Empirical Models for Estimating Maximum Allowable Mass for Personal Fall Arrest Energy Absorbers

Chensong Dong [a, *], Yang Miang Goh [b]

[a] Department of Mechanical Engineering, Curtin University, GPO Box U1987, Perth, Western Australia 6845, Australia

[b] School of Public Health, Curtin Health Innovation Research Institute (CHIRI), Faculty of Health Sciences, Curtin University, GPO Box U1987, Perth, Western Australia 6845, Australia

Abstract

Two criteria for determining the capacity of personal fall arrest energy absorbers are maximum extension and maximum arrest force. There are concerns that despite the increasing weight of workers, most energy absorbers of personal fall arrest systems are only tested to 100kg. In a previous study, a series of dynamic drop tests based on the Australian and New Zealand fall protection equipment standard, AS/NZS 1891.1:2007, were conducted on seven types of energy absorbers (total of 31 samples). Based on the data from the experiments, empirical models for the extension and maximum arrest force are presented in this paper. Using these models, the maximum allowable mass can be calculated.

Keywords: Occupational safety; working-at-height; fall from height; fall arrest; energy absorber

1 Introduction

Besides being a major health concern, obesity has been associated with traumatic occupational injuries (Ostbye, 2007; Pollack, 2007) and impose serious occupational safety and health concerns (Australian Safety and Compensation Council, 2008). Pollack (Pollack, 2007) identified that the

---

[*] Corresponding author (Email: c.dong@curtin.edu.au)

association between obesity and traumatic injuries is due to factors such as fatigue or sleepiness, physical limitations, ergonomics, poor health, lower tolerance to hazardous mechanical energy, and lack of comfort, fit and availability of personal protective equipment (PPE). The problem of lack of comfort, fit or availability of PPE for obese workers is contributed by the lack of current anthropometric data that reflects the increased weight and size of workers (Australian Safety and Compensation Council, 2009; Barroso, 2005). The lack of current anthropometric data can also lead to obese workers using PPE not designed for their body weight and related circumferences (Australian Safety and Compensation Council, 2009). Such incompatibility can cause PPE failure and thus injuries or even fatalities.

Personal fall arrest system is a type of personal protective equipment (PPE) that is designed to absorb the energy created by its user during an accidental fall from height. Personal fall arrest system is an indispensable PPE in workplaces that are dynamic and require employees to work at height, for e.g. construction (Beavers, 2009; Bobick, 2004; Huang & Hinze, 2003; Kines, 2002; Sa, 2009), building maintenance (Chan, 2008) and aircraft maintenance (Neitzel, 2008).

A typical personal fall arrest system is made up of the following components: (1) full body harness, (2) connectors, (3) lanyard, (4) energy absorber, and (5) anchor. Each component is critical in safely arresting a fall and this paper evaluates the capacity of energy absorbers in relation to heavy workers. The Canadian Standards Association (2005, pp. 5) defines an energy absorber as “any device that dissipates kinetic energy and does not return it to the system or into the human body.” In most personal fall arrest systems, the energy absorber is the key component for absorbing the energy created during the user’s fall. Most fall arrest equipment standards (e.g. ANSI/ASSE, 2007; British Standards Institution, 1993; Canadian Standards Association, 2005; Standards Australia/ Standards New Zealand, 2007) require personal fall arrest systems to be dynamically tested using a test mass of 100kg. In view of the increasing weight of workers there are concerns that the 100kg test mass underestimates the weight of heavy workers (Haines, 2005; Wingfield, 2008). According to Safe Work Australia (Safe Work Australia, 2011), falls from height is the number three cause of work-related fatalities.

The recent studies on fall arrest equipment commissioned by the Health and Safety Executive (Crawford, 2003; Haines, 2005; Riches, 2002; Seddon, 2002) focused on the dynamic performance testing of fall arrest equipment. In addition, the influences of weather conditions (Baszczynski, 2004) and anchor devices (Baszczynski, 2006) were studied. However, none of these studies focused on the capacity of energy absorbers in relation to heavy workers.

Two characteristics of energy absorbers specified in standards are the maximum arrest force, F_m, and the extension of energy absorbers, X. Based on Hooke's law, the analytical models for F_m and X are given by

$$F_m = mg\left[1+\sqrt{1+\frac{2kh}{mg}}\right] \tag{1}$$

$$X = \frac{mg}{k}\left[1+\sqrt{1+\frac{2kh}{mg}}\right] \tag{2}$$

where m = test mass; k = stiffness of the energy absorber; and h = free fall distance.

