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# RESEARCH ON ELASTIC-DAMPING PROPERTIES OF UNIT LOADS

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***Abstract***

*In the paper, the results of tests of free-fall of unit load (cubicoidal package) from a height on the stiff ground are presented. The aim of this study is to determine the elastic-damping properties of packaging for all surfaces, edges and corners. These tests allow us to evaluate the protective ability of packages in case of impact in any direction - typical for real transport systems. The maximum accelerations registered during experimental tests are subjected to approximation by means of B-spline surface. It enables the visual interpretation of data in three-dimensional space, allowing detection critical packaging places for the safety of transported goods. In addition, the registered acceleration waveforms were used to determine the coefficients of: restitution, damping and rigidity. These parameters are required to the analytical descriptions of loads contact with obstacles - such as in the models of sorting or positioning processes of packagings.*

**Keywords:** *free fall test, impact, damping coefficient, restitution coefficient, rigidity coefficient*

## 1. Introduction

Products sent from the manufacturer to the customer are closed in the protective packaging (unit loads) to improve their transport susceptibilities. The unit loads during transport and storage are subject to handling operations (such as loading, unloading, download, positioning, sorting) which pose a risk of mechanical damage of packaging and their content. To the most serious causes of security breaches of unit loads is mechanical exposure of a impact character caused by fall of unit loads on ground, on other unit loads or caused by impact when entering into contact with manipulators performing e.g., the sorting process of unit loads transported on conveyors [14], [15].

Available scientific papers dealing with the study of unit loads in the range of mechanical interactions of impact character relate to the analysis of influence of dynamic overloads on packaging damage. Not many works take an attempt to use, in this application, the finite element method [13]. The basic technique for assessing the mitigation effectiveness of overloads caused by impact is experimental test. One of the main methods for evaluation of the protective ability of packaging prototypes is test of free fall from a height (drop test). The plan of drop test realisation is based on the guidelines of standards, e.g. [10], [11], [4], [3]. This test consist in fall of the load from assumed height on the smooth and stiff ground, respectively oriented surfaces, edges and corners. The visual inspection of the packaging and its content form the basis for assessing the protective packaging properties. The content damage of loads, that cause the lack of recipient acceptation, is connected with the need of introduction of structural changes in the packaging or in the product also.

Standards relating to the method of free fall concern only the experimental tests of unit loads [2], [1]. They do not describe any method for determining the parameters that could be used in mathematical models of process of sorting or positioning of load streams [14], [15].

In the present work it was assumed that the method of the free-fall (included in the standards) will be a reference to determine the coefficient of restitution, stiffness and damping of loads. An extension of this method involves in replacing the unit load content with substitute material and use of triaxial acceleration recorder mounted inside the package. Acceleration waveforms (recorded by the sensor) are the base to determine the change velocity and impact duration. Further, these values (assuming knowledge of the free fall height) allow specifying the restitution, stiffness and damping coefficients of loads for each individual directions of impact.

## 2. Program of experimental tests of impact phenomenon

To record the impact process (during the tests of free fall of unit load on stiff ground) the triaxial acceleration recorder type 3L30 SAVER made by Lansmont (placed inside the package) was used. The device can save 100 waveforms of accelerations not exceeding the maximum value of ±100G (1G - gravity acceleration). It is an autonomous recording system made in the form of aluminium cube of size 0,076 x0, 076x0, 04 m and weight 0.4 kg.

For testing it was prepared cuboidal unit load of dimensions 0,136 x0, 136x0,1 m and a total mass 0.5 kg. This load consists of a package made of a three-layer corrugated cardboard, filled with polystyrene foam (EPS). The packaging material (fulfilling anti-shock role in the load) has a thickness of 0.03 m.

