Feasibility of Newton's cradle coupled with particle image velocimetry to examine the rockfall impact-energy-absorbing material

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ABSTRACT

The Rock Shed with energy-absorbing system have been used to prevent the slope rockfall disaster in recent years. To study the effect of energy-absorbing system, an expensive and disposable full-scale test was usually adopted. This study was effort to develop a new technique to examine the characteristics of energy-absorbing material using Newton's cradle model coupled with contact and non-contact measurements. The two contact measurement device, accelerometer and dynamic load cell, was embedded in cradle spheres. During the testing, non-contact measurement method, particle image velocimetry (PIV), was synchronized conducted. Therefore, the local/global displacement and acceleration field with respect to energy-absorbing characteristics of material subjected to impact force can be obtained. In this study, the Expandable Polystyrene (EPS) was used as an energy-absorbing material to test the feasibility of the proposed method.

Keywords: Rockfall, Newton's cradle, Particle image velocimetry (PIV), Expanded Polystyrene (EPS), Impact energy dissipation

1 INTRODUCTION

Because of steep terrain, loose soil, seasonal rainfall, and frequent typhoons, rockfalls often occur in Taiwan, causing death and property damage. Global climate change has also led to an increase in regional extreme rainfall events. Under such conditions, the frequency and scale of rockfalls are increasing. Therefore, it is an important issue to reduce the rockfall damage in Taiwan to enhance transportation safety for the public. In general, rockfall protection techniques aim to reduce rockfall kinetic energy. Japan has similar conditions as Taiwan and previously implemented a technique in which sand was placed on the roof of rock shed to provide cushion to diminish the impact force of a rockfall. Japan later developed a three-layer cushion structure composed of sand, reinforced concrete (RC) slabs, and EPS (Fig. 1). To assess the reliability and validity of the designed experiment for evaluating the behavior of energy-absorbing materials (i.e., expanded polystyrene; EPS), this study refined the conventional full-scale rockfall experiment using a Newton's cradle test.

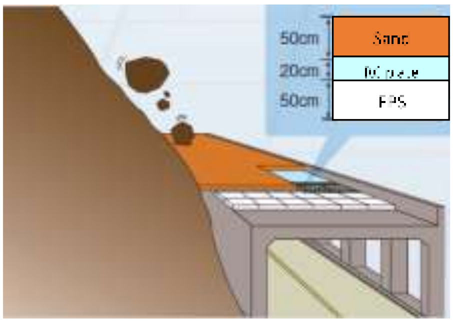

Fig. 1. Japanese three-layer cushion structure (https://www.co-jsp.co.jp/product/product04_2.html).

2 ENERGY-ABSORBING MATERIAL: EPS

Energy-absorbing materials are also known as cushioning materials, among which foam materials are the most commonly used. Known for their excellent gas storage capability and porous structure that can sustain severe plastic deformation, foam materials are light and functional for soundproofing, thermal insulation, and energy absorption. Examples of foam materials include Expandable Polystyrene (EPS), Expandable Polyethylene (EPE), and Expandable Polypropylene (EPP).

EPS is a solid compound obtained from styrene polymerization. In 1839, a German, Eduard Simon, extracted EPS from natural resins. In 1930, Dow Chemical Company produced styrene monomers by pyrolyzing ethylbenzene and in 1941 began to manufacture commercial EPS particles (Scheirs and Priddy 2004). EPS materials are lightweight and exhibit superior shock-absorbing ability, thermal retentivity, constructability, and low hygroscopicity, all of which render them highly useful for use in engineering tasks.

3 OPTICAL IMAGING TECHNOLOGY

The relationship between displacement and deformation can be determined by incorporating optical noncontact measurement with the theory of morphing. During measurement, the involved coordinate systems must be corrected to prevent optical deformation and image distortion (Yang et al. 2012). Sutton (2009) clarified the relationships between world coordinates, camera coordinates, normalized coordinates, and image coordinates (Fig. 2). Using the Camera Calibration Toolbox for Matlab (CCTB), Saurger (2013) acquired relevant intrinsic and extrinsic parameters in a camera without needing to perform calculations. The author proceeded to calibrate a dual-camera stereo system for three-dimensional stereo triangulation measurement.

