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Study The Mechanical Behavior Of Corrugated Box Using The Finite Element Method

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Abstract:
Numerical simulation is a very important step in the product design process. One of the remaining problems in the process of performing numerical simulations is the long calculation time, many models require high-configuration computers, especially for large and complex models.Therefore, it is required to build simple equivalent models to replace the original model.In this study, the mechanical behavior of carton boxes subjected to load when transporting goods is studied using the finite element method. The FEM model of the box, with all components, was built by applying a homogenization model to the corrugated core plate. The mechanical behavior of the box when subjected to static and dynamic loads is studied through numerical simulations. A method to quickly determine the durability of cardboard boxes when subjected to impact through finite element analysis. This model is validated by comparing the obtained simulation results with experimental results.
Key Word*:Simulation, Finite Element, Carton, Mesh,*

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I. Introduction

Packaging plays a very important role in protecting and transporting goods, preventing products from being damaged due to excessive impact and vibration that can occur during distribution and transportation. With outstanding advantages: lightweight, easy to fold, environmentally friendly, beautiful printing surface, and quite high durability, cardboard paper has been widely used as packaging. To reach consumers, products, and packaging must endure countless mechanical impacts during transportation, handling, loading, and unloading as well as storage in warehouses. Developing packaging that is appropriate for the product and distribution channel requires a good knowledge of the impacts that the packaging and product are subjected to during transportation. Nowadays, there have been many studies using experimental methods to examine the vibrations caused by packaging during transportation. Several studies have analyzed vibration levels during road and rail freight transportation to propose PSDs for each type of transport [1-5]. Then, packaging system testing methods based on these data were proposed. Low-frequency vibrations (0.1-10 Hz) are considered much more harmful to products than high-frequency vibrations [6]. Vibration testing on carton packaging is also performed in a laboratory using a vibration table instead of conducting direct testing during the actual transportation process. Jamialahmadi [7] performed dynamic tests by placing the packaging system on a vibrating table. The contact forces existing in the stack of boxes provide useful and important results for further analysis of the fatigue resistance and damage-prone locations of the boxes. Many other vibration tests on cardboard packaging have also been performed by other researchers. Guo et al [8] studied the vibration behavior of corrugated panels using slow sinusoidal vibration tests to analyze the resonance frequency, vibration transmission capacity, and damping ratio of the panels. different. Zhang et al [9] tested the vibration resistance of three types of corrugated cardboard boxes by subjecting them to vibration testing and vibration plus drop testing. Marcondes and Batt [10] analyzed the vibration behavior of corrugated cardboard boxes on a force-controlled vibrating table. The above studies are based on experiments to analyze the mechanical behavior of corrugated cardboard boxes when subjected to vibration. However, physically checking all possible damage situations will be costly in terms of money and time. To solve these problems, finite element analysis (FEA) has been used in packaging design. However, there are still many issues that have not been analyzed using the finite element method, especially issues related to the fatigue resistance of the packaging.

In this study, we will build a finite element model for a cardboard box subjected to static and dynamic loads. The model is built based on the homogenization method to reduce model building time significantly. At the same time, the study proposes a method to quickly determine the durability of carton boxes through FEA for a cardboard box subjected to static and dynamic loads. The model is built based on the homogenization method to reduce model building time significantly. Simultaneously, the study proposes a method to quickly determine the durability of carton boxes through FEA.

II. Material and Methods

The material used in this study is paper in the composition of corrugated core cardboard. The paper has linear elastic behavior up to a certain limit called the elastic limit. The value of the elastic limit is usually achieved for a relative elongation of 0.2%. The properties of the fibers and the board manufacturing process create a material that can be considered orthotropic. This means that the material will have different properties in three main orthogonal directions: MD (machine direction), CD (diagonal direction), and ZD (thickness direction) (Figure 1). The constitutive law governing the behavior of orthotropic materials can be written about (x, y, z) which corresponds to (MD, CD, ZD).