However, these analytical models neglected the difference of static and dynamic properties and may not be directly applicable to the analysis of fall arrest energy absorbers. To design and assess energy absorbers, it is essential to conduct dynamic tests, as textile materials (polyamide (PA), polyester (PES), etc.) usually show a velocity-dependent, visco-elastic behaviour (Bao, M., M., Nakazawa, & A., 2002). From the dynamic tests conducted by Spierings and Stampfli, it is shown that the maximal forces are reduced while the corresponding elongations are in the same range as in quasistatic tests (Spierings & Stampfli, 2006). For the indicated yarns, a higher test impact velocity results in a higher force-level in the plateau section and a reduced maximal strength, respectively, which allows to absorb more energy at lower forces—a general goal in engineering energy-absorbing products. From this viewpoint, using the analytical models will significantly overestimate the capacity of energy absorbers and lead to potential catastrophic accidents.

In our previous research (Goh & Love, 2010), the capacity of fall arrest energy absorbers in relation to the weight of heavy workers was evaluated for the purpose of providing recommendations for improvements to current standards. The study found that when exposed to a worst credible scenario fall, heavy workers using fall arrest energy absorbers certified to current standards are likely to experience high arrest force or the energy absorber may reach maximum extension, which may result in injuries. Because of the cost associated with the experiments, limited samples were obtained. It is thus desirable to have a generic model to relate the maximum arrest force and extension to mass. This model can help adjust the usage of fall arrest equipment by heavy workers, and also serve as a guideline for personal fall arrest system design. In this paper, preliminary empirical equations were developed to estimate the maximum arrest force and the extension of energy absorbers analytically.

2 Methods

2.1 Experiment Setup and Procedure

The details of experiments can be found in our previous study (Goh & Love, 2010). However, for completeness, the experiment setup and procedure are briefly presented here. Seven types of energy absorbers, commonly used in Australia and certified to the AS/NZS 1891.1:2007 standard (Standards Australia/ Standards New Zealand, 2007) were used in this study. These energy absorbers were identified by a fall protection expert, with at least 20 years of practical experience, and all were made of polyamide webbings that are stitched or woven together (Work at Height Safety Association, 2006).

The experiment setup, in accordance to Appendix H of AS/NZS 1891.1:2007, is shown in Figure 1. For each test, the energy absorber was connected to the rigid test mass and the anchor on a rigid structure. The test mass was then hoisted to a suitable height that would provide a free fall distance of 3.8 m and the horizontal distance was minimised (maximum of 300 mm). The hoist was connected to the test mass via a quick release mechanism that limited horizontal movement during the initiation of the drop. All samples were only tested once. Two trial runs were conducted to familiarise the technicians with the procedure and to ensure that the setup was functioning as expected.

