

EXPERIMENTAL AND NUMERICAL SIMULATION OF DROP TESTS OF CORRUGATED CARDBOARD PACKAGING USING AN ANALYTICAL HOMOGENIZED MODEL

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Abstract. *This paper presents experimental and numerical studies of drop tests of corrugated cardboard packaging containing different foam inserts. An efficient homogenization model for the corrugated cardboard has been developed. In our H-model, the corrugated cardboard is represented by a 2D plate. Instead of using a local constitutive law (relating the strains to the stresses) at each material point, the homogenization process leads to a generalized constitutive law (relating the generalized strains to the resultant forces) for the equivalent homogeneous plate. Our H-model was implemented into the finite element software ABAQUS. The foam behaviour was experimentally determined and modeled with a crushable foam model of ABAQUS. The drop tests were performed as a free fall from a given height onto a rigid floor. The acceleration of the packed product was recorded using a triaxial accelerometer. The numerical results obtained using the FE simulation with our H-model agree very well with the experimental results. We have also shown that the contribution of the corrugated cardboard box to the shock response is very important.*

1 INTRODUCTION

During storage and transportation, products can accidentally fall onto the floor causing some damages on the products. The corrugated cardboard packages and the foam inserts are designed to protect the product from the shock it can undergo. As the product design always tends towards light, a high impact performance becomes extremely critical for product design issues [1-2]. Conventionally, a product reliability test to prevent impact-induced damage is carried out by a procedure of “design – prototype – test – redesign” which is highly cost and time consuming. A numerical modelling of the product and its packaging provides an efficient methodology to predict the structural strength during impact [3]. Moreover, the finite element simulation allows to avoid numerous experimental drop tests and to predict possible failures during the design stage. This study deals with the drop impact problem of product-packaging systems using both numerical and experimental methods. Different packaging systems, using corrugated cardboard box and different foam inserts, are studied to analyse the influence of corrugated cardboard and the foam inserts configurations.

Firstly, we present the experimental setups and results. Then, we describe the homogenization model for the corrugated cardboard and its implementation in the finite element code ABAQUS. Finally, the accelerations measured during the shock using the data acquisition system of drop test platform are compared with the results obtained from ABAQUS simulations.

2 EXPERIMENTAL TESTS

2.1 Materials and products

The corrugated cardboard boxes with interior dimensions of $150 \times 150 \times 90 \text{ mm}^3$ are used for the experimental drop tests (figure 1). The product in the box is a thick steel plate of $87 \times 87 \times 30 \text{ mm}^3$, with a total mass of 1.686 kg. The boxes are made with a corrugated C flute cardboard. The insert between the boxes and the product is the Ethafoam 400 extruded polyethylene (PE) foam produced by DOW, with a density of 58 kg/m^3 . In this study, we have used two configurations shown in figure 2: the foam surrounds the product (figure 2.a), or it is only placed in the corners of the product (figure 2.b).

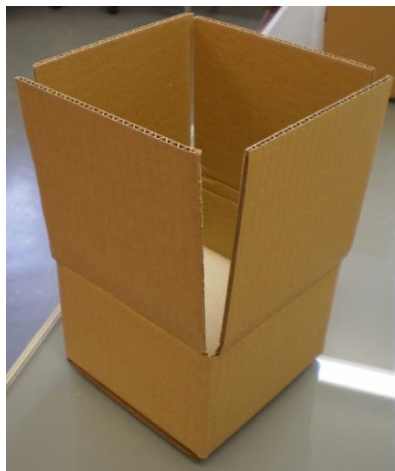


Figure 1: Corrugated cardboard box.



Figure 2: Two types of foam configurations.

2.2 Characterization of corrugated cardboard constituents

The procedure to determine the elastic parameters of the corrugated cardboard constituents is described below. The corrugated cardboard consists of two flat layers and a flute (figure 3). These constituents are separated according to the French norm NFQ03-043 in order to determine the material parameters of each layer. The tensile test samples are cut using the ELCEDE MFT20 cutting table. The tensile tests are performed on the 3 layers in the Machine Direction (MD), Cross Direction (CD) and 45° Direction. We observe that the paperboards have a higher strength in the MD direction (figure 4).