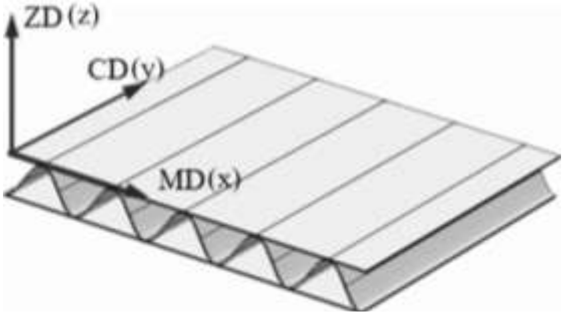

Figure 1. The directions of the corrugated cardboard plate

In the study of Stenberg [11] was shown that the elastic modulus in the ZD direction is about 200 times lower than the modulus in the MD direction. Another study by Stenberg et al [12] observed that in-plane deformation is negligible during compression along the thickness direction and Poisson's ratio and hence their values are close to zero. Young's modulus Ez in the ZD direction, as well as the shear modulus Gxz and Gyz, are difficult to determine experimentally. Baum's empirical relations often approximate these coefficients [13-14]:

$$\begin{cases} \dfrac{E_1}{E_3} \approx 200 \\ \dfrac{E_1}{E_{13}} \approx 55 \ (1) \\ \dfrac{E_1}{E_{23}} \approx 35 \end{cases}$$

The basis for building a FEM model for corrugated cardboard boxes is the homogenization method. Accordingly, for a corrugated cardboard sheet, the homogenization method is summarized as follows:
Consider a representative element of a corrugated cardboard sheet as shown in Figure 2[15].

$$\begin{cases} \theta(x) = \tan^{-1}\left(\dfrac{dh(x)}{dx}\right) \\ h(x) = \left(\dfrac{h_c}{2} - \dfrac{e_2}{2}\right)\sin\left(2\pi\dfrac{x}{p}\right) \end{cases} \quad (2)$$

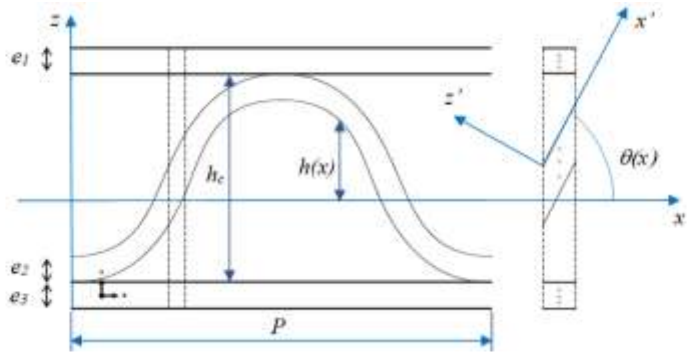

Figure 2. Unit period of corrugated core cardboard and integration points along the thickness [15]

A_{ij}-membrane stiffness, D_{ij}-bending and torsion stiffness, F_{ij} -transverse shear stiffness, and B_{ij} the interaction matrix between membrane and bending-torsion are calculated according to the following formulas:

$$A_{ij}(x) = Q_{ij}^{(1)} e_1 + Q_{ij}^{(2)}\left(\theta(x)\right)\frac{e_2}{\cos\theta(x)} + Q_{ij}^{(3)} e_3 \quad (3)$$

$$B_{ij}(x) = Q_{ij}^{(1)} z_1 e_1 + Q_{ij}^{(2)}\left(\theta(x)\right) z_2 \frac{e_2}{\cos\theta(x)} + Q_{ij}^{(3)} z_3 e_3 \quad (4)$$

$$D_{ij}(x) = Q_{ij}^{(1)}\left(z_1^2 e_1 + \frac{e_1^2}{12}\right) + Q_{ij}^{(2)}\left(\theta(x)\right)\left(z_2^2\frac{e_2}{\cos\theta(x)} + \frac{e_2^2}{12\cos^2\theta(x)}\right) + Q_{ij}^{(3)}\left(z_3^2 e_3 + \frac{e_3^2}{12}\right) \quad (5)$$

$$F_{ij} = \frac{5}{6}\left(C_{ij}^{(1)} e_1 + C_{ij}^{(2)}\left(\theta(x)\right)\frac{e_2}{\cos\theta(x)} + C_{ij}^{(3)} e_3\right) \quad (6)$$

