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Modelling head impact safety performance of polymer-based foam protective devices

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Abstract

The aim of this paper is to investigate an iterative statistical procedure, based on a small and censored sample of impact test experiments, useful for interval estimation of head impact safety parameter as critical fall height of protective devices. An adaptive testing routine was developed that was mainly constituted by a series of at least four impact test experiments, followed by the comparison of at least two parameter estimates based on incremental exponential regression fittings and a final confirmation experiment. A total number of 23 protective devices, mainly made of polyethylene foam, were investigated in order to validate the adaptive routine. The routine, applied to critical fall height of protective devices, was 19 times convergent within a maximum of 6 impact test experiments. 4 times the sample was censored because the iterative procedure has exceeded the available number of specimens. Confidence intervals at the 90 % level were always less than 0.18 m. The applicability of the adaptive routine was satisfactory demonstrated with reference to devices made of PE-foam and safety threshold of peak acceleration a-max equal to 200 g. The target of a confidence interval below the state-of-art was achieved.

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*Keywords:*Sports Safety; ASTM F 1292; Impact Attenuation; Critical Fall Height

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1. Introduction

Sports area provides many opportunities for athlete's body to experience impacts such as player to player contact and collisions with facilities or equipments. Many studies conducted by international associations for health care, i.e. by Harmon et al. (2012), have shown high frequency of athlete traumas during sport activities, especially referring to team ball sports where protection devices are not strictly recommended by rules. In order to guarantee the passive safety of the athletes during sports practice, it appears to be necessary to install suitable impact protection devices, i.e., made of cellular foam. Klempner et al (2004) reported a significantly increased use of the latter in recent years due to their high impact attenuation properties.

On the other hand, international organizations for standardization such as CEN or ASTM provide testing procedures useful to obtain the impact attenuation properties, i.e. for gymnastic equipment or playground surfaces. These standards aim to identify a critical fall height (CFH) as the measure of impact attenuation of a specimen, which is related to a specified threshold such as a crucial head injury criterion (HIC) and/or peak acceleration (a-max) scores. For example, ASTM F 1292 (2004), defines an HIC score equal to 1000 or an a-max equal to 200 g as the limiting performance criterions. This standard requires an increasing of the drop height by 0.3 m until the result of impact tests exceeds the limiting performance criterions. The CFH of the tested surface shall then be rounded to the nearest whole foot (0.3 m) equal to or below the actual value. In previous studies by Costabile et al. (2013) it was found that testing with increments of 0.3 m lacked discriminatory power to assess CFH of low density polymer-based foam specimen. Furthermore, it was observed that the same materials exceeded a-max prior to HIC performance criterion. In addition, an exponential regression model was introduced by the same authors aiming to reach a more accurate CFH evaluation.

The aim of this paper is to define and to validate a novel statistical procedure. It is mainly based on at least three impact test experiments needed for the first estimation the head impact safety parameter CFH for polymer-based foam protective equipments to a confidence interval on a level of 90 %, less than 0.3 m within the minimum number of iterations.

2. Materials and Methods

2.1. Specimen

In this study 23 different types of protective devices, mainly made of fully cross-linked polyethylene closed cell foam, were tested. A typical device as shown in Fig. 1 was structured by overlapping of layers with different number (3; 4; 5; 6 layers), thickness (5; 10 mm), density (30; 60; 100 kg/m³), structural homogeneity (cut; full) and covering (1 mm). As required in ASTM F1292 the dimensions of each sample were 500 x 500 mm.

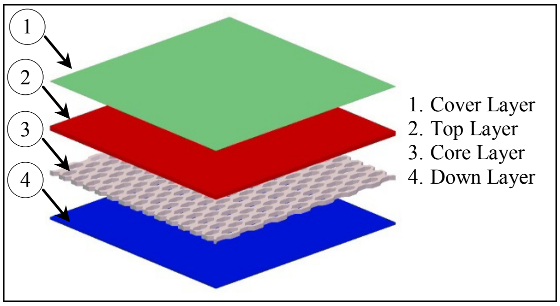

Fig. 1. Scheme of device structures

2.2. Apparatus

Fig. 2. Impact test apparatus

The testing apparatus (see Fig. 2) used in this study represented a guided drop tester as described in ASTM F 1292. It consisted of a vertical linear rail system (IGUS® GmbH, type DryLin® T) with a maximum drop height of 3 m. In parallel it offered a mechanical drop height adjustment and measurement framework. A hemispherical missile was lifted manually to an electromagnet attached to this framework. By switching on a power supply of the magnet the missile was released to a guided fall. As requested in the guidelines the missile incorporated a single axis accelerometer (Kistler Inc., type 8614A500M1, measurement range ±500 g). The velocity of impact was detected by a Laser sensor (Keyence Inc., type LK-G152, ±40 mm). Data recording was performed through an 8-channel compact measurement device (IMC Meßsysteme GmbH, type CS 7008). An Online FAMOS routine processed HIC scores, a-max and velocity for each impact test.