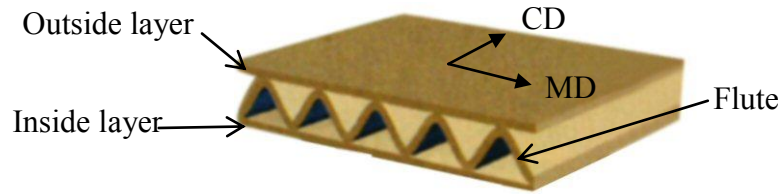


Figure 3: Corrugated cardboard constituents.

The orthotropic constitutive relation between the stresses and strains is defined as follows:

$$\{\sigma\} = \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_{12} \end{Bmatrix} = [D]\{\varepsilon\} = \begin{bmatrix} E_1 & \nu_{12}E_2 & 0 \\ 1-\nu_{12}\nu_{21} & 1-\nu_{12}\nu_{21} & 0 \\ \nu_{21}E_1 & E_2 & 0 \\ 1-\nu_{12}\nu_{21} & 1-\nu_{12}\nu_{21} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} \quad (1)$$

where the subscripts 1 and 2 refer to the MD and CD directions respectively.

The Young's moduli are obtained by calculating the slopes of the tensile curves in the elastic zones. The empirical relations established by Baum *et al.* [4] are used to determine the Poisson ratios and the in-plane shear modulus:

$$\begin{cases} \sqrt{\nu_{12}\nu_{21}} \approx 0.293 \\ G_{12} \approx 0.387\sqrt{E_1E_2} \end{cases} \text{ with: } \frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2} \quad (2)$$

The above characterization procedure allows obtaining the elastic properties of the three cardboard layers (Table 1).