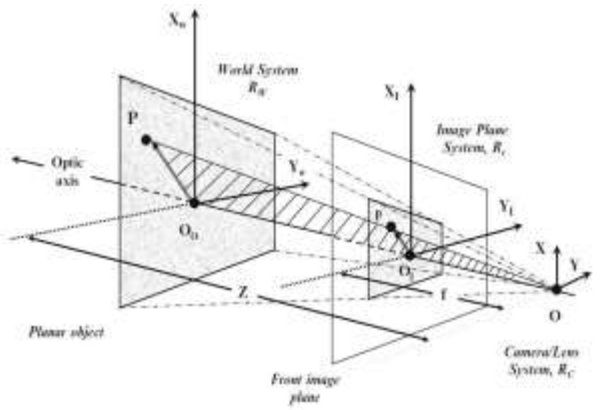

Fig. 2. Relationships between world, image, and camera coordinates.

4 EXPERIMENTAL DESIGN

4.1 Preparation of EPS

The weight of an EPS particle is roughly 1/100 that of a sand particle (Chen et al. 2015). The thin slice EPS with 20 kg/m^3 unit weight was used in this study. EPS is a superior energy-absorbing material, and this study conducted a compression test on EPS according to the JISK 7220 regulations to evaluate whether EPS would meet the requirements stated in the Handbook of SAM Design and Construction (SAM 2011). The results enabled the researchers to quickly determine the toughness and energy-absorbing efficiency of EPS in a static test. Following the method of Chen et al. (2015) for measuring the compressive strength of EPS at different strain rates, this study obtained the compressive dynamic increase factors of EPS to predict the amount of energy that can be absorbed by EPS in a dynamic impact test. Thus, the researchers could determine the suitable energy settings in the Newton's cradle test.

4.2 Principle and design of the Newton's cradle test

The Newton's cradle test is conducted by allowing a series of swinging spheres to collide with one another. Because of the conservation of momentum and energy, no energy loss occurs (in a resistance-free situation) during the entire process. Therefore, the spheres can ceaselessly elastically collide (Fig. 3). To conduct an energy-absorption test using the Newton's cradle, the energy-absorbing material (EPS) was placed between the third and fourth spheres. Then, the first sphere was lifted to a predetermined location and released to generate an impact force; when the first sphere arrived at the lowest point of its trajectory, it struck the second sphere. When the impact force was transmitted to the EPS material between the third and fourth spheres, the material endured the force and was compressed and deformed. The EPS sample absorbed a specific amount of force, and the remaining force was transmitted to the fifth sphere. The fifth sphere was thus set in motion on an upward trajectory. At this moment, the first sphere's motion was slightly upward, but the remaining momentum in the entire device did not change. The angle of the rise of the first sphere and that of the fifth sphere were then measured to determine the potential energy (i.e., the remaining momentum), and the results were used to determine the energy-absorbing efficiency of EPS.

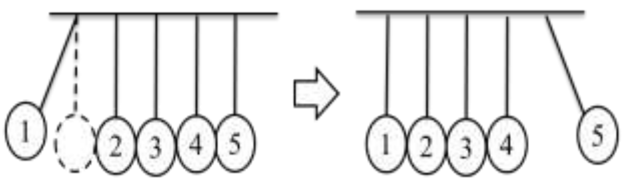

Fig. 3. The first-round swing of the Newton's cradle.

4.3 System of multiple physical measurements

1. Contact measurement

The equipment for contact measurement was an accelerometer (Model 350C02) and a dynamic load cell (Model 200C50) manufactured by PCB Piezotronics and a dynamic signal acquisition device (Model PXI-4462) manufactured by National Instruments. LabView2014 was used to develop a program for the synchronized acquisition of acceleration and impact force. Fig. 4 presents the accelerometer and impact force sensor. Contact measurement was conducted to measure the acceleration and force endured by the Newton's cradle from the moment when the first sphere was lifted to the moment when the spheres ceased to move.