Homogeneity along the MD direction involves calculating the average stiffness of all dx slices over a sinusoidal time interval P:

$$A_{ij}^H = \frac{1}{p}\int_0^p A_{ij}(x)dx \quad (7)$$

$$B_{ij}^H = \frac{1}{p}\int_0^p B_{ij}(x)dx \quad (8)$$

$$D_{ij}^H = \frac{1}{p}\int_0^p D_{ij}(x)dx \quad (9)$$

$$F_{ij}^H = \frac{1}{p}\int_0^p F_{ij}(x)dx \quad (10)$$

The membrane forces and the bending and torsional moments, in the plastic case, are obtained by integrating the stresses over the thickness of the sheet by replacing the elastic matrices $[Q_{(k)}]$ with contact matrices. route $[Q_{p(k)}]$ in equations (3), (4), and (5) to arrive at the terms of the overall stiffness matrix.

$$A_{ij}(x) = \frac{e_1}{2}\sum_{k=1}^{3} Q_{pij}^{(1)} w_k + \frac{e_2}{2\cos\theta(x)}\sum_{k=1}^{3} Q_{pij}^{(2)}\left(\theta(x)\right) w_k + \frac{e_3}{2}\sum_{k=1}^{3} Q_{pij}^{(3)} w_k \quad (11)$$

$$B_{ij}(x) = \frac{e_1}{2}\sum_{k=1}^{3} Q_{pij}^{(1)} z_k w_k + \frac{e_2}{2\cos\theta(x)}\sum_{k=1}^{3} Q_{pij}^{(2)}\left(\theta(x)\right) z_k w_k + \frac{e_3}{2}\sum_{k=1}^{3} Q_{pij}^{(3)} z_k w_k \quad (12)$$

$$D_{ij}(x) = \frac{e_1}{2}\sum_{k=1}^{3} Q_{pij}^{(1)} z_k^2 w_k + \frac{e_2}{2\cos\theta(x)}\sum_{k=1}^{3} Q_{pij}^{(2)}\left(\theta(x)\right) z_k^2 w_k + \frac{e_3}{2}\sum_{k=1}^{3} Q_{pij}^{(3)} z_k^2 w_k \quad (13)$$

Where: w_k represents the numerical integral weight corresponding to the integral point k of the class under consideration.

The plastic homogeneity model of corrugated cardboard has been implemented into the Abaqus/Standard software using the UGENS user subroutine.

Next, we build a FEM model for the carton box based on the application of the homogenization method (Figure 3). This model includes all the components of a carton box used in practice such as the box lid and the glue part (Figure 4). Carton box dimensions and material properties are shown in Figure 3.3 and Table 1.