2.3. Impact test routine

In order to assess the head impact safety parameter CFH through the minimum number of impact test experiments (ITE) according to ASTM F 1292 requirements, an adaptive routine was implemented. It mainly consisted of a variable number of ITE (minimum 4) followed by numerical curve fittings (FIT, min. 2) and comparisons (min. 1). The output of a completed routine was the experimental validated CFH, the number of ITE and the confidence interval at the 90 % level. The nomenclature below structures the routine displayed in Fig. 3.

Nomenclature of the adaptive routine

n	number of impact test experiments	$n \geq 3$
m	number of curve fitting	$m=n-2$, $m \geq 1$
i	counter of impact test experiments	$i=1,\ldots, n$
k	counter of fittings and steps	$k=1,\ldots, m$
$a_{e,i}$	averaged a-max scores (of the 2nd and 3rd impact test) obtained with the i^{th} impact test experiment	
$h_{e,i}$	drop height scores obtained with the i^{th} impact test experiments	
$f_k(h)$	exponential regression model of the k^{th} curve fitting process	
$a_{f,k}$	averaged a-max scores obtained with the k^{th} curve fitting process	
$h_{f,k}$	fitted drop height obtained with the k^{th} curve fitting process	
N_{max}	maximum number of available specimens	
M_{max}	maximum number of curve fitting processes	

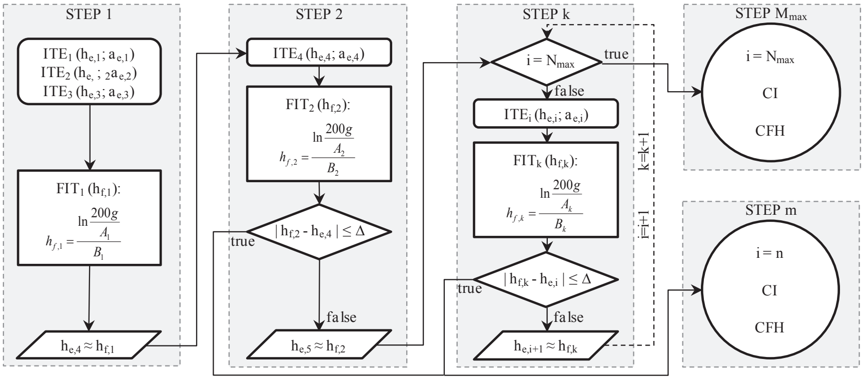

Fig. 3. Scheme of the adaptive routine

STEP 1: An entire ITE of one sample at a particular drop height $h_{e,i}$ consisted of a series of three consecutive impact tests (single impact events) with a time interval of 90 s. The performance parameter scores a-max and HIC were averaged for the 2nd and 3rd impact test. Starting with an ITE at the first trial height $h_{e,1}$ the drop height was increased in order to overcome the performance criterions and a 2nd and 3rd ITE performed using new specimens of the same protective device. Due to the specific impact attenuation properties of the tested devices, the consecutive drop height increments were adopted neglecting the recommendations of ASTM F 1292 (0.3 m). Thus, $h_{e,1}$ and increments were chosen by experience. Furthermore, HIC scores were not taken into account in the further numeric modelling because of the fact that all of the investigated devices have reached a-max performance criterion prior to HIC one's (acceleration limit of 200g prior to HIC limit of 1000).