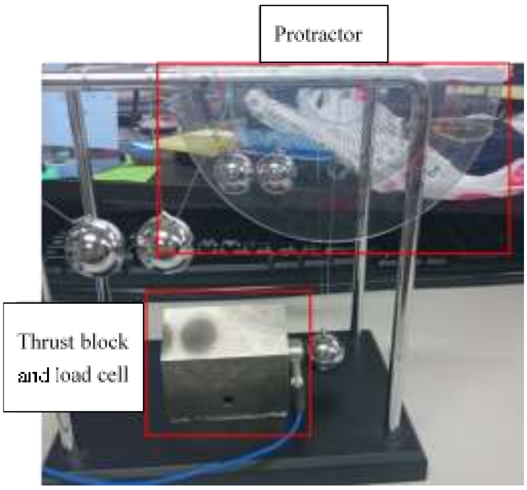

Fig. 4. Configuration of the contact measurement test using Newton's cradle.

Particularly, the acceleration of the interval between the moment when the third sphere hit the EPS sample and the moment when the sample separated from the fourth sphere was measured. The resultant acceleration was used to determine the force endured (Newton's second law of motion) and deformation (double integral of the acceleration–time value) of the EPS sample. Next, a stress–strain curve was drawn to calculate the strength, toughness, and energy-absorbing efficiency of EPS.

2. Noncontact measurement

For noncontact measurement, this study used single- and dual-lens cameras to photograph synchronized images of the entire test (Fig. 5). Subsequently, the acquired data were processed using the techniques of image processing and triangulation to determine the displacement or deformation field. This process was divided into image acquisition and image processing. The images were acquired using high-speed cameras and frame grabbers, and the program for single-camera synchronized image acquisition was developed using the graphical programming language LabVIEW. Image analysis was performed by calculating the intrinsic and extrinsic parameters for stereo calibration through CCTB, and the velocity field of single-camera images was analyzed using a two-dimensional particle image velocimetry tool for MATLAB (PIVlab) based on PIV.

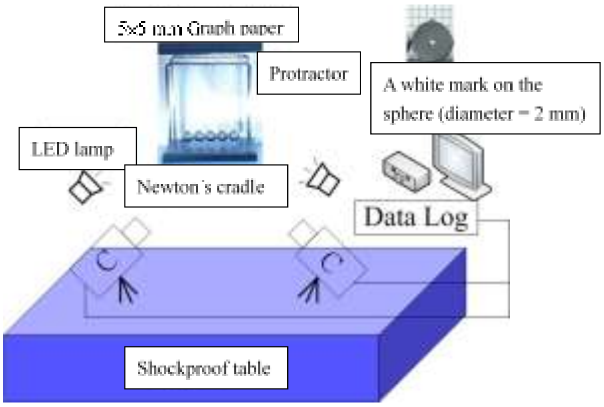

Fig. 5. Field of image measurement using Newton's cradle.

5 RESULTS AND ANALYSES

5.1 Results of contact measurement

The dynamic load cell was placed at the contact point of the steel sphere being struck, and the accelerometer was placed on the other side of this sphere to measure the acceleration that occurred between the point where the first sphere hit the second one and the fifth sphere was moved (i.e., cushion acceleration). To compare the resultant value with the theoretical value, this study referred to the Hertz contact theory adopted by the Japan Road Association and incorporated the experimental analysis to simplify the formula of sphere–surface contact:

$$p = 2.108 \cdot (m \cdot g)^{2/3} \cdot \lambda^{2/5} \cdot H^{3/5} \tag{1}$$

where P is the impact force of a rockfall (kN), m is the rockfall mass, g denotes the gravitational acceleration (m/s^2), H represents the rockfall height (m), and λ represents the Lamé constant of the struck matter. The Lamé constant of hard matter (steel) is 10,000 kN/m^2. The resultant impact values corresponded to the theoretical values (Table 1).