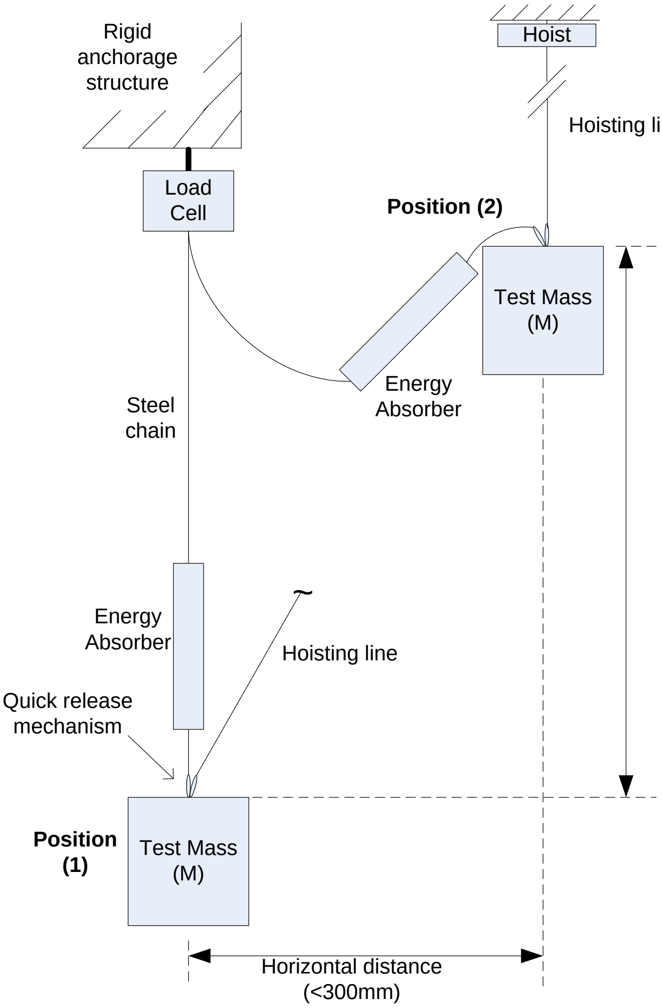

Figure 1: Test set up in accordance to AS/NZS 1891.1:2007

For each type of energy absorber, the experiment started with a 100 kg test mass and the test mass was increased progressively at 10 kg interval until the capacity was determined, i.e. when the maximum extension reached 1.75 m, as specified in AS/NZS 1891.1:2007, or bottom out started to occur. A total of 31 samples of the seven types of energy absorbers (types A to G) were conducted and they are summarised in Table 1.

Table 1: Experiments conducted

Specimen No.	Type	Mass (kg)
A-01	A	100
A-02	A	120
A-03	A	120
A-05	A	110
B-01	B	110
B-02	B	100
B-03	B	120
B-04	B	120
C-01	C	110
C-02	C	100
C-03	C	120
C-04	C	130
C-05	C	130
D-01	D	110
D-02	D	100
D-03	D	120
D-04	D	120
E-01	E	110
E-02	E	100
E-03	E	120
E-04	E	120
F-01	F	110
F-02	F	100
F-03	F	110
F-04	F	120
G-01	G	110
G-02	G	100
G-03	G	120
G-04	G	130
G-05	G	130
G-06	G	140

2.2 Fall Arrest Analysis

In order to understand the impact due to fall arrest, the kinetics during fall arrest were analysed. If the positive direction of velocity is defined downwards, the variation of velocity during fall arrest is given by

$$\Delta v = \left(g - \frac{F}{m} \right) t \tag{3}$$

where F = arrest force.

The arrest forces and velocities of specimen A-01 (test mass 100 kg, no bottom out) and A-02 (test mass 120 kg, bottom out) are shown in Figure 2.

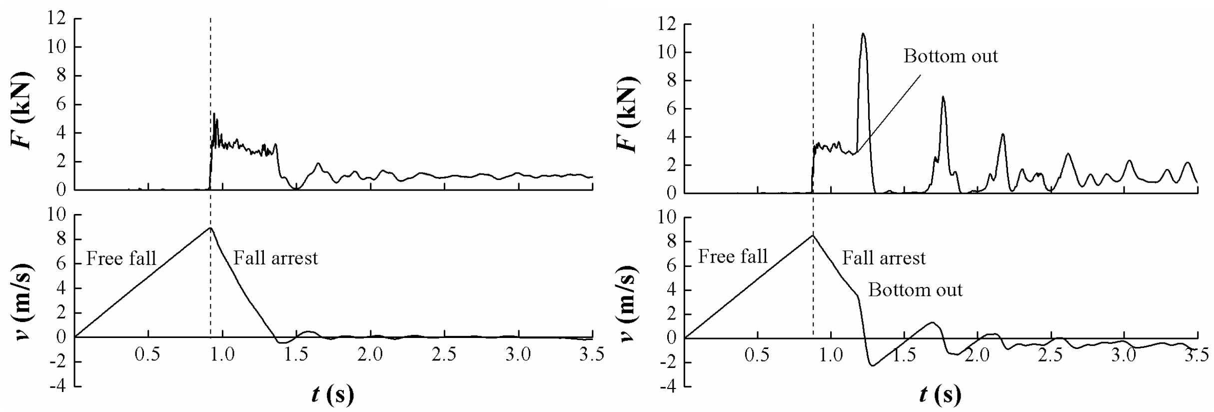

Figure 2: Arrest force and velocity during fall (Left: *m* = 100 kg; right: *m* = 120 kg)

It is seen from Figure 2 that maximum extension, or bottom out, does not occur when the test mass is 100 kg. The velocity linearly increases to the maximum at t_0 = 0.88 s and then linearly decreases due to the fall arrest until t_1, when the velocity is zero. After that oscillation is induced due to the inertial effect until it is fully damped out. When the test mass was 120 kg, the energy absorber bottomed out. This is indicated by a sharp peak in the force-time chart. It is seen from the velocity-time chart that when bottom out occurs, there is a sudden increase in deceleration when the energy absorber reaches its maximum extension.