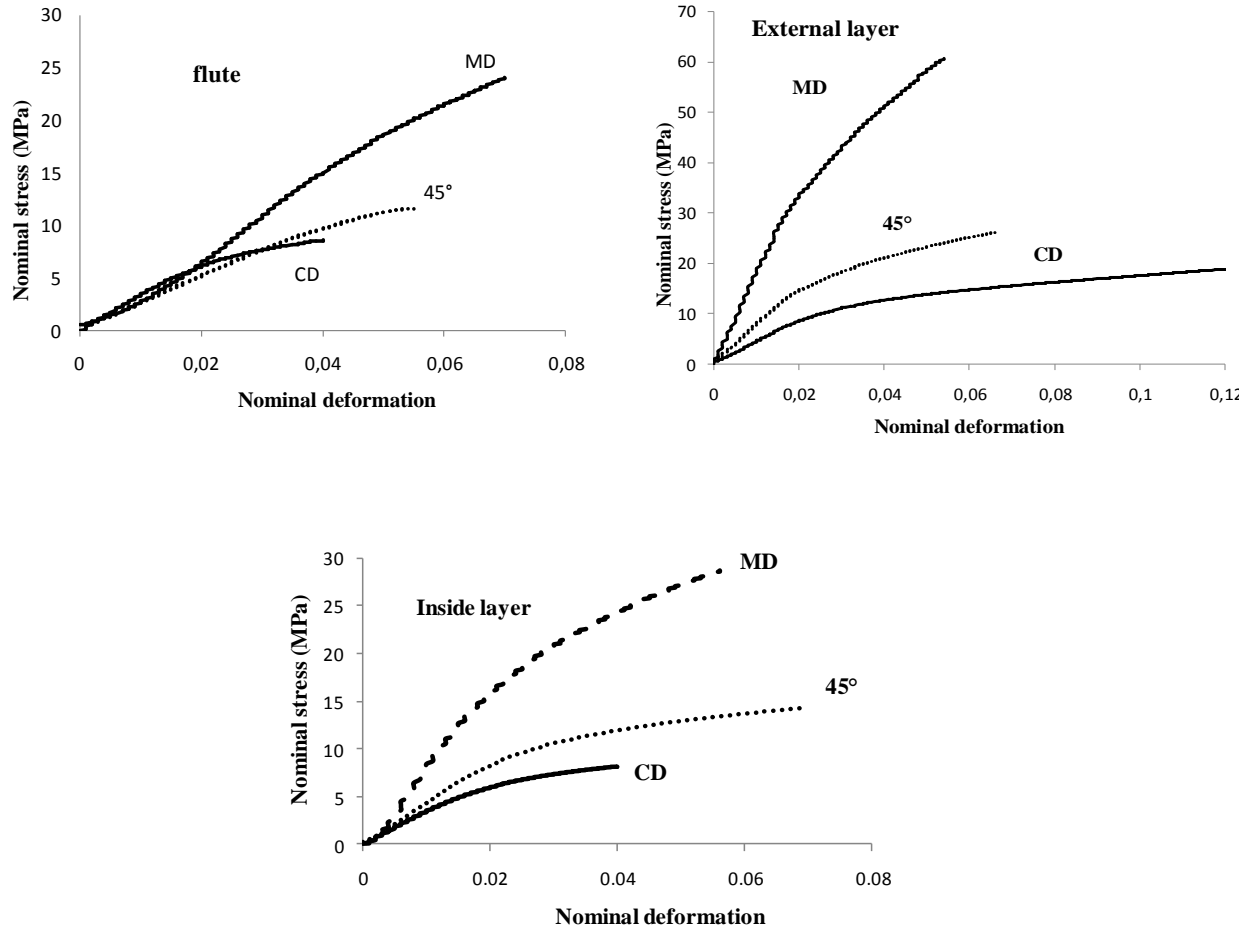


Figure 4: Tensile test on the corrugated cardboard constituents.

Layers	E_1 (MPa)	E_2 (MPa)	ν_{12}	G_{12} (MPa)	Thickness (μm)
Outside layer	1913.7	526.2	0.56	322.0	216.5
Flute	464.3	355.9	0.33	93.0	191.0
Inside layer	1006.8	279.8	0.56	214.0	282.4

Table 1: Material characteristics of the corrugated cardboard constituents.

2.3 Characterization of the foam

Uniaxial and hydrostatic compression tests are performed to characterize the foam. The nominal stresses versus nominal strains are plotted in figure 5. These curves are used to determine the elastic modulus ($E_{foam} = 1.5 \text{ MPa}$) and the hardening curve needed for the crushable foam model of ABAQUS.

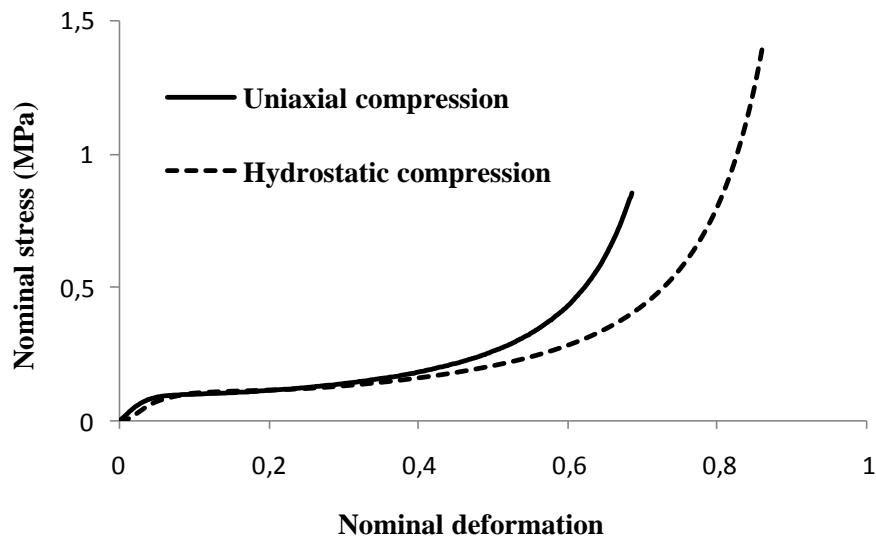


Figure 5. Uniaxial and hydrostatic compression curves of Ethafoam 400.

2.4 Drop tests

The drop test is a simple test method and corresponds well to the reality. The impact velocity of the package is a crucial parameter since great forces affect the package during a short time. This velocity depends on the drop height. The package is placed on a fork at a given height. The fork is withdrawn very fast and the package falls to the ground.

The drop test equipment used here is an AccruDrop Tester from L.A.B. Equipment Inc. (figure 6). The drop height is fixed to $H_{drop} = 1.05 \text{ m}$. To record the acceleration of the product, a triaxial accelerometer (Andevco Isotron 2258A-10) is glued to its horizontal top face as shown in figure 2. The analysis and the visualisation of the measurements are done with Lansmont Test Partner 3 software.