Table 1. Comparison between the experimental and theoretical values of the impact force and duration time

Angle	Sampling rate (1/s)	Maximum impact force P (N)		Duration t (μs)	
		Experimental value	Theoretical value	Experimental value	Theoretical value
30	10k	644.2± 12.7	664.27	123 ± 3.34	150
45		1053.3 ± 26	1048.28	113 ± 3.34	138
60		1474.2 ± 42	1466.56	110 ± 0	131
90		2192.5 ± 94	2222.89	113 ± 3.34	122

5.2 Results of noncontact measurement

The noncontact measurement consisted of photographing the motion of the Newton's cradle and analyzing the displacement field and velocity of the motion. The measurement results not only provided optical images of the swinging motion but also helped calibrate the accuracy of the Newton's cradle. A single camera was used to continuously photograph motion trails (Fig. 6), and the PIVlab software for image analysis developed on the MATLAB platform was run to calculate the theoretical solutions of classical dynamics. Subsequently, the resultant values were compared with the maximum velocity resulting from the aforementioned tests using the Newton's cradle.

Fig. 6. PIVlab vector image of the single-camera measurement (angle of fall = 45°).

Table 3 presents a comparison of the experimental and theoretical solutions. The small differences between the two groups of values demonstrated the applicability of the designed experiment. The displacement–time relationship of the model without any sample was compared with that of the model with the EPS sample, and the results indicated that when the EPS sample was placed in the cradle, the swinging angle of the fifth sphere decreased considerably, thereby demonstrating the energy-absorbing behavior of EPS (Fig. 7).

Table 2. Comparison between the experimental and theoretical solutions of the single-camera image measurement

Angle	Maximum velocity (m/s)	
	Theoretical solution	PIVlab solution
45	0.89	0.82
60	1.17	1.05

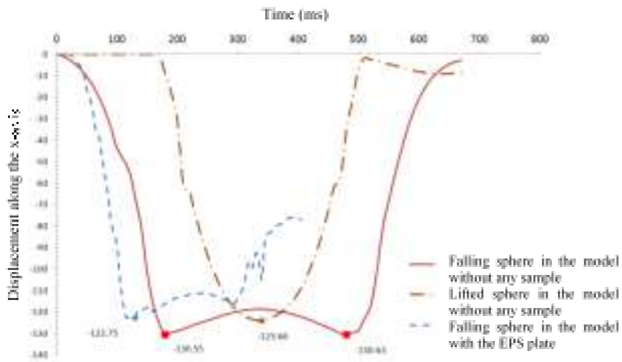

Fig. 7. Comparison between the Newton's cradle test without any sample and with the EPS plate.

3 CONCLUSION

This study calibrated the energy-absorbing efficiency of EPS using the Newton's cradle. The experimental values that were obtained from contact measurement and determined from the dynamic load cell and accelerometer concurred with the theoretical values. PIV was adopted in the noncontact measurement to analyze the single-camera images before and after the impact occurred, and the results confirmed the correspondence between experimental and theoretical values. The aforementioned results demonstrated that the designed experimental method achieves satisfactory results and is applicable for use in testing.

REFERENCE

Scheirs, J., and Priddy D. B. (2004). Modern Styrenic Polymers: Polystyrenes and Styrenic Copolymers, translated by Gao M.C., et al. Chemical Industry Press, Beijing.

Yang, Y.S., Huang, C.W., and Wu, C.l. (2012). A simple image‐based strain measurement method for measuring the strain fields in an RC‐wall experiment. Earthquake Engineering & Structural Dynamics, 41(1), 1-17.

Sutton, M.A., Orteu, J. J. and Schreier, H. (2009). Image correlation for shape, motion and deformation measurements: Basic concepts, theory and applications. Springer Science & Business Media, 1-116.

Saurer, O., Koser, K., Bouguet, J. Y. and Pollefeys, M. (2013). Rolling shutter stereo. In Proceedings of the IEEE International Conference on Computer Vision, 465-472.

Chen, W., Hao, H., Hughes, D., Shi, Y., Cui, J. and Li, Z.X. (2015). Static and dynamic mechanical properties of expanded polystyrene. Materials & Design, 170-180.

SAM Association. (2011). Handbook of SAM Design and Construction. SAM Association, 1-12.

Japan Road Association. (2000). Japan rockfall countermeasures.