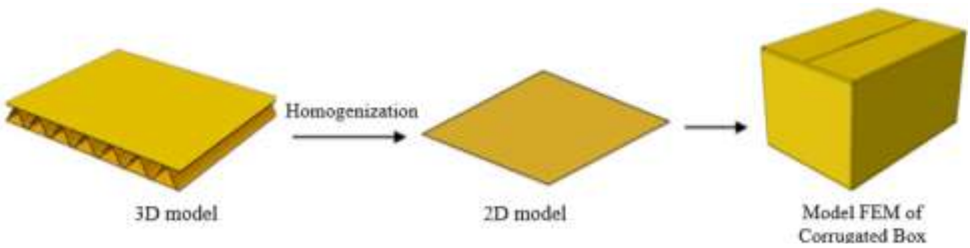

Figure 3. Build a FEM model for carton boxes

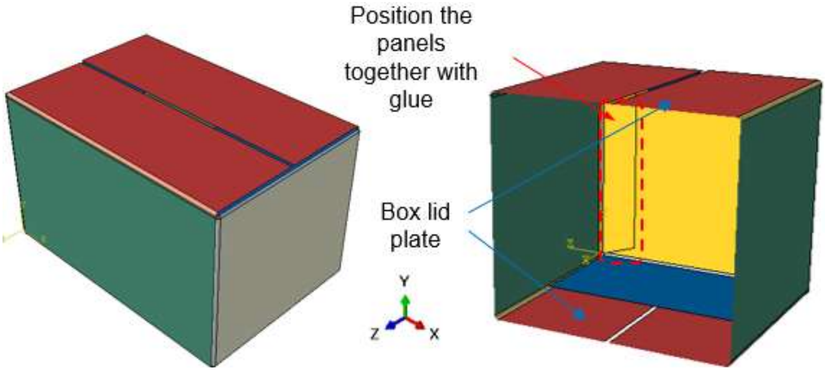

Figure 4. FEM model of carton box

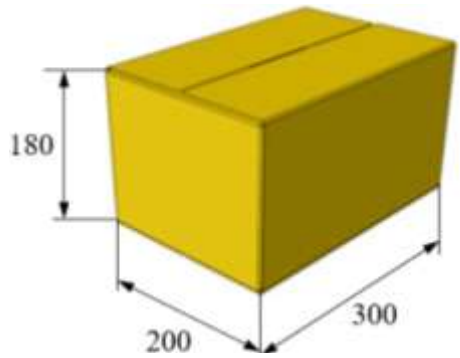

Figure 5. Carton box size

Table 1. Properties of paper materials [16]

Paper	E_x (MPa)	E_y (MPa)	ν_{xy}	G_{xy} (MPa)	E_0	n	A	B	C	D	ε_0
1,3	2433.2	859.91	0.0829	1077.2	96.45	4.97	1.0	2.498	2.498	1.622	0.48e-3
2	1130.4	625.85	0.0717	303.05	87.31	4.247	1.0	2.178	2.178	1.871	0.92e-3

III. Result

To determine the damage limit of the carton box during numerical simulation, we performed a compression simulation of the carton box constructed using the homogenization method. The obtained simulation results will be compared with experimental results to verify the reliability of the model and determine the equivalent plastic deformation limit of the material. The carton box model and boundary conditions are shown in Figure 6. The carton box is placed between two rigid plates, the lower rigid plate is fixed, and a vertical displacement u_2=7mm is placed at the reference point RP of the upper rigid plate.The carton box is simulated with different mesh sizes: 2 mm, 4mm, 6 mm. At the corner of the box, use a grid size of 1 mm.

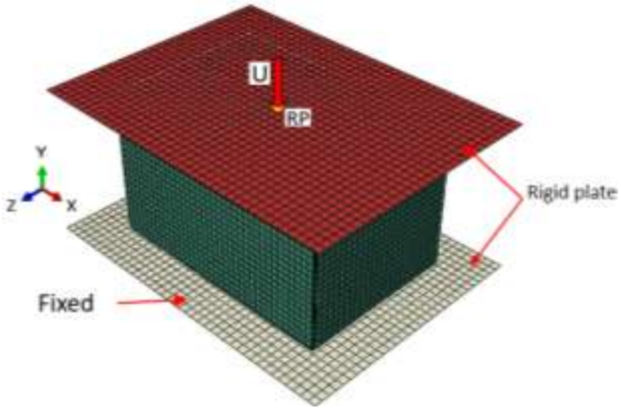

Figure 6. Compression corrugated box model and boundary conditions for simulation

The obtained results are compared with the experimental results as shown in Figure 7. It is easy to see that the case with a mesh size of 2 mm gives results closest to the experiment. The vertical compression capacity of the box obtained by numerical simulation is F_{max}=1598.8 N and the experimental value is F_{max}=1560 N. The difference between these two force values is about 3%.From this result, it can be determined that the maximum plastic deformation on the box is $\varepsilon_{max}^{p} = 0.267$ shown in Figure 8.