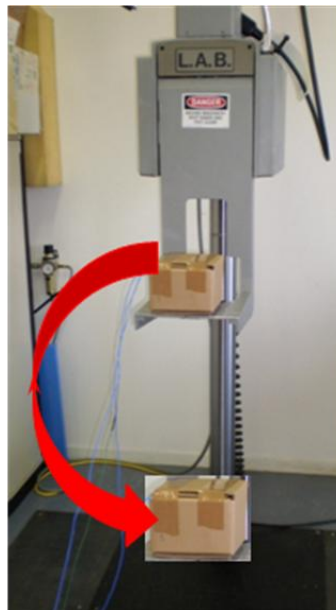


Figure 6: Drop test equipment.

Two types of tests are carried out to study the influence of the packaging for the product protection. In the first one, the product is protected only by the foam. In the second one, the

product is protected by the foam and the corrugated cardboard box. Figure 7 shows typical curves of acceleration versus time corresponding to the shock of the box on the floor. We observe that the protection by the foam insert alone gives the maximum acceleration, which is about 20% higher than the acceleration recorded when using both the foam insert and the corrugated cardboard. Two configurations are studied, one with the foam inserts surrounding the product and the other with the foam inserts on the corners of product.

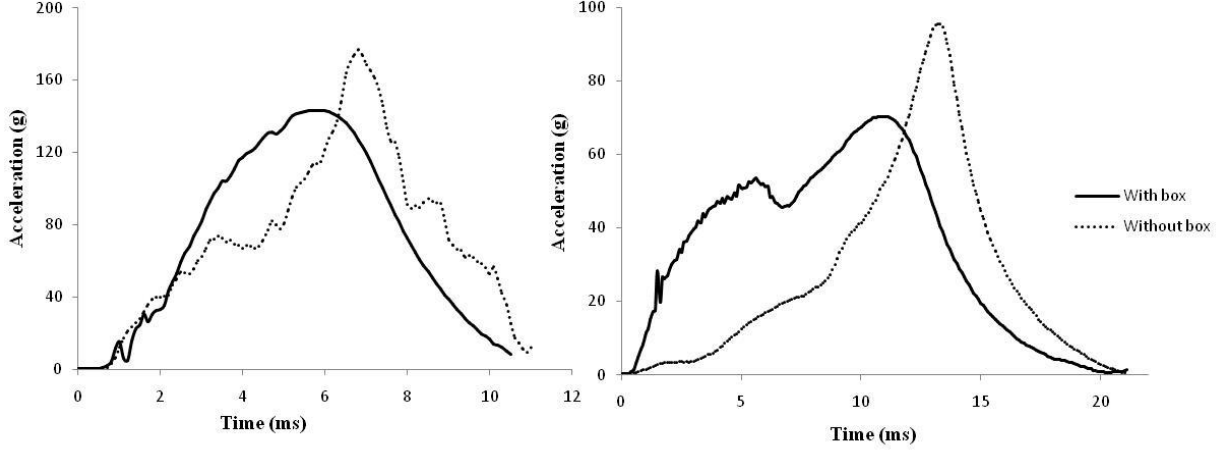


Figure 7: Drop tests with/without corrugated cardboard box using the foam surrounding product (left) or only on the corner of the product (right).

3 MATERIAL MODELS

The material models in the FE simulation are presented in this section. The 3D corrugated cardboard structure is homogenised and replaced by an orthotropic elastic shell. The H-model is then implemented into ABAQUS using UGENS subroutine [5]. The crushable foam model of ABAQUS is used for the foam which is considered as an isotropic material, whose hardening behaviour is a function of the volume change [6].

3.1 Homogenization model of the corrugated cardboard

A 3D geometrical modelling of the three layers of the corrugated cardboard is very tedious and time consuming. In our homogenization model, the corrugated cardboard is represented by a 2D plate. Instead of using a local constitutive law (relating the strains to the stresses) at each material point, the homogenisation leads to a generalised constitutive law (relating the generalised strains to the resultant forces) for the equivalent homogeneous plate. The integrations through the thickness and the machine directions MD are required.