The load with built in sensor was subjected to series of tests of free fall from the height of $h$=0.30 m on the rigid ground. This height is equivalent to the dynamic interactions of impact character, on which is exposed about 20% of loads in the whole transport process (from the supplier to the end user) [7]. During tests, the load was positioned manually. The falls were so planned to hit the object four times on each corner, edge and surface. In addition, the centre of mass gravity of the load was placed on a normal of collision. Thus the potential energy of gravity was maximally dissipated by the springy-damping forces of the impact process, and in the minimally manner - was converted into kinetic energy of the load rotation.

## 3. The experimental results and numerical analysis

Fig. 1 shows results of free-fall tests of the unit load from a height of $h$=0.3 m (acceleration - Fig. 1a and the impact duration - Fig. 1b). In the graphs are placed lines representing the average values of measurements (lines marked by reference 1) and limits of confidence interval around the average value, with 95% confidence level (lines marked by references 2 and 3). In addition, for each graph was determined coefficient of trials which were registered outside the confidence interval:

$$\delta = \frac{n_p}{n} 100\% \tag{1}$$

where:

$n_p$ – number of trials, the results of which go beyond the confidence interval around the average value, with 95% confidence level,

$n$ – the total number of trials.

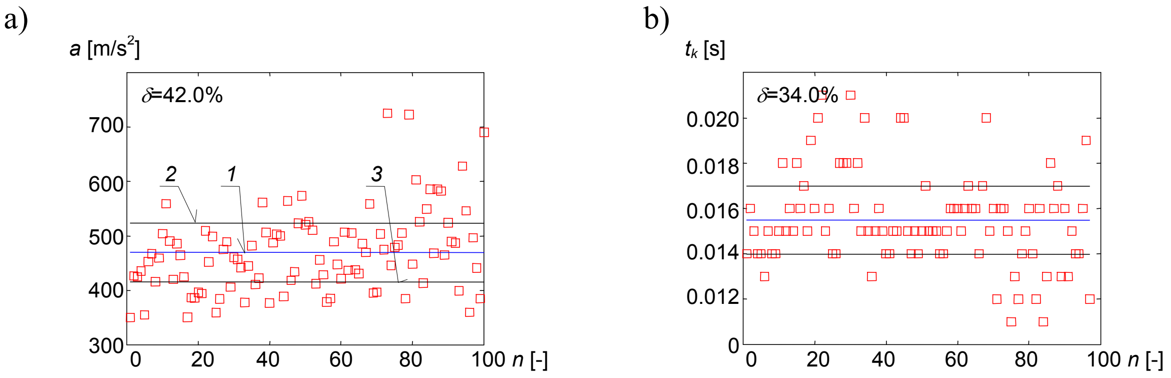

*Fig. 1. Data registered during impact tests: a) maximum acceleration, b) the impact duration; 1 - average value, 2, 3 – limits of confidence interval around the average value, with 95% confidence level, δ - rate of test results registered outside the confidence interval*

Presented data show a wide variation of results, confirming their strong dependence on the impact direction.

In order to capture the relationship between the direction of impact and registered accelerations the approximation by means of B-spline surface was applied - Fig. 2, [12], [5], [19], [17]. From the analysis of presented graphs show, that in case of the fall of the load on the edges and corners, the dissipation ability of impact energy of the package is greater than the fall on the walls.

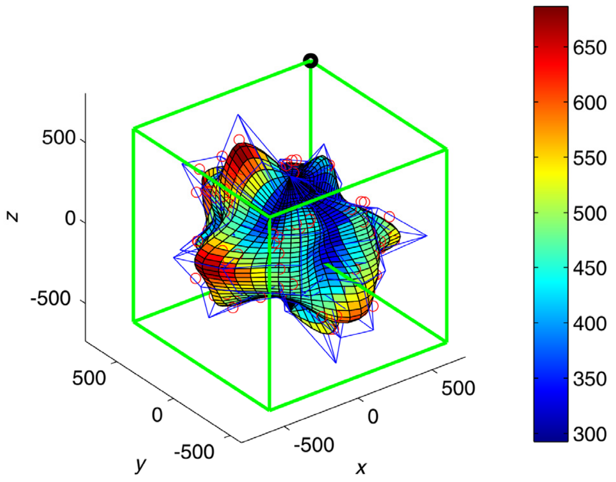

*Fig. 2. Result of approximation (in isometric projection) of the of load accelerations registered during free fall from height h=0.3 m [17]*