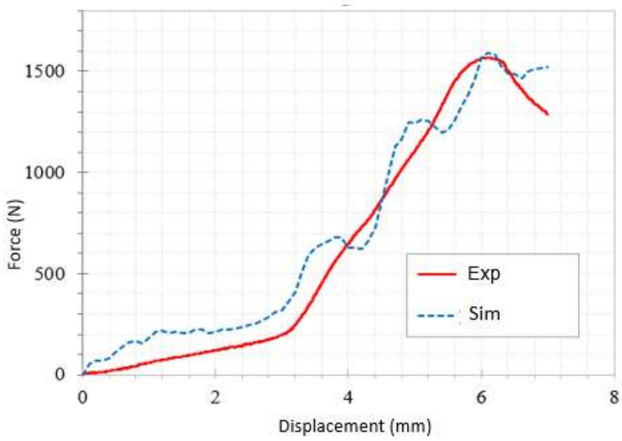

Figure 7. Force and displacement relationship in numerical simulation and experiment.

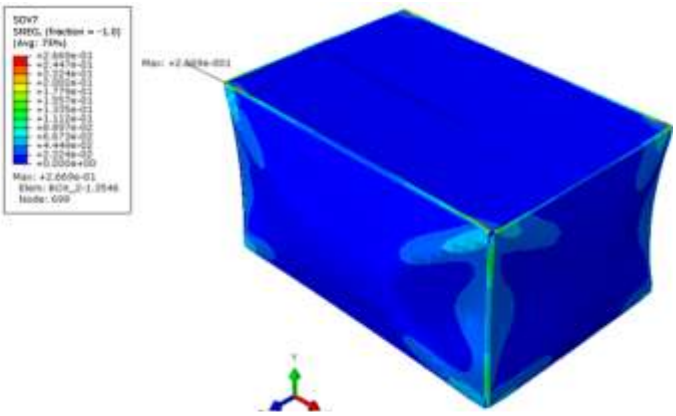

Figure 8. Simulation of carton boxes subjected to compression

Next, we perform numerical simulations of carton boxes subjected to impact loading. According to research [16], the carton box is placed on a vibrating table, fixed by a structure consisting of connecting bars connected to the table with bolts, and subjected to a total load (M = 8.4 kg) as shown in Figure 9.

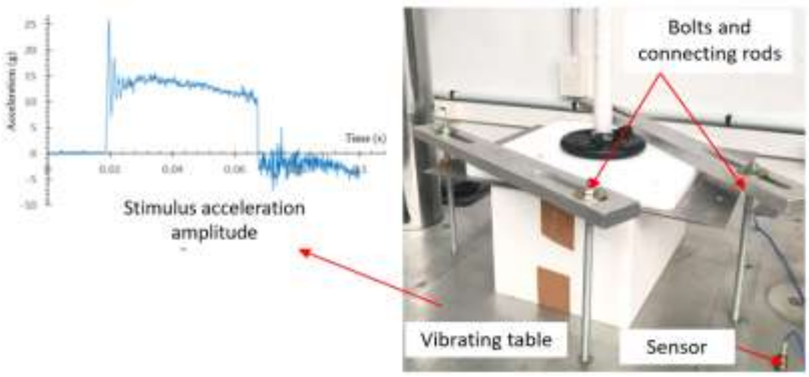

Figure 9. Set up an experiment to test impact durability on a vibration table[16]

The experimental procedure was conducted as follows: the vibrating table generated a shock in the vertical direction and each pulse was recorded. A carton box undergoes a series of impacts of the same intensity until it is damaged, and the number of impacts for each box is recorded.

The experimental model is modeled using a finite element model as shown in Figure 10. The box is placed between two rigid plates. The bolts are responsible for connecting the two rigid plates. A mass of 8.4 kg is placed on the upper rigid plate. An excitation pulse is applied to the lower absolute rigid plate for a short time. The acceleration amplitude and velocity change were recorded on the bottom plate during the simulation.