After the integrations or other calculations based on the beam theories [7-8], we obtain the generalised constitutive law in a matrix form:

$$\begin{Bmatrix} \{N\} \\ \{M\} \\ \{Q\} \end{Bmatrix} = \begin{bmatrix} [A] & [B] & 0 \\ [B] & [D] & 0 \\ 0 & 0 & [F] \end{bmatrix} \begin{Bmatrix} \{\varepsilon_m\} \\ \{\kappa\} \\ \{\gamma\} \end{Bmatrix} \quad (3)$$

where $\{N\}$, $\{T\}$ and $\{M\}$ are the internal forces and moments obtained by integrating the local constitutive laws through the thickness of the corrugated cardboard, $[A]$ is the membrane rigidity matrix, $[D]$ is the bending-torsion rigidity matrix, $[F]$ is the transverse shear rigidity matrix and $[B]$ is the membrane-bending coupling matrix.

The corrugated cardboard is more complex than a laminated plate because of the fluting core and the cavities between the two flat layers. In the above matrix, some global effective rigidities obtained by the theory of laminated plates should be modified, such as the rigidities related to the membrane forces and bending moments on the MD section, the transverse shear forces and the torsion moments.

In this paper, the corrugated cardboard is modelled by shell elements, the strains and stresses at every integration point of an element are calculated incrementally. Let $\{dN\}$ the external forces and moments per unit length, they have the following relationship with the increments of the membrane strains and bending curvatures:

$$\{dN\} = [Q]\{d\varepsilon\} \quad (4)$$

The resultant forces and generalized strains at a given point are updated as follows:

$$\{N\} = \{N\} + \{dN\}; \{\varepsilon\} = \{\varepsilon\} + \{d\varepsilon\} \quad (5)$$

The above homogenization model is implemented into ABAQUS using a user subroutine UGENS. The main purpose of this subroutine is to compute the element material stiffness matrix $[Q]$ defined in equation (4), which is used to define the elemental stiffness matrix.

3.2 Model of the foam plastic behaviour

The foam materials have a cellular structure and hence behave in a complex manner, especially under crush conditions [9]. A usual stress–strain curve of polymeric foam has distinct major regions, which are caused by different mechanisms. A linear elastic region, followed by an almost horizontal plateau; this plateau is caused by the cells' collapsing; they buckle elastically and recover completely when the foam is unloaded. When the cells collapse completely, the stress rises steeply (densification) [9-11]. In this section a phenomenological plasticity model, based on the models presented, is proposed for isotropic crushable foam materials. It consists of a modified plasticity model that accounts for a different response in compression or tension, which incorporates uniaxial and hydrostatic compressive hardening laws.

This model with volumetric hardening uses a yield surface with an elliptical dependence of the deviatoric stress $[s]$ on the pressure p in the meridional plane. The elastic behaviour of the foam can be considered as isotropic and linear. The yield surface and the flow potential for the crushable foam model is defined in terms of the pressure $p = -\frac{1}{3} \text{trace}[\sigma]$ and the von Mises stress $q = \sqrt{\frac{3}{2} [s]:[s]}$. The yield surface is defined as follows:

$$F = \sqrt{q^2 + \alpha^2(p - p_0)^2} - B = 0 \quad (6)$$

where the parameter α represents the shape of the yield ellipse in the p - q stress plane; α can be calculated from the initial yield strength in an uniaxial compression (σ_c^0 taken as a positive value), the initial yield strength in hydrostatic compression (p_c^0) and the yield strength in hydrostatic tension (p_t):

$$\alpha = \frac{3k}{\sqrt{(3k_t+k)(3-k)}} \quad \text{with } k = \frac{\sigma_c^0}{p_c^0} \quad \text{and} \quad \sigma_t = \frac{p_t}{p_c^0} \quad (7)$$

The plastic flow potential G is given by:

$$G = \sqrt{q^2 + \beta^2 p^2} \quad (8)$$

where β is related to the plastic Poisson's ratio ν_p as:

$$\beta = \frac{3}{\sqrt{2}} \sqrt{\frac{1-2\nu_p}{1+\nu_p}} \quad (9)$$

The plastic Poisson's ratio, which is the ratio between the transverse and the longitudinal plastic strains under uniaxial compression, must be in the range of -1 and 0.5.