Peak accelerations $a_{e,1;2;3}$ over drop heights $h_{e,1;2;3}$ were plotted and a curve fitting process performed (eq. 1) in order to calculate the fitted drop height $h_{f,1}$ for an $a_{f,1} = 200$ g. The curve fitting approach based on an exponential regression model, following the findings of Costabile et al. (2013) on head injury performance parameters, especially with regards to foam characteristics.

$$a_{f,k} = f_k(h) = A_k \cdot e^{(B_k \cdot h)} \tag{1}$$

STEP 2: The apparatus was then set to an approximated (rounded to the nearest 0.01 m) $h_{e,4} \approx h_{f,1}$, another ITE was conducted and the corresponding $a_{e,4}$ obtained. The procedure continued with a 2nd curve fitting process (eq. 1) by adding the 4th data point ($h_{e,4}$; $a_{e,4}$) into the regression model and receiving back an $h_{f,2}$ that was finally compared to the previous experimental one $h_{e,4}$. In this case, if a difference Δ of ±0.02 m occurred (as in Fig. 3), the routine ended and the output as described in the following step "m" was declared.

STEP k/m: The routine of experiment-fitting-validation was repeated (see STEPs 1,2,...,k in Fig. 3) until two condition types were achieved. In type I cases, the final fitted height $h_{f,m}$ was within the Δ-value compared to the previous experimental one $h_{e,n}$. Otherwise, in type II cases, the iterative procedure exceeded maximum number of available specimens. Then, to calculate a confidence interval $CI_{n,0.90}$ of $h_{f,m}$ in terms of a confidence level of 90 %, the standard error of the estimate s_{EST} was multiplied by the student t_n value (eq. 2). CFH was calculated as the lower confidence interval by means of $h_{f,m}$ and $CI_{n,0.90}$. In order to refer CFH to a free fall, it was multiplied by the velocity ratio of the testing apparatus (eq. 3). The latter (≤ 1.0, due to its definition in physics) was determined by means of friction in the linear guidance system, or rather, of measured and theoretical velocity of the missile.

$$CI_n = t_n \cdot s_{EST} \tag{2}$$

$$\widehat{CFH} = (h_{f,m} - CI) \cdot \left(\frac{v_{measured}}{v_{theoretical}} \right)^2 \tag{3}$$

3. Results

In Fig. 4, an example of the adaptive routine for a 4 layers protective device (thickness 35 mm; density 30 kg/m³ in core layers, 100 kg/m³ in the outer layers) is given. The routine ended as a type I case after 5 ITE with a $h_{f,3}$ of 0.86 m ±0.05 m (Fig. 4-c). CFH was calculated to be 0.63 m, due to CI and the velocity ratio.

In the first fitting (see Fig. 4-a) the exponential model gave an $h_{f,1}$ of around 0.96 m. The consecutive ITE from $h_{e,4}$ (Fig. 4-b) resulted in an $a_{e,4}$ of 286.53 g. A new fitting was performed taking previously collected experimental data points into account. Thus, the so obtained height $h_{f,2}$ was compared to the previous experimental one $h_{e,4}$. This resulted in a negative proof and the routine continued with an additional ITE (Fig. 4-c). By applying a new fitting using five experimental data points the drop height $h_{f,3}$ was calculated to be around 0.86 m, that was in the interval of ±0.02 m around $h_{e,5}$. This condition confirmed the end of the process.

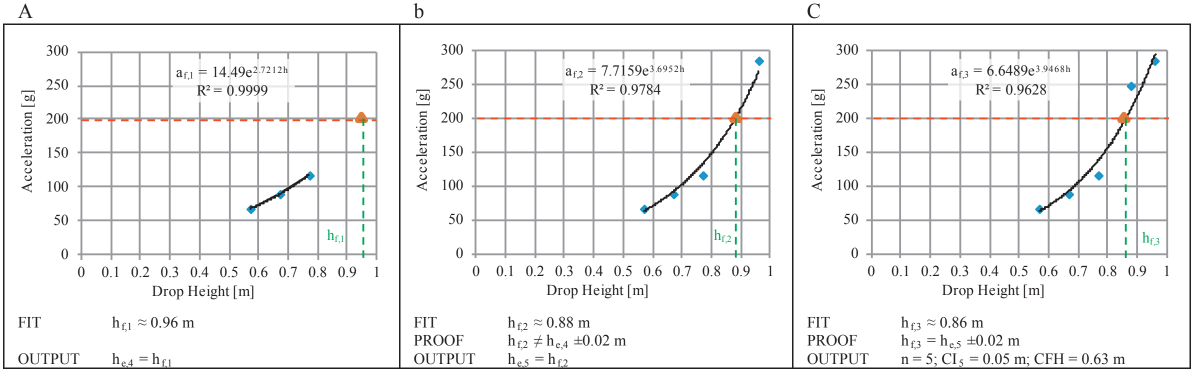

Fig. 4. Routine example for a 4 layers device (a) Step 1; (b) Step 2; (c) Step 3=m