3 Empirical Model Development

3.1 Extension

The capacity of an energy absorber is limited by its maximum extension (first test criteria). In AS/NZS 1891.1:2007 and EN355:2002 (British Standards Institution, 2002), the maximum allowable extension of the energy absorber is 1.75m. Our previous study (Goh & Love, 2010) show that the extension of energy absorbers is proportional to test mass until bottom out occurs, where the maximum extension, X_m, is reached, as shown in Figure 3.

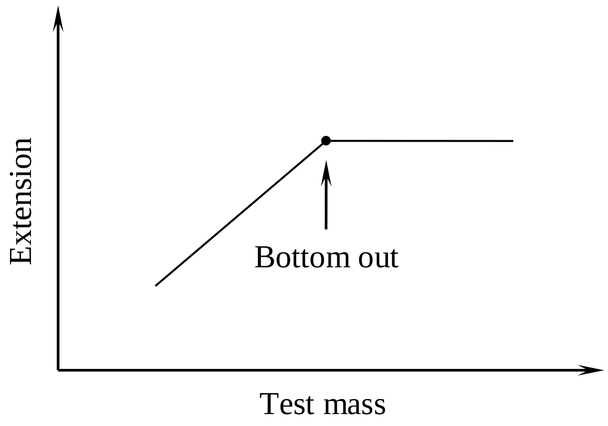

Figure 3: Extension of energy absorbers vs. test mass

Despite the same maximum allowable extension specified in the standards, the functional relationships between the extension and test mass vary from one type of energy absorbers to another. This may be due to different designs of the manufacturers. For each type of energy absorber, a linear regression model was fitted to the experimental data, i.e.

$$X = X_0 + km \tag{4}$$

where X_0 is the initial extension when there is no mass and k is the compliance (m/kg). Since X_0 is derived by regression, its value is sometimes negative.

Table 2: Intercepts and slopes of linear regression models for extension

Type	Initial extension (m)	Compliance (m/kg)	Bottomed out extension
A	-0.05	0.016	1.73
B	1.141	0.0029	1.715
C	-0.498	0.0167	1.68
D	0.23	0.012	1.83
E	0.15	0.0125	1.76
G	-0.67015	0.01726	–

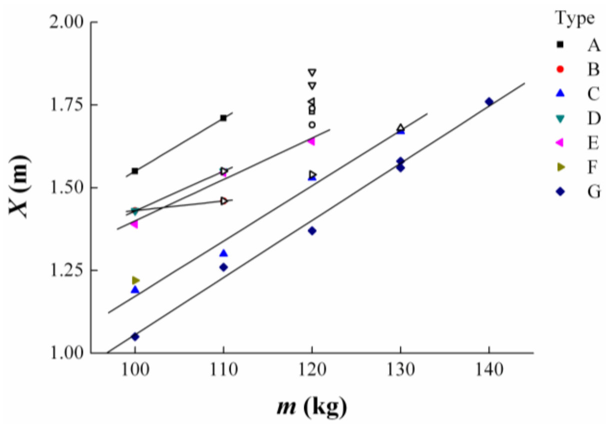

Figure 4: Extension of energy absorber vs. test mass (Open symbols stand for bottomed out)

It is seen from Figure 4 that except type B, all the other energy absorbers have similar compliances that range from 0.012 m/kg to 0.017 m/kg, which is the increase of extension when test mass increases by 1 kg. Types A and G form the upper bound and lower bound, respectively. For type G energy absorbers, the extension was also derived by the analytical model given by Eqn. 2. A comparison of the empirical model and analytical model derived based on Hooke's Law is shown in Figure 5, and it is clearly shown that the analytical model significantly underestimates the extension in fall arrest, and the difference increases with test mass. To account for this difference, Eqn. 2 is modified to be

$$X = \frac{mg}{k}\left[1 + \sqrt{1 + \frac{2kh}{mg}}\right]\frac{m}{c} \qquad (5)$$

where c is a constant.