4 RESULTS AND DISCUSSION

The product is considered as a rigid body. The corrugated cardboard box is modelled with a 1024 S4R linear quadrilateral shell elements. The foam is modelled with a 4892 C3D4 tetrahedral elements. The ground is considered as a flat rigid body and fixed in the space. A frictionless contact is assumed between the ground-box, box-foam and foam-product.

The box is positioned 2 mm from the ground and has an initial velocity $V = \sqrt{2gH_{drop}}$, with $H_{drop} = 1.05m$.

The comparisons of experimental and simulated curves of acceleration versus time for three configuration tests are shown in figures 8, 9 and 10. We can see that the finite element simulation results agree well with the experimental results. In table 2, we present the maximum acceleration and the duration of the shock for different configurations. Between the experimental and the numerical results, we have an error of 2.8% for the case with the foam around the product, 9.7% for the case with the foam on the corners of the product and 7.7% for the same case but for the shock in the lateral direction.

It can be noted that the corrugated cardboard box contribute about 20% to the shock absorption. We observe that the corrugated cardboard box undergoes higher von Mises stresses than the foam as shown in figure 11. The comparison between figures 8 and 9 shows also that the surrounding foam gives a more rigid support to the product, leading to a shorter shock so a much stronger impact to the product with respect to the corner foams.

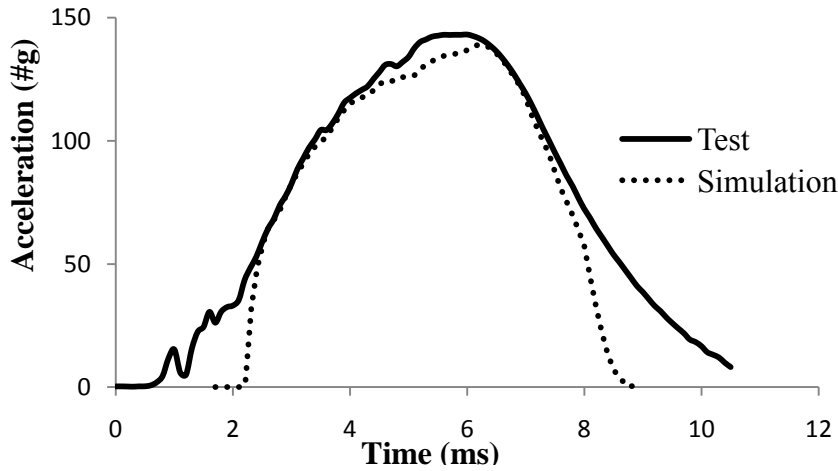


Figure 8: Experimental and numerical curves of acceleration vs. time in the case of surrounding foam.

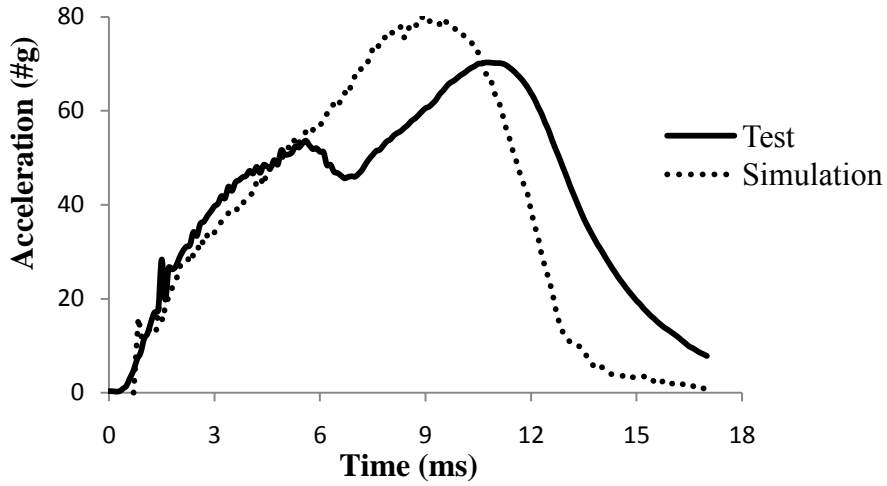


Figure 9: Experimental and numerical curves of acceleration vs. time in the case of corner foams.