An overview of the received results is displayed in Fig. 5-a. Having examined 23 impact protective devices, the routine completed in type I cases for a total number of 19 within 4 ITE (13 devices), 5 ITE (3 devices) up to 6 ITE (3 devices). Due to a scant number of specimens the routine was completed as type II cases for 4 protective devices. The confidence intervals revealed a maximum of 0.18 m. Arithmetic mean of CI in the total number of 23 devices was (0.07 ±0.04) m. In Fig. 5-b the frequency distribution of the parameter CI after having executed 4 ITE is illustrated in 8 classes up to 0.025 m each.

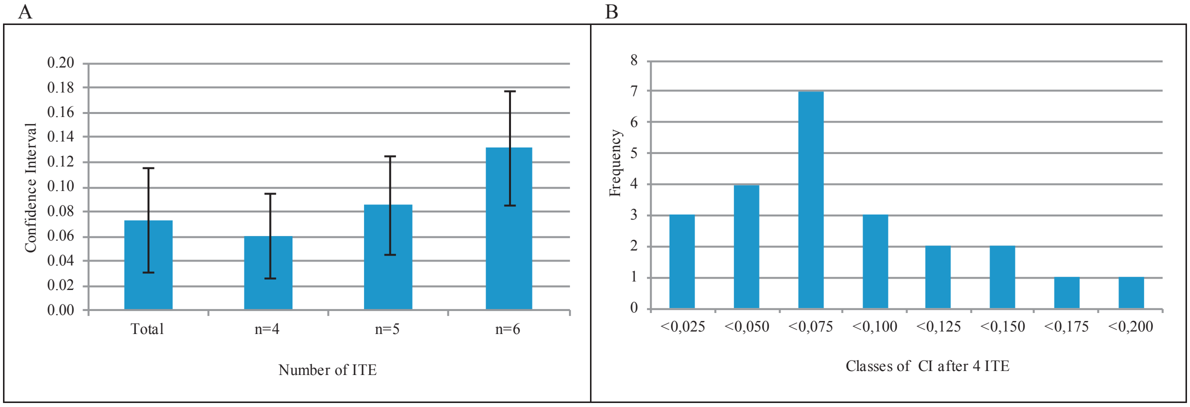

Fig. 5. (a) Arithmetic mean of final CIs; (b) frequency distribution of CI-classes after 4 impact test experiments

4. Discussion

It was shown that a maximum number of six ITE allowed obtaining the CFH of various impact protection devices in consideration of measurement uncertainty, expressed by the confidence interval on a 90 % level of the estimated drop height. In order to respect the safety function of this kind of equipment, CFH was calculated as the minimum within the confidence interval, indicating that 90 % of impacts from that height would cause peak accelerations less than (or equal) 200 g.

Compared to the state of the art, the resolution of CFH for the protective devices under examination was refined to approximately 2 times by applying the adaptive routine. The maximum confidence interval described in ASTM F 1292 is 0.29 m. Within this study the maximum CI was 0.18 m in the guided fall. Taking the typical velocity ratio between measured and theoretical velocity of the used apparatus into account, the maximum CI was 0.14 m referring to a free falling object as it is done in the test standard ASTM F 1292.

5. Conclusions and Outlook

Within this work an adaptive routine was achieved aiming to experimentally obtain the CFH of impact protection devices on a 90 % level of confidence. Therefore, an adaptive routine was used incorporating 3 initial ITE. The so obtained a-max – drop height behaviour was used to run an exponential regression in order to calculate the CFH of the device in reference to an a-max of 200 g. The experimental validation of that fitted height by performing a 4th ITE revealed different characteristics, dependent on the choice of the 3 initial drop heights and obtained accelerations. In order to minimize the number of ITE to complete the adaptive routine by increasing the precision of the 1st fitting process, it is required to develop a method that allows to find appropriate $h_{e,1;2;3}$. To this end, the initial experiments $ITE_{1;2;3}$ should approximate the performance criterion as close as possible. Therefore, it is necessary to investigate into the relation of foam density as well as device thickness referring to CFH.

Even if the experiments were carried out by centring on the a-max performance criterion (due to the specific behaviour of the PE-foam based devices), further research efforts will be carried out to improve regression fittings and to test the goodness of results for other performance criterion as HIC of 1000 and for other material as well.

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