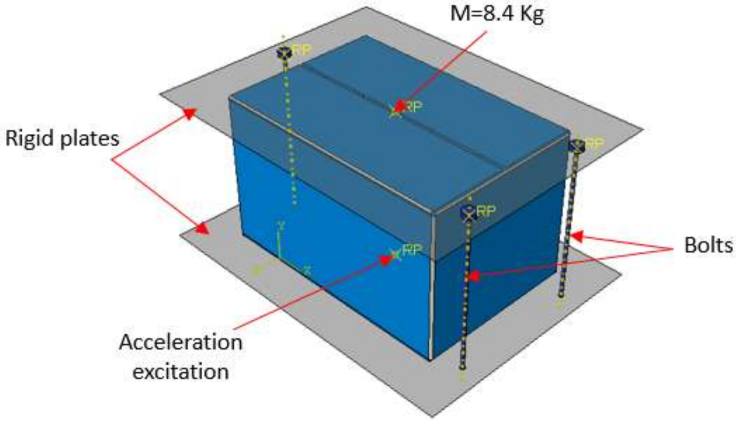

Figure 10. Modeling impact experiments on vibrating table

After each impact simulation, the equivalent plastic strain value (SDV7) is determined. A carton box is considered damaged when the equivalent plastic strain exceeds 10% of the maximum plastic strain value $\varepsilon_{\max}^{p} = 0.267$. The reason is that when conducting experiments, boxes are considered damaged when fractures appear on the panels of the box. However, according to the numerical simulation results, the folded edges of the box are always the location with the largest plastic deformation. Therefore, when analyzing the results to determine the number of collisions, these parts of the model are often ignored. Figure 11 shows that the maximum plastic deformation value of the box is $\varepsilon_{\max}^{p} = 0.513$. After ignoring the corners of the box, the maximum plastic deformation value is obtained: $\varepsilon_{\max}^{p} = 0.0576$. After each impact simulation, the maximum equivalent plastic strain value determined on the box is compared with the $\varepsilon_{\max}^{p} = 0.294$

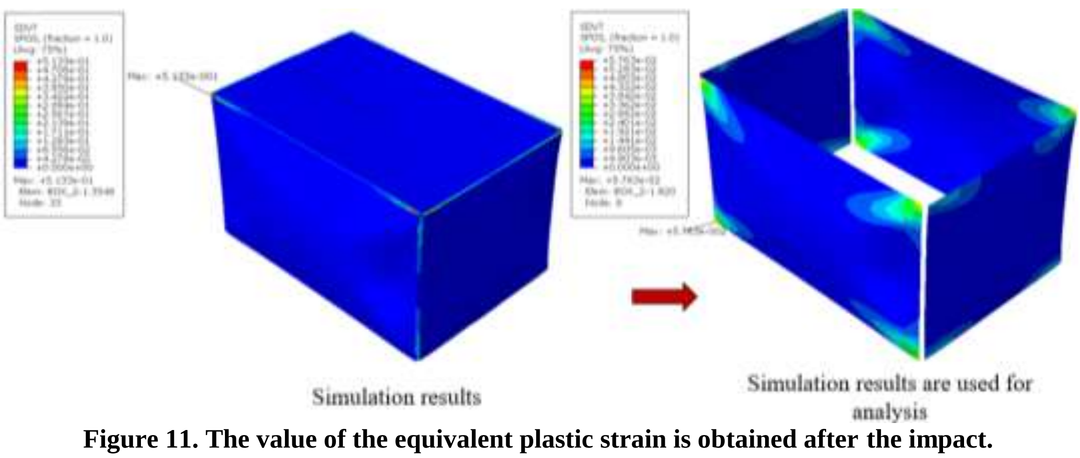

Figure 11. The value of the equivalent plastic strain is obtained after the impact.

A linear regression is proposed to determine the number of collisions the box can withstand. The procedure is carried out through the results of several simulations conducted. Equivalent plastic strain values (SDV7) are determined corresponding to each impact. Extrapolation of this relationship then makes it possible to determine the approximate number of collisions that caused the carton to be damaged.