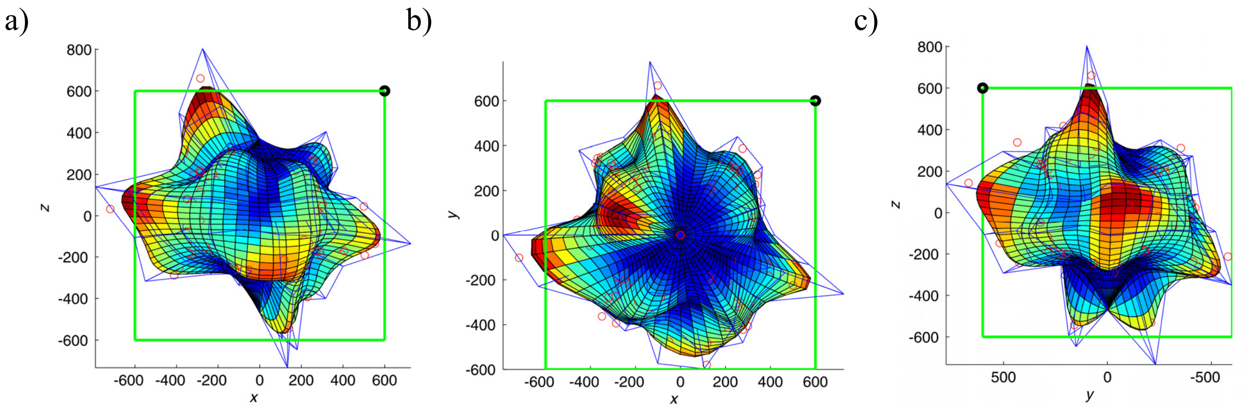

*Fig. 3. Orthogonal projection of chart from Fig. 2: a) in the xz plane (main view), b) in the xy plane (top view), c) in the yz plane (left-side view) [17]*

### 3.1. The method of the restitution coefficient determination

On the basis of data obtained (Fig. 4a) during tests of the load free-fall, directly can be determined shapes of acceleration waveform, their extreme values, the extremes' positions, the impact duration. Moreover, in an indirect way also can be determined additional information: the velocity change $\Delta v$ and coefficient of restitution $e$.