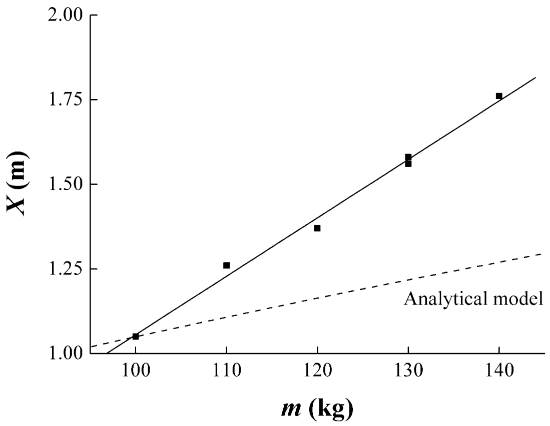

Figure 5: Comparison of developed model and analytical model on extension for type G energy absorbers

Even though the experimental data does not facilitate the development of a generic model for all energy absorbers, the linear regression model for type A can be used as a conservative estimate. Based on the maximum allowable extension (1.75 m) specified in AS/NZS 1891.1:2007 it is calculated that the maximum allowable mass is 112.5 kg. It should be noted that this regression model for type A was developed based on only two data points, thus it is significantly affected by the variations.

3.2 Maximum Arrest Force

The arrest force or arrest deceleration influences the probability of injury (Eiband, 1959). In AS/NZS 1891.1:2007 and EN 355:2002, the maximum allowable arrest force is 6 kN. The value of 6 kN was conservatively determined based on experiment and tests on ejection seats and parachutes in military settings (Crawford, 2003). Despite having referred to similar set of literature and data, the North American standards (ANSI/ASSE, 2007; Canadian Standards Association, 2005) have selected 8 kN as the maximum allowable arrest force for personal arrest systems. As a compromise, 7 kN was used as the maximum allowable arrest force in this study. Note that the test criteria are meant to facilitate estimation of capacity in accordance to the research purpose; they do not imply that the energy absorbers tested are unsafe.

The maximum arrest force from our previous experiments is shown in Figure 6.

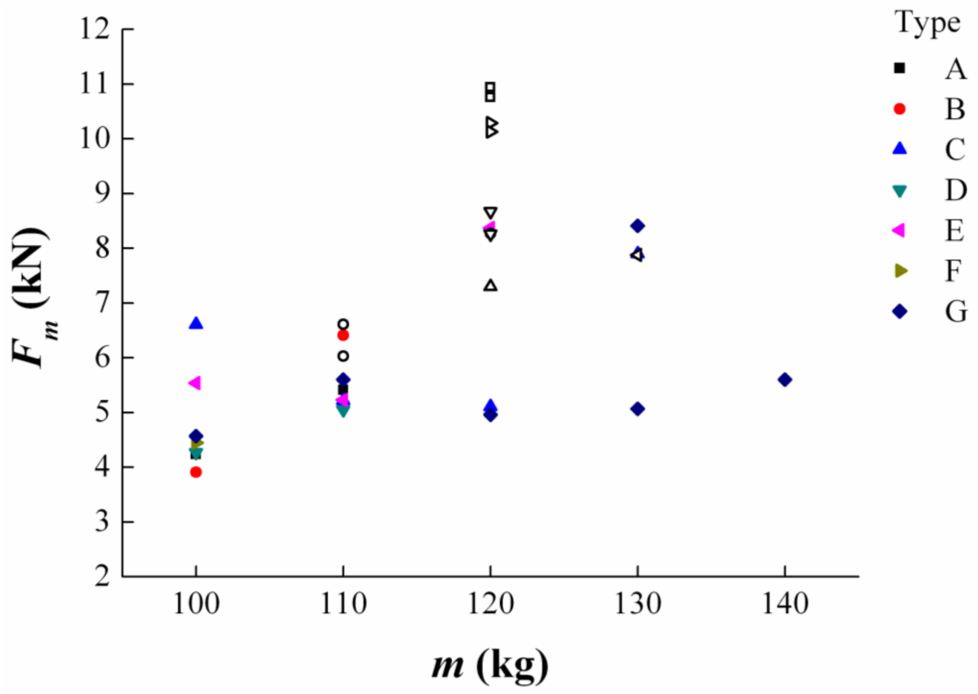

Figure 6: Maximum arrest force vs. test mass (Open symbols stand for bottomed out)