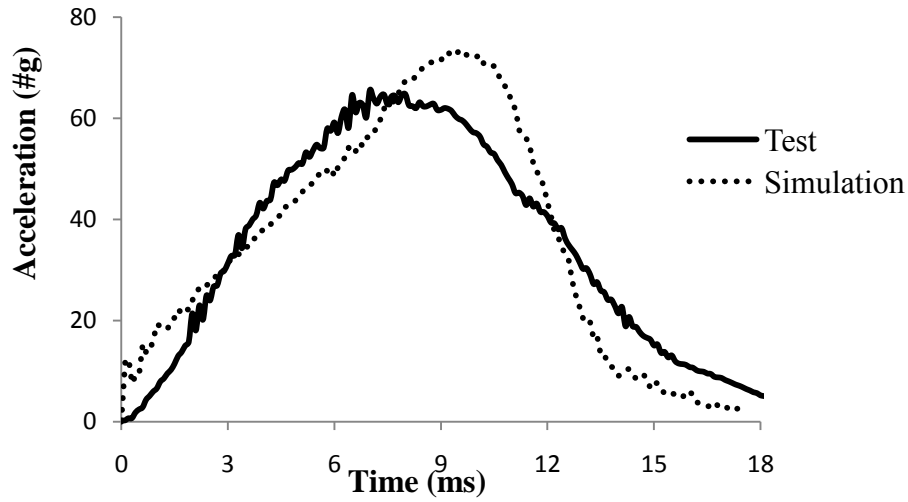


Figure 10: Experimental and numerical curves of acceleration vs. time in the case of corner foams with the shock in lateral direction.

	Foam around product		Foam on the corners		Foam on the corners under lateral shock	
	Simulation	Test	Simulation	Test	Simulation	test
Maximum acceleration (#g)	139	143.12	80	70.2	73.2	65.5
Duration of shock (ms)	6.5	9.3	16.2	19.5	17.3	19.1

Table 2: Comparison of the results obtained by the drop test and the FE simulation.

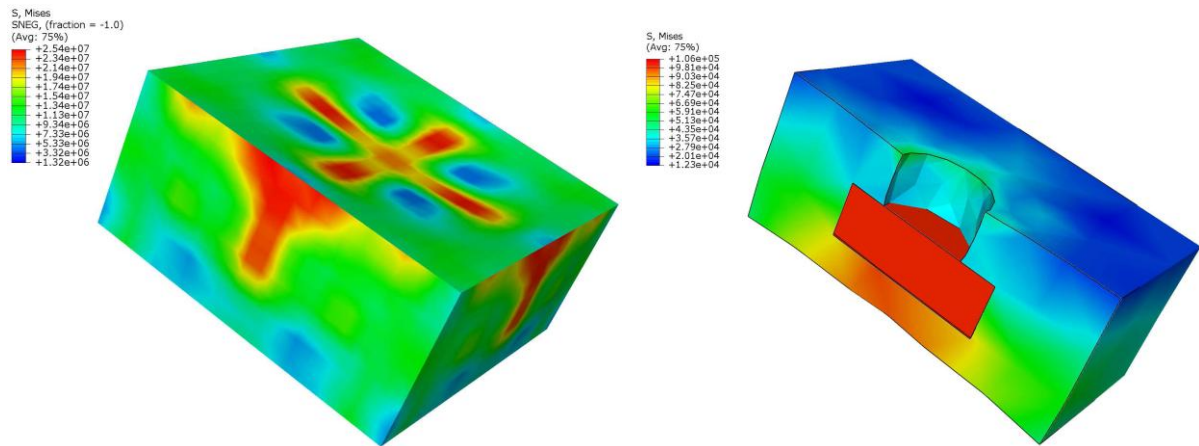


Figure 11: Von Mises stresses on the corrugated cardboard box and on the foam insert.

5 CONCLUSION

In the design stage of packaging systems, we need to simulate the contributions of both the corrugated cardboard box and the foam. According to the drop tests, it is evident that one cannot neglect the corrugated cardboard contribution in the protection of the product. An efficient homogenization model for the corrugated cardboard is developed and implemented into the FE software ABAQUS through the user subroutine UGENS. This model has been used to simulate the drop test of corrugated cardboard box containing different foam inserts and a rigid product. The drop test is instrumented, giving the curves of acceleration vs. time. The FE simulation results agree well with the experimental results. We have also shown that the corrugated cardboard box with supple foams gives a more damping effect to the shock response of the product.

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