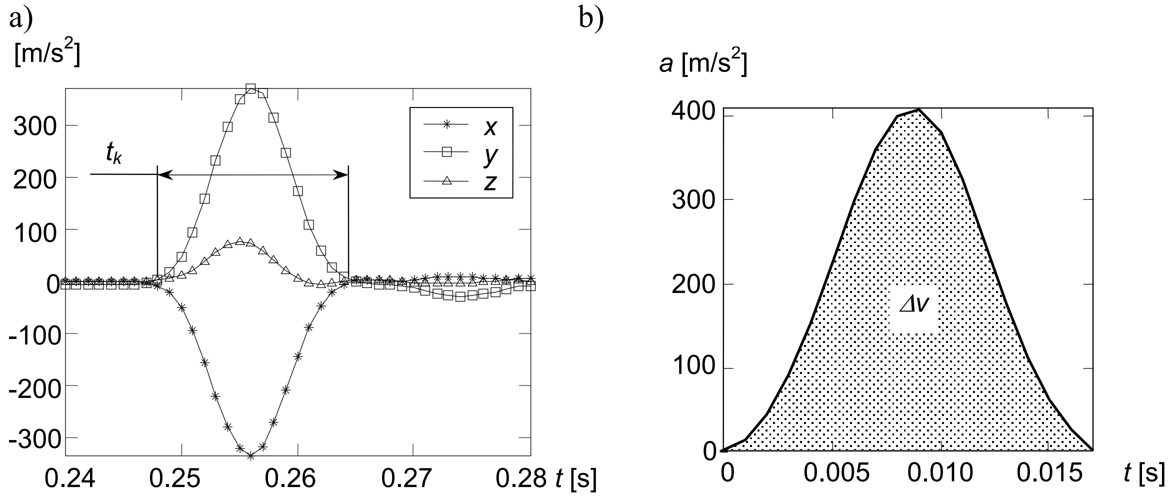

*Fig. 4. Example of acceleration waveforms recorded during impact: a) "raw" acceleration waveforms , b) "cut out" acceleration course corresponding to the time of contact between the load and stiff ground; $a_x$, $a_y$, $a_z$, $a$ – components and resultant of acceleration, $t_k$ – time of impact duration*

The velocity change $\Delta v$ of the unit load during impact is determined by single integration of acceleration.

$$\Delta v = \int_0^{t_k} a\, dt \tag{2}$$

where:

$t_k$ – the impact duration.

The velocity change $\Delta v$ is the area contained between the acceleration curve and the abscissa $t$ - Fig. 4b. The time of impact $t_k$ is treated as duration of the compression forces occurring between the load and the ground. These forces appearance corresponds to the moment of impact initiation, and their disappearance - to the impact end.

The unit load velocity (achieved during free fall tests) just before contact with the stiff ground is determined on the basis of conservation principle of the potential and kinetic energy, and the knowledge of the free fall height $h_0$:

$$v_0 = -\sqrt{2gh_0} \tag{3}$$

where:

$g$ – gravity acceleration.

The velocity achieved by the unit load just after impact (at the moment $t_k$, Fig. 4a) is defined by equation:

$$v_k = \Delta v - v_0 \tag{4}$$

Knowing the load velocity just before and after impact, the kinematic coefficient of restitution (the Newton's coefficient of restitution - Fig. 5) can be determined:

$$e = -\frac{v_k}{v_0} \tag{5}$$

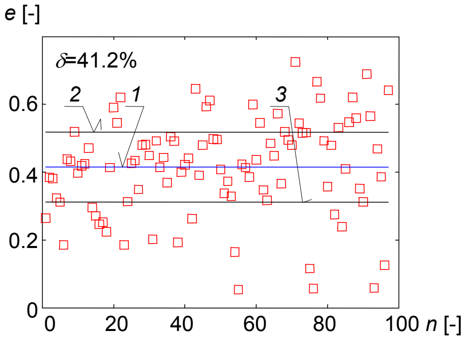

*Fig. 5. Restitution coefficient; 1 - average value, 2, 3 – limits of confidence interval around the average value, with 95% confidence level, δ - rate of test results registered outside the confidence interval*

## 3.2. The method of coefficients determination of the rigidity and damping

Coefficient of restitution is required in so-called discrete (classical) impact models (based on Newton's model), in which the impact is treated as an instantaneous (timeless) process - lasting in an infinitely short time. These models allow determining the motion parameters of bodies just before and after collision. However, they are not able to determine the impact reaction forces, nor accelerations and deformations of colliding bodies. To determine these quantities it is necessary to use the continuous impact models, to which belongs local strain model - based on Hertz's theory of contact problems [20], [9], [21]. An example of this class of models is a modified nonlinear Kelvin model (proposed by authors of the work, Fig. 6 [16]):

$$N = b_1 m_p^{0,4} \dot{D} D^2 + k_1 D^4 \tag{6}$$

where:

$b_1$ – damping coefficient,
$k_1$ – rigidity coefficient,
$m_p$ – mass of the unit load,
$D, \dot{D}$ – strain and strain velocity, respectively, of colliding bodies.