Consider the case of stimulus acceleration: 5g, impact time: 4.98e-2 s. After several simulations, the number of collisions received is shown in Figure 12. The linear approximation equation between the points is determined

y=0,0001x + 0,1135 (1)

From equation (1), the number of impacts can be determined as 1805.

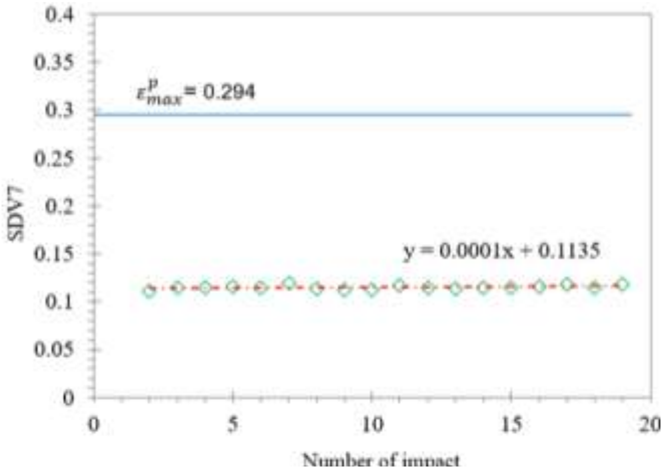

Figure 12. Relationship between equivalent plastic strain and number of impacts for A = 5 g and t = 4.98e-2 s

Consider the case of stimulus acceleration: 12g, impact time: 2.01e-2 s. After several simulations, the number of collisions received is shown in Figure 13. The linear approximation equation between the points is determined

y=9e-05x + 0,1884 (2)

From equation (2), the number of impacts can be determined as 1173.

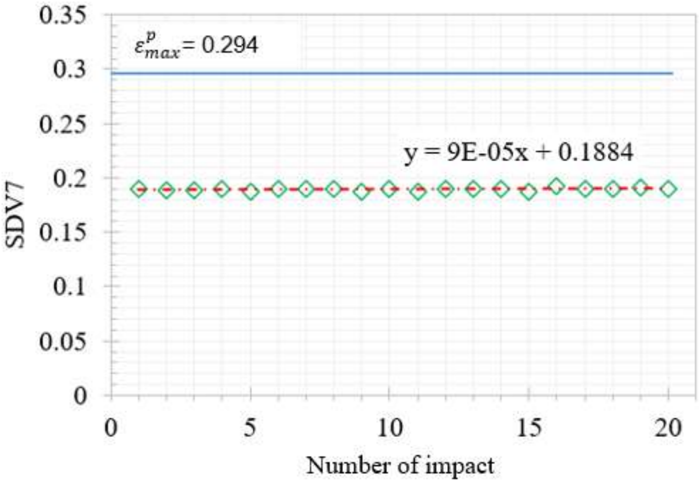

Figure 13. Relationship between equivalent plastic strain and number of impacts for A = 12 g and t = 2.01e-2 s

The comparison results between simulation and experiment are shown in Table 2. Table 2 shows that the number of impacts obtained by numerical simulation agrees well with the experimental results.

Table 2. Compare collision results between numerical simulation and experiment

Box serial number	Acceleration (g)	Impact time (s)	Number of collisions (Experiment)	Number of collisions (Simulation)
1	5	4.98e-02	>1000	≈ 1805
2	12	2.01e-02	>1000	≈ 1173

IV. Conclusion

In this study, a full carton box model was built in Abaqus finite element analysis software using the homogenization method. This model is used to simulate vertical compression resistance. Comparison with experimental results shows similarities in the force-displacement relationship. In addition, the model is also used to conduct a series of numerical simulations of cardboard box impact experiments. Based on the results obtained, a method for quickly determining the durability of boxes is developed. The accuracy of the method is confirmed through the results of comparing the number of collisions of the box in the experiment and numerical simulation. This model is the basis for further development in cases of quickly determining the DBC damage curve during the design process of carton boxes subjected to vibration.

Acknowledgments

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