical potential impact energy, E_{cr}	J	62.8	55.4
Energy-based safety margin, η	%	3.0	13.1

The underlined values are derived theoretically considering a system frictional energy loss of 12%. $F_{\max}^{\text{std}}$ (std = ANSI or EN397) and $F_{\max}^{\text{test}}$ is the maximal peak impact force specified in the test standards and measured in the tests, respectively. E_{std} (std = ANSI or EN397) and E_{cr} is the potential impact energy specified in the test standards and the critical impact energy measured in the tests, respectively. The safety factor ρ and safety margin η are defined in Eqs (2) and (3), respectively. $\rho > 1$ is required to pass the standardized tests.

evaluate the helmets' safety margin. Although the peak impact forces at the critical potential impact energy may still be well below the maximal allowable impact forces required by the standards, as illustrated in the current results, the helmets would become mechanically unstable in this condition (i.e., zero safety margin according to the proposed approach) and tend to lose their shock absorption capacities.

The proposed approach is not intended to replace the testing standards ANSI/Z89.1 or EN397, but to enhance the existing test standards to evaluate the performance of the helmets. The helmets passing the standardized tests will mean they are qualified for industrial applications. If helmets are further tested using the proposed approach to obtain the critical potential impact energy, we could tell the performance level of these helmets or how good these helmets are for head protection. If the existing standardized tests are comparable to a binary grade system (i.e., pass or fail), the proposed approach would provide a quantitative measurement or scale for the shock absorption performance of Type I industrial helmets.

The fundamental difference between the ANSI/Z89.1 and EN397 standards is that an impact velocity is specified in ANSI/Z89.1, whereas a drop height is specified in EN397 (Table 2). Physically, ANSI/Z89.1 designates a net kinetic energy involved in the impact, whereas EN397 designates a potential energy applied to the impactor. During the drop impact process, the potential energy of the impactor is converted into kinetic energy via the drop tower system which also has a frictional energy loss. These two approaches would be equivalent if the frictional energy loss of the system is negligible. However, the friction in the drop tower system is non-negligible. If the EN397 standard is applied, the kinetic impact energy will be different if different drop tower devices are used. In comparison, the ANSI/Z89.1 standard has a more precise description of the test condition. Theoretically, there is no concern of the frictional energy loss in ANSI/Z89.1, because it specifies the impact velocity that is associated with the net kinetic energy actually involved in the impact. However, if the ANSI/Z89.1 standard is applied, the drop tower system must first be calibrated to determine the system's frictional energy loss, whereas drop impact tests based on the EN397 standard can be conducted without pre-calibration tests. According to the observations on peak impact forces and analysis of the energy-based safety margin for a selected helmet model, our results suggest that the ANSI/Z89.1 standard is more stringent than the EN397 standard.

A limitation of the current study is that Type I helmets from only one representative model have been tested. Different shell materials and different suspension systems in different helmet models would likely result in different shock absorption characteristics. Therefore, different Type I helmet models are expected to have different critical impact energy values if tested using the proposed approach. However, the patterns of the general trends for the relationships between the peak impact force and potential impact energy for different Type I helmets should be consistent. The proposed approach will need to be further validated by conducting comprehensive impact tests using helmet samples of different models and by different manufacturers.

5. Conclusion

The current study developed a method to analyze the failure of Type I industrial helmets using the standardized testing setups and applied the proposed method to quantitatively evaluate the shock absorption performance of Type I industrial helmets. The relationships between peak impact force and potential impact energy for Type I helmets have been determined based on the impact tests using two different impactor masses (i.e., 3.6 kg and 5.0 kg). When the potential impact energy is smaller than the critical potential impact energy (E_{cr}), the peak impact forces are linearly dependent on potential impact energy; when the potential impact energy is greater than the critical potential impact energy (E_{cr}), the peak impact forces increase steeply with increasing impact energy. Helmets tend to become mechanically unstable at smaller potential impact energy when impacted with an impactor of larger mass. Furthermore, a concept of the safety margin for construction helmets based on potential impact energy is proposed to quantify the helmets' shock absorption performance in the current study.

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Conflict of interest

None of the authors of this manuscript has a conflict of interest.

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Disclaimer

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