To enable employers to determine the risk that workers of different body mass are exposed to, it is important to understand the relationship between the maximum arrest force (F_m) and mass. For this reason, the maximum arrest force of the energy absorber samples that did not bottom out during the experiment were statistically analysed for each test mass. An Anderson-Darling normality test (NIST/SEMATECH) was conducted ($A^2 = 0.6$, p-value = 0.071) and the data can be regarded as normally distributed. Figure 7 shows the distribution of F_m for 100 kg test mass. From this perspective, because of the limited number of samples, the data of all types of energy absorbers were tested as a whole population to investigate the influence of test mass on the maximum arrest force. This is reasonable because (1) all energy absorbers are made according to the same standard, and (2) the widths of all energy absorbers are similar. Thus, the stresses induced during fall arrest are similar and the data from all energy absorbers are comparable.

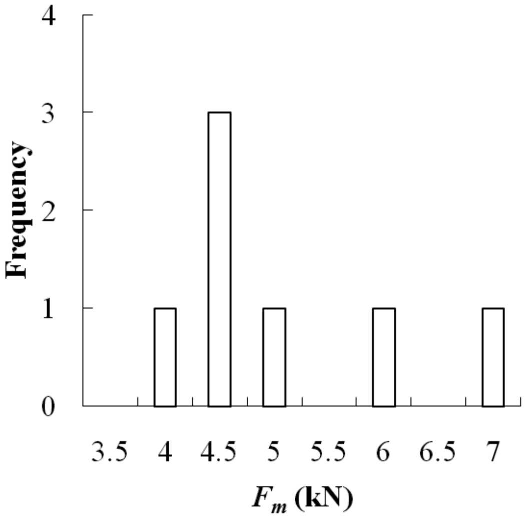

Figure 7: Distribution of maximum arrest force when *m* = 100 kg

The means and standard deviations of the maximum arrest force for all test masses are given in Table 3.

Table 3: Mean and standard deviation of maximum arrest force

m (kg)	F_m (kN)	
	Mean	Standard deviation
100	4.799	0.877
110	5.487	0.447
120	6.147	1.573
130	7.127	1.469

The mean maximum arrest force is given in Figure 8. It is seen from Figure 8 that the mean maximum arrest force is proportional to test mass and a power function can be fitted to the data as

$$F_{mavg} = 4.75\left(\frac{m}{100}\right)^{1.51} \tag{6}$$

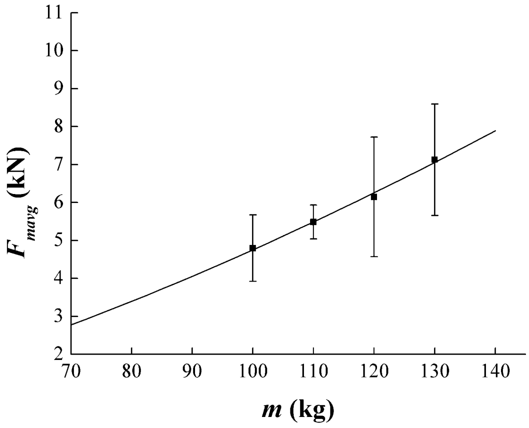

Figure 8: Average maximum arrest force vs. test mass

However, using the mean will result in a number of instances that exceed the standards and may cause serious injuries. Thus, instead of the mean, the upper bound of the test data is used, and the regression model is