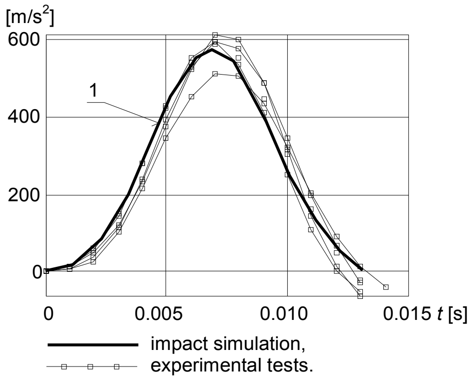

*Fig. 6. Chart of impact simulation (curve marked by reference 1) and acceleration courses, registered during experimental tests [16]*

The main input parameters of the impact model (equation (6)) are the coefficients of: rigidity $k_1$ and damping $b_1$. These coefficients can be obtained on the basis of numerical solution of the system of equations:

$$\begin{cases} \hat{e}(b_1, k_1) - e = 0 \\ \hat{t}_k(b_1, k_1) - t_k = 0 \end{cases} \tag{7}$$

where:

$\hat{e}(b_1,k_1), \hat{t}_k(b_1,k_1)$ – restitution coefficient and time of impact, respectively, determined during simulation of impact model (6),

$e, t_k$ – the values of restitution coefficient and time of impact duration determined on the basis of free-fall tests of load dropped from the height.

The results of calculations of damping and restitution coefficients are shown in Fig. 7. A surprising effect is the number of data located in the confidence interval - higher compared to data presented in Fig. 1 and Fig. 5.

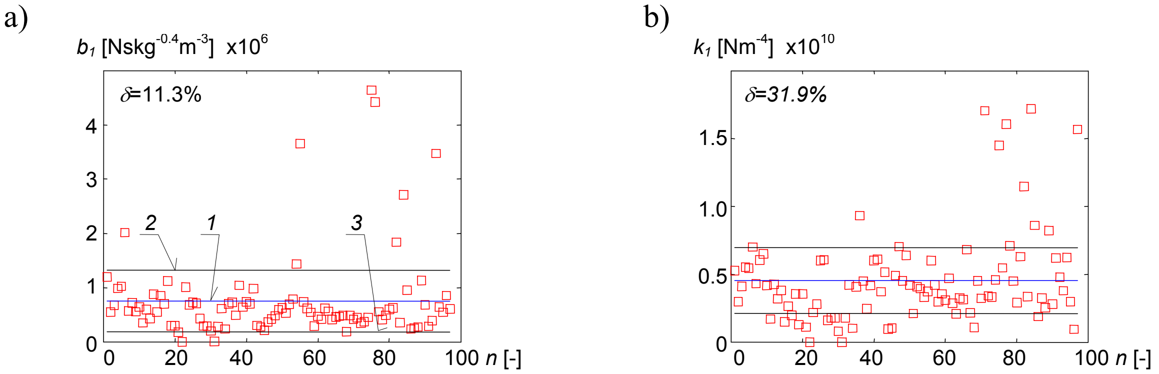

*Fig. 7. Springy-damping properties of unit load: a) damping coefficient, b) rigidity coefficient; 1 - average value, 2, 3 – limits of confidence interval around the average value, with 95% confidence level, δ - rate of test results registered outside the confidence inter*

## 4. Summary

The following concluding remarks were formulated:

- The drop tests of unit loads designed to the experimental verification of packaging prototypes can also be used to determine the parameters required in models of the impact phenomenon: coefficient of restitution, damping and stiffness of the package (in any direction of impact).
- To describe the impact phenomenon (and calculate the springy-damping properties of packaging) a modified nonlinear Kelvin model can be used. This model effectively reproduces impact course registered during tests - in relation to the unit load considered in the paper.
- Approximation of test results of a free-fall with the use of B-spline surface allows intuitive identification of places (in the package in three dimensions) that are critical for the safety of the content of load and require changes in its design and construction.

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