$$F_m = 6.61\left(\frac{m}{100}\right)^{1.29} \tag{7}$$

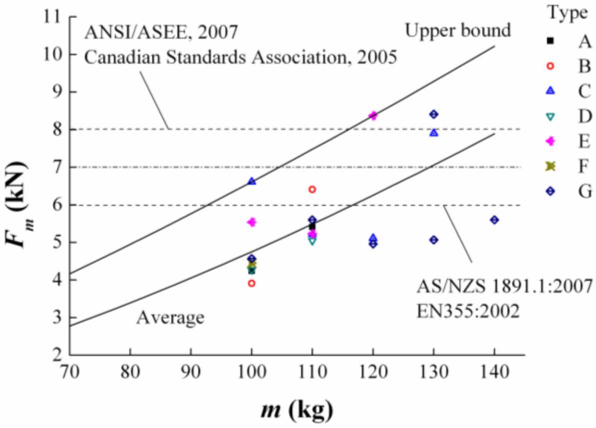

Figure 9: Developed model for maximum arrest force

The maximum allowable mass can be derived from Eqn. 7, which reads

$$m_{allow} = 100\left(\frac{F_{allow}}{6.61}\right)^{\frac{1}{1.29}} \tag{8}$$

The maximum allowable masses calculated using Eqn. 8 in accordance to different standards are shown in Table 4. It is seen from Table 4 that the average model significantly overestimates the maximum allowable mass.

Table 4: Calculated maximum allowable mass

	Maximum allowable mass (kg)	
	Upper bound model	Average model
AS/NZS 1891.1:2007 EN355:2002	93	117
Compromised standard in our study	105	129
ANSI/ASEE2007, Canadian Standards Association, 2005	116	141

A comparison of the developed model and analytical model is shown in Figure 10, and it is clearly shown that the analytical model based Eqn. 1 significantly underestimates the maximum arrest force.

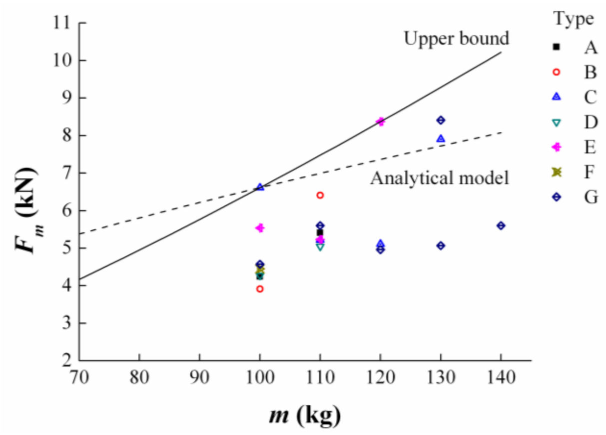

Figure 10: Comparison of developed model and analytical model on maximum arrest force

4 Conclusions

A series of dynamic drop tests based on the Australian and New Zealand fall protection equipment standard, AS/NZS 1891.1:2007, were conducted on seven types of energy absorbers (total of 31 samples). Based on the data from the experiments, preliminary empirical models for the extension and maximum arrest force are presented in this paper. Using these models, the maximum allowable mass can be calculated. In comparison to the analytical models based on Hooke's Law, which ignore the dynamic effects of fall arrest, the proposed models are based on the experimental data, and thus provide more reliable results. The proposed models can assist safety or technical specialists determine the allowable mass of workers when using personal fall arrest equipment.

It should be noted that the presented models are preliminary ones being developed from experimental data. Only the energy absorber instead of the whole fall arrest system was modelled. The extension model is only based on two data points. The accuracy and reliability are also limited by the sample size. The reliability of the models can be improved with more data being available. Caution must be taken when using these models due to these limitations.

References

ANSI/ASSE. (2007). ANSI/ASSE Z359.1-2007 Safety requirements for personal fall arrest systems, subsystems, and components. *American Society of Safety Engineers/ American National Standards Institute, Illinois*.

Australian Safety and Compensation Council. (2008). Overweight and obesity: Implications for workplace health and safety and workers' compensation (Publication. Retrieved October 1, 2009, from http://safeworkaustralia.gov.au/:

Australian Safety and Compensation Council. (2009). Sizing up Australia: How contemporary is the anthropometric data Australian designers use? (Publication. Retrieved September 1, 2009, from http://safeworkaustralia.gov.au/:

Bao, L., M., S., M., T., Nakazawa, M., & A., S. (2002). Restitution characteristics of yarn in the axial direction. *Textile Research Journal, 72*(8), 689-692.

Barroso, M. P. e. a. (2005). Anthropometric study of Portuguese workers. *Int. J. Ind. Ergon, 35*, 401-410.

Baszczynski, K. (2004). Influence of weather conditions on the performance of energy absorbers and guided type fall arresters on a flexible anchorage line during fall arresting. *Safety Science, 42*, 519-536.

Baszczynski, K. (2006). The influence of anchor devices on the performance of retractable type fall arresters protecting against falls from a height. *Int. J. Occup. Saf. Ergon., 12*, 307-318.

Beavers, J. E. e. a. (2009). Steel erection fatalities in the construction industry. *Journal of Construction Engineering and Management-ASCE, 135*, 227-234.

Bobick, T. G. (2004). Falls through roof and floor openings and surfaces, including skylights: 1992-2000. *Journal of Construction Engineering and Management-ASCE, 130*, 895-907.

British Standards Institution. (2002). BS EN 355:2002 - Personal protective equipment against falls from a height - Energy absorbers. *British Standards Institution, London*.

Canadian Standards Association. (2005). Z259.11-05 Energy absorbers and lanyards. *Canadian Standards Association, Ontario*.

Chan, A. P. C. e. a. (2008). Work at height fatalities in the repair, maintenance, alteration, and addition works. *Journal of Construction Engineering and Management-ASCE, 134*, 527-535.

Crawford, H. (2003). HSL/2003/09 Survivable impact forces on human body constrained by full body harness (Publication. Retrieved April 15, 2008, from Health and Safety Executive, http://www.hse.gov.uk/:

Eiband, A. M. (1959). Human tolerance to rapidly applied accelerations - A summary of the literature. *NASA Memorandum 5-19-59E, NASA, Washington D.C.*

Goh, Y. M., & Love, P. E. D. (2010). Adequacy of personal fall arrest energy absorbers in relation to heavy workers. *Safety Science, 48*(747-754).

Haines, V. e. a. (2005). Research Report 342 Revision of body size criteria in standards - Protecting people who work at height. *Health and Safety Executive, London*.

Huang, X. Y., & Hinze, J. (2003). Analysis of construction worker fall accidents. *Journal of Construction Engineering and Management-ASCE, 129*, 262-271.

Kines, P. (2002). Construction workers' falls through roofs: Fatal versus serious injuries. *Journal of Safety Research, 33*, 195-208.

Neitzel, R. L. e. a. (2008). Exposure to fall hazards and safety climate in the aircraft maintenance industry. *Journal of Safety Research, 39*, 391-402.

NIST/SEMATECH. e-Handbook of Statistical Methods (Publication. Retrieved 27 April 2010, from http://www.itl.nist.gov/div898/handbook/:

Ostbye, T. e. a. (2007). Obesity and workers' compensation - Results from the duke health and safety surveillance system. *Archives of Internal Medicine, 167*, 766-773.

Pollack, K. M. e. a. (2007). Association between body mass index and acute traumatic workplace injury in hourly manufacturing employees. *American Journal of Epidemiology, 166*, 204-211.

Riches, D. (2002). 411/2002 Analysis and evaluation of different types of test surrogate employed in the dynamic performance testing of fall-arrest equipment. *Health and Safety Executive, London*.

Sa, J. e. a. (2009). Comparison of risk factors for falls from height between commercial and residential roofers. *Journal of Safety Research, 40*(1), 1-6.

Safe Work Australia. (2011). Work-related traumatic injury fatalities, Australia 2008–09 (Publication., from http://safeworkaustralia.gov.au/:

Seddon, P. (2002). Contract Research Report 451/2002 Harness suspension: review and evaluation of existing information (Publication. Retrieved April 15, 2008, from Health and Safety Executive, http://www.hse.gov.uk/:

Spierings, A. B., & Stampfli, R. (2006). Methodology for the development of an energy absorber: Application to worker security ropes. *International Journal of Impact Engineering, 32*, 1370-1383.

Standards Australia/ Standards New Zealand. (2007). AS/NZS 1891.1-2007 Industrial fall-arrest systems and devices - Part 1: Harnesses and ancillary equipment (Publication. Retrieved January 8, 2008, from Standards Australia Online, http://www.saiglobal.com:

Wingfield, R. (2008). Fall protection for the heavy worker. In R. Wingfield (Ed.), *International Fall Protection Symposium*. Las Vegas: International Fall Protection Society.

Work at Height Safety Association. (2006). WAHSA technical guide note no. 4 - Guidance on the use of single and twin energy absorbing lanyards (Publication. Retrieved March 13, 2009, from www.wahsa.org.uk: