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Simulation of the Mechanical Behavior of Corrugated Cardboard Boxes, Octabins and Trays Using a Simplified Elastic Model

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ABSTRACT

The mechanical behavior of corrugated cardboard can be simulated by considering the material as elastic, when the loads are spread over a wide area. The parameters that define its behavior could be obtained from a compression test, for example ECT test, as occurs with other materials that have anisotropy. This study presents a simple methodology to determine the modulus of elasticity both in the corners of the boxes where the cardboard is flattened, and in the central areas where the cardboard retains its thickness. This methodology is applied to several cases of containers subjected to vertical, lateral loads (due to the transport of liquids or substances in bulk), or combined. The results of the simulations are compared with laboratory tests or field tests. In conclusion, it is observed that the stress-strain curves obtained are similar, with a margin of error of around 10%, which is within the dispersion of results observed in laboratory tests.

Keywords: corrugated cardboard boxes; octabins; ECOBOX; elastic behavior corrugated cardboard.

ABBREVIATIONS

ECT: Edge Crush Test

CAE: Computer Aided Engineering

INTRODUCTION

Corrugated cardboard boxes are used in the transport of goods, housing loads of more than one ton of various products, such as frozen food in bags, bulk substances, rigid pieces and so on. In recent years its use has increased by the emerge of e-commerce, and exportation of bulk materials making the analysis of these boxes a subject of interest. This type of boxes is subjected, among others, to vertical or lateral loads. Thus, the thickness and strength of the cardboard must be selected in order to avoid failure of the packaging.

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Figure 1. Different ways in which the box breaks at the end of zone 2.

For the vertical load, numerous empirical studies that propose a way to determine the BCT load have been published, [1-3] among others. The most commonly used model is the McKee's model. This model allows to obtain the load capacity BCT from the Edge Crush Test (ECT) (that gives the load per unit of length ECT) of the cardboard box, perimeter p and wall thickness.

For lateral loads, there is no specific empirical study on the deformation suffered by cardboard containers subjected to lateral loads, produced by bulk materials or by fluids. When these containers are deformed in excess, or when they break, they cause great inconveniences in the industrial supply lines. For this reason, a model that allows estimating the stresses and deformations of the aforementioned packages is of great interest.

If cardboard containers and boxes transport bulk substances or to transport liquids, a lateral force arises in the walls of the container. Excessive forces are able to deform the cardboard walls so that the dimensions exceed the space that is available for the transport. In extreme cases, they can weaken also the container, Figure 2. This type of containers, with a square, rectangular or octagonal basis, are used in the transport of liquids or solid bulk materials. Octagonal-basis boxes are called octabins.

Figure 2. Crease that appears when the deformation of the box is accelerated.

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Bulk substances are made up of fragments, grains, small pieces. They are characterized by the fact that friction forces appear between them when they are in contact. Due to friction, if the bulk is deposited on a flat surface at rest, it would form a cone. The angle formed by its generatrix and the horizontal plane is called friction angle. Examples of transported bulk substances are seeds, plastic grains, stamped metal parts, and so on.

In this article, containers for industrial use are tested by measuring the deformations suffered during compression test, such as BCT, or suffered during it filling with water. Afterwards, the results of the experiments are compared with the results of a simulation using a CAE (Computer Aided Engineering) tool in which it is considered that the cardboard behaves as an elastic and isotropic solid, with a low modulus of elasticity (less than 200*M*N/m^2). The values of the elasticity modulus that are used are in the same range of the values obtained in [3]. The article is organized as follows: in Section 2 the test performed and the data are explained; in Section 3 results are presented; and Sections 4 and 5 are devoted to discussion and conclusions.

TEST PERFORMED

For vertical forces the samples tested are described in table 1. The loading is made under the conditions of the BCT test was carried out in accordance with the UNE 131000 standard. This test is performed on box samples, and the maximum load before the sample collapses is measured, namely *BCT*. The value of E is calculated by E=60·ECT/h. The value of S_{yECT}=ECT/h represents the yield limit of the corrugated card board.

Figure 2. Compression Test (BCT) on corrugated card board boxes.

Table 1. Data of the cardboard boxes tested with compression load (BCT).

Id.	Type	*h* (mm)	*z* (mm)	*p* (mm)	*a* (mm)	*b* (mm)	*x* (mm)	*f*	*n*BCT	*n*ECT
O-04	Octabin	14	1060	3640	455	455	455	16.1	2	10
R-04	Rectangular	13	815	3980	1185	785	-	18.5	2	1

Id.	*BCT*(kN)	*δ*(mm)	*E*(N/mm^2)	ECT(N/mm)	*Sy*,ECT(N/mm^2)
O-04	56.3 ± 2.78	13.3	75.59	27.6 ± 0.7	1.97
R-04	28.9 ± 0.8.	11.3	53.96	23.5 ± N.A.	1.48

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For lateral forces caused by water a rectangular and octagonal basis containers are tested by filling them with water. In Table 2, the geometric data of the boxes is available: thickness (*h*), height (*z*), footprint perimeter (*p*), long side (*a*), short side (*b*), and for octabins the measure of the corner side (*x*). The corner side is zero for square and rectangular containers. A compression test called ECT (according to DIN EN ISO 3037) is performed in a sample taken in the ring. In the case of article OCTA-200, they are put in a pallet of dimensions 1200 × 1000mm^2. The dimensions of the samples are suitable for placing them on pallets of dimensions 1200 × 1000mm^2 and 1140 × 1140mm^2. They can hold a volume of water around 1000 liters which is never reached during the test.

Table 2. Data of the cardboard boxes filled with water to induce lateral stress in the walls.

Article	Type	Pallet (mm^2)	p (mm)	z (mm)	H (mm)	ECT (N/mm)	a (mm)	b (mm)	x (mm)
C12X10-A	Rectangular	1200 × 1000	4160	940	20	32	1140	940	0
OCT-455	Octagonal	1140 × 1140	3640	940	20	33	455	455	455

Containers have been filled using a hose of 1.5 inches (32*mm*) with a pressure of 3.5daN/cm^2 (3.5 bar), similar to those used in fire hydrants. The filling is carried out from the upper part, in a freeway, as it can be seen in Figure 1 (left). The filling flow is regulated at 100l/*min*, so that they are required about 5 to 10 minutes to fill a container of 500 to 1000 liters. During the filling process, measurements of the lateral deformation and the filling height are taken. During each measurement phase, the filling valve is closed, and we wait 1 minute until the fluid is stabilized inside the container. Once the measurement has been carried out, the filling continues. A 500-liter container requires about 10 to 15 minutes to fill, and a 1000-liter container needs about 20 to 25 minutes.

The lateral deformation suffered by the walls of the samples is measured at the midpoint of the longest face, and at a fixed height of 470*mm* from the basis of the container and 604*mm* from the ground (all containers are placed on a 134*mm* high pallet). The measuring height is the same for all containers.

The pallets are built with C22 wooden boards of 18 × 80mm2 section, and no deformation or crushing is observed due to the water load. To measure the deformation, a laser distance meter Model Bosch GLM 50 with a precision of ±1.5*mm* is used, located on a level tripod fixed at a height of 604*mm*, see Figure 2. The filling height, *zw*, is measured by means of a ruler, located inside the container. The weight *W* of the fluid is measured with a forklift scale. It is observed that the weight measured with the forklift coincides with the one calculated using the area of the basis and the height of the fluid.

Figure 3. Measurement of the lateral deformations, δ, of a point on the wall of the box.

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Corrugated board billets made from bonded BC board sheets are also tested. This is done to verify the proposed methodology with a solid structure instead of a sheet. Billets are made with corrugated board sheets and common white glue (polyvinyl acetate) that makes some kind of blocks as shown in figure 3.

Table 3. Geometrical data of the billets and mechanical properties of the corrugated cardboard.

Id.	*num*	*H* (mm)	*HA* (mm)	*B* (mm)	*Z*(mm)
B-01	6	6.7	40.2	300	300
B-03	30	6.7	201	300	300

Id.	*R*(kN)	δ(mm)	*Sy,*B(N/mm²)	*E*(N/mm²)
B-01	8.87	1.9	0.74	116.1
B-03	61.9	9.9	1.03	31.12

Figure 4. Measurement of the lateral deformations, δ, of a point on the wall of the box.

METHODOLOGY

The simulation of stresses and strains is carried out with the ABAQUS software. For the configuration of this software or any other, the following indications must be followed.

The material is assumed to be elastic until the average stress reaches a value equal to ECT/h. From that point on, the material weakens in a process that we will call plastification. When plasticizing occurs, the layers of paper are crushed, or folded, and stick together.

The value of the modulus of elasticity is related to the value of the ECT and the thickness h through the following equation E=60*ECT/h. From the tests compiled in [1], the value oscillates between a maximum and a minimum that is shown in the attached graph.

The load increases gradually and acts on the deformed surface generated in the previous step. To achieve this, the Riks algorithm is usually used to determine the load increment on the previous deformed surface. In the case of filling a container with a bulk liquid or solid, each load increment is applied to the deformed mesh that is imported from the one obtained in the previous step.

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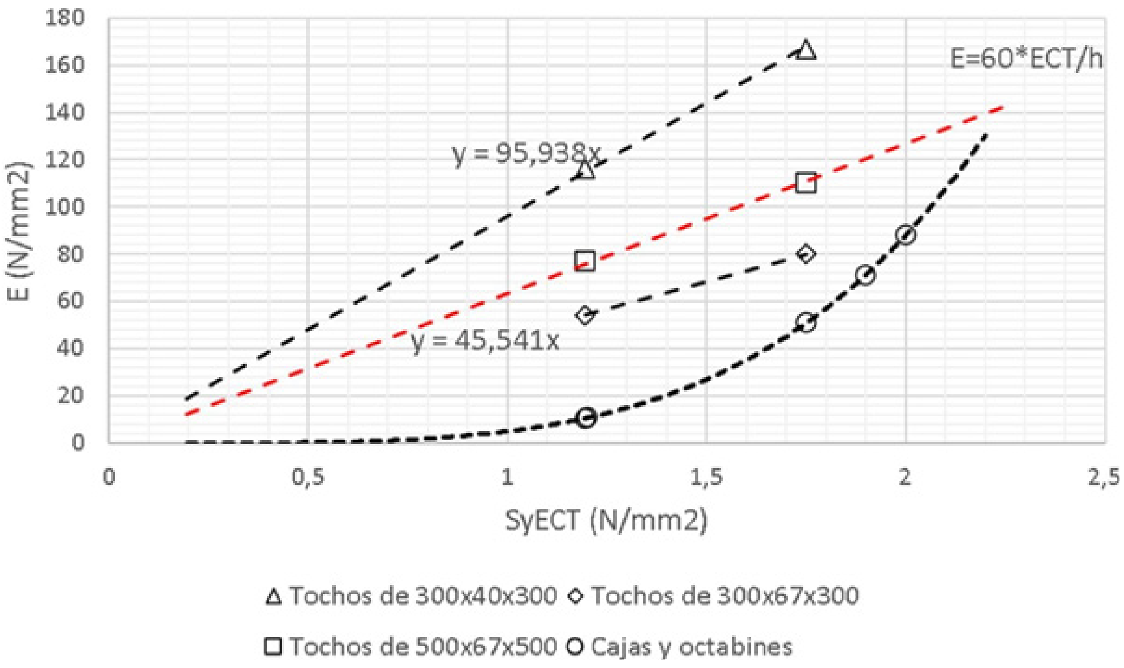

Figure 5. Chart to estimate the Young modulus of the corrugated cardboard.

For the vertical loads, two samples are analyzed, the octabin O-04 and the rectangular R-04 items, respectively. The properties of these items are taken from Tables 1 and 2 and the results are given in tables 4 and 5 and figures 6 to 9. Specifically, Table 5 gathers ECT as a property of the material to be known from experimentation. With this, the stress S_{yECT}= ECT/h and represents the approximate stress limit of the corrugated cardboard and after it is reached the material suffer plastic deformation. For the CAE, the modulus E is estimated using the chart in figure 5. Data for the finite element and mathematical models. The O-04 model has 2200 elements and 2288 nodes. The R-04 model has 8232 elements and 8036 nodes. The mesh is formed of type S4R elements. The mesh nodes in the box foundation are supposed to have pinned condition, with allow rotation of the mesh but constrains movement. To increase the load and calculate the deformation Riks algorithm is used to calculate the vertical deformation δ. The tensions and deformations calculated with the Riks algorithm start from the combination of the first 20 eigenvalues of the buckling modes of the structure.

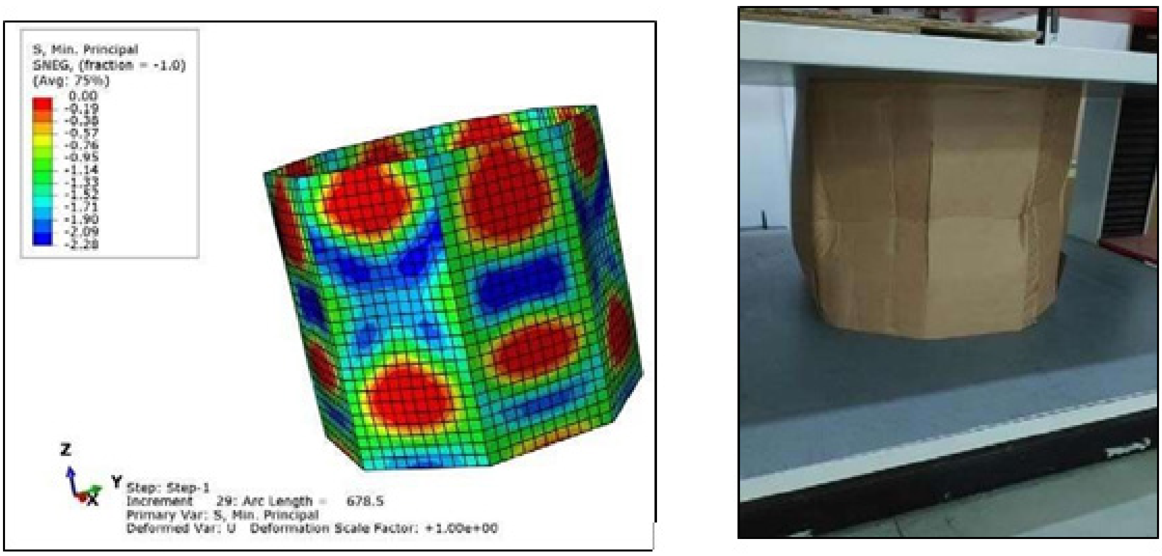

Figure 6. Images of the octabin in CAE simulation and in the testing machine.

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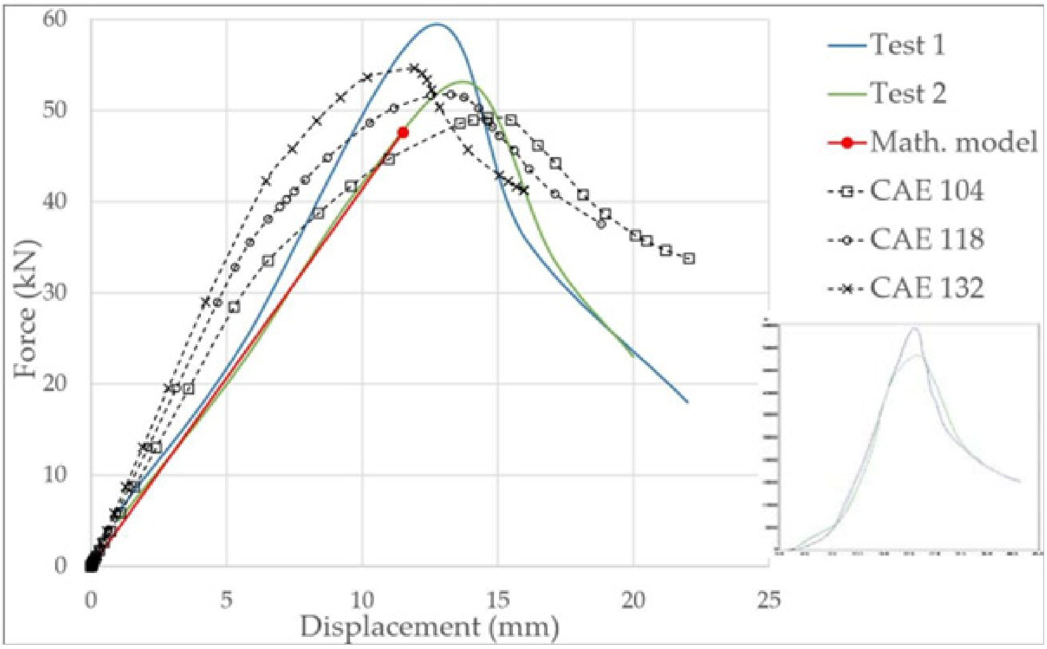

Figure 7. Force vs displacement curve from test and for CAE simulation of octabin under vertical load.

Table 4. Results of the BCT and vertical displacement in the test and in the CAE model.

Model		*BCT* (kN)	δ (mm)
	E = 104 N/mm²	49.2	14.6
CAE	*E* = 118 N/mm²	51.8	13.2
	E = 132 N/mm²	54.7	11.9
Experimental	Test 1	53.5	14.0
	Test 2	59.1	12.5

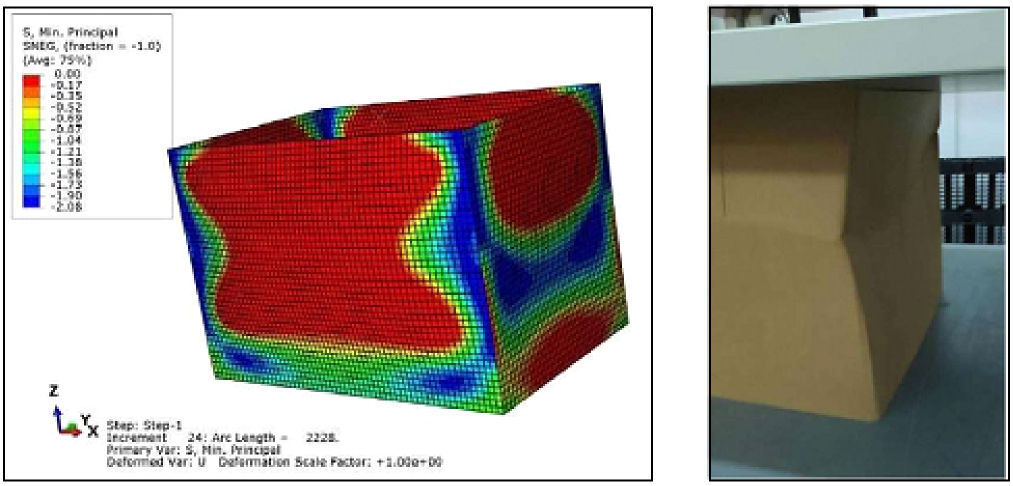

Figure 8. Image of rectangular box R-04 of CAE and in the testing machine.

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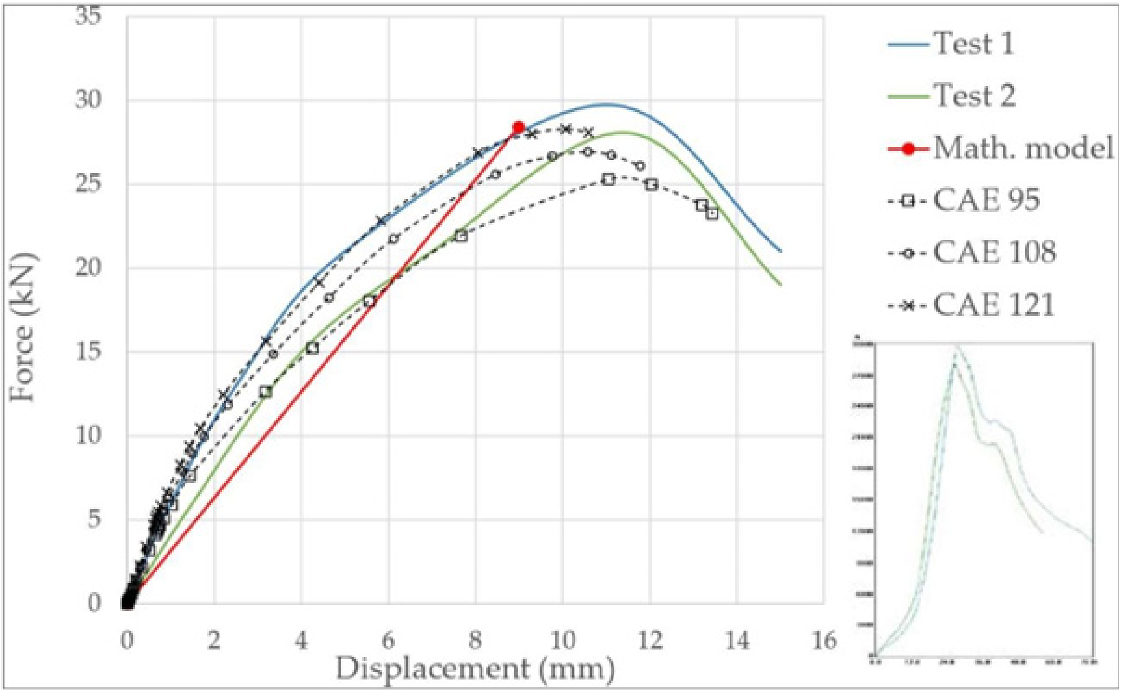

Figure 9. Force vs displacement curve from test and for CAE simulation of rectangular box R-04 under vertical load.

In the case of lateral forces, they are analyzed in two different ways. In the case of octabin O-455, an analysis similar to that used for vertical forces and a mesh type S4R of 9200 elements and 9384 nodes is used. For the increase of the loads, the Riks algorithm is used and the deformations are determined from the combination of the first 20 buckling states. However, in the case of square boxes, as both the load and the area where they are applied change substantially, the Riks algorithm cannot be used. To solve it, first fill levels are established (every 150*mm*). The pressure at a filling level is applied normal to the deformed mesh obtained at the previous level. In the case of the first level, the initial mesh has a strain of 0. The stresses and strains are resolved from the classical equations of statics. In the case of the rectangular box C12x10, a mesh with 10 elements and 11000 nodes is used. The foundation of the box is considered to be encastred, which does not allow displacement or rotation, this applies only to footprint nodes this applies only to base nodes, which is a very limited area. This is so selected because the weight of the fluid compresses the bottom flaps of the box.

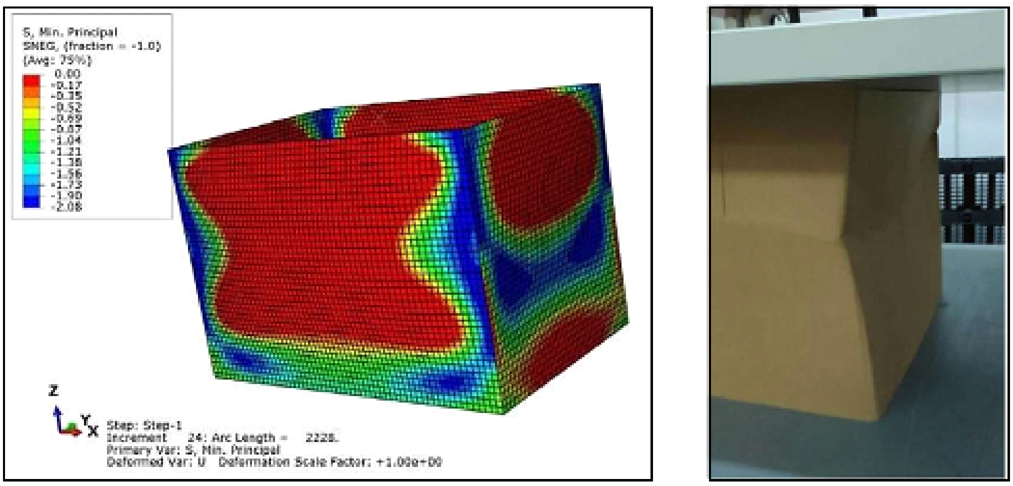

Figure 10. Test sample of the rectangular box (front left) and for the octabin (right).

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Table 6. Deformations, filling height and weight of fluid inside the box.

Article	Δ (mm)	zw (mm)	W (N)
C12X10-A	0.5	170	1821.7
	2	260	2786.2
	3	30	3536.3
	7	400	4286.4
	11	490	5250.8
	25	600	6429.6
	33	640	6858.2
	47	690	7394.0

Article	δ (mm)	zw (mm)	W (N)
OCT-455	1	250	2498.8
	2	350	3498.3
	1	440	4397.9
	2	570	5697.2
	3	650	6496.9
	3	750	7496.4
	6	750	7496.4
	8	810	8096.1
	8	880	8795.7
	9	1000	9995.2

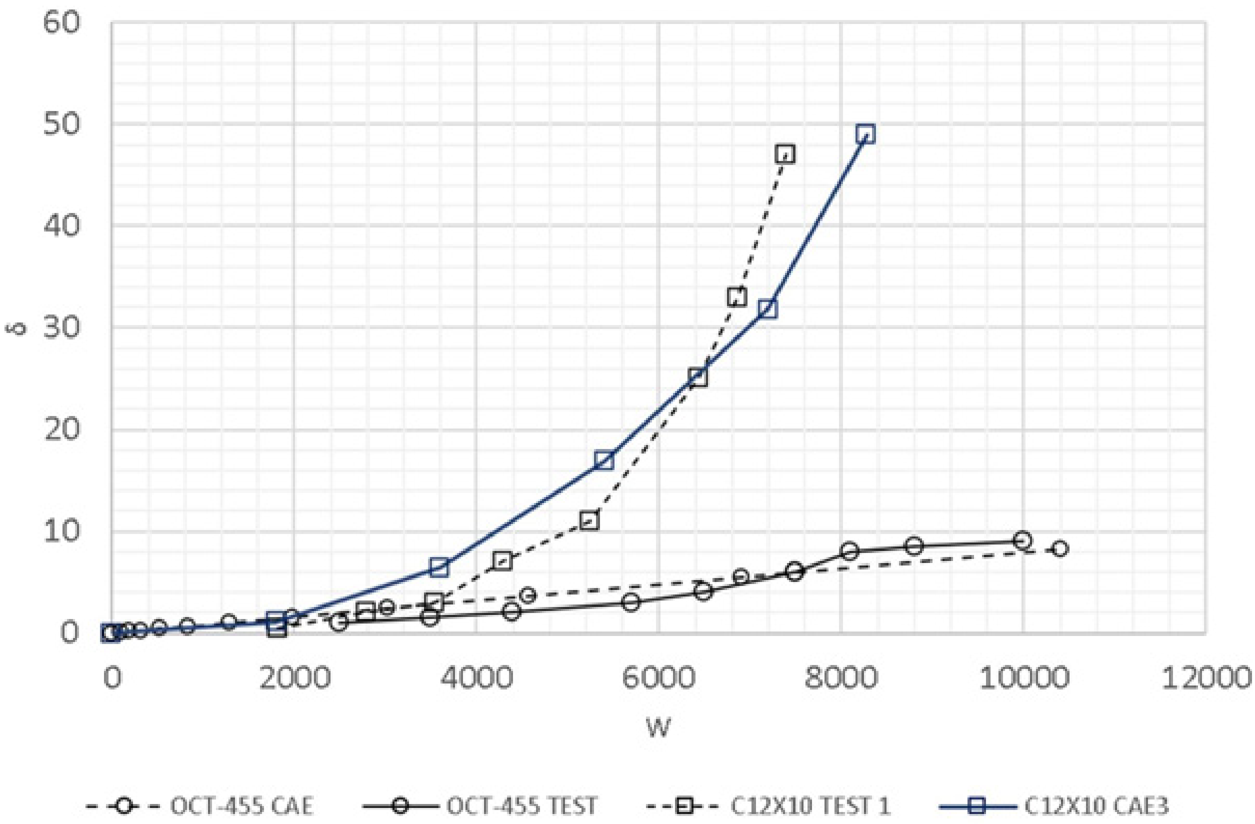

Figure 11. Lateral displacements in the wall of the box and water filling weight in CAE simulation and the tests for the octabin and rectangular boxes.

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Table 4. Comparison of calculated and tested deformations.

Article	p	z	h	ECT	*zw*	*E*	*μ*	a	*W*	δe	δc
C12X10	4160	940	20	32	690	96.0	0.42	1140	8200	47	49
OCT-455	3640	940	20	33	940	99.0	0.42	455	10000	9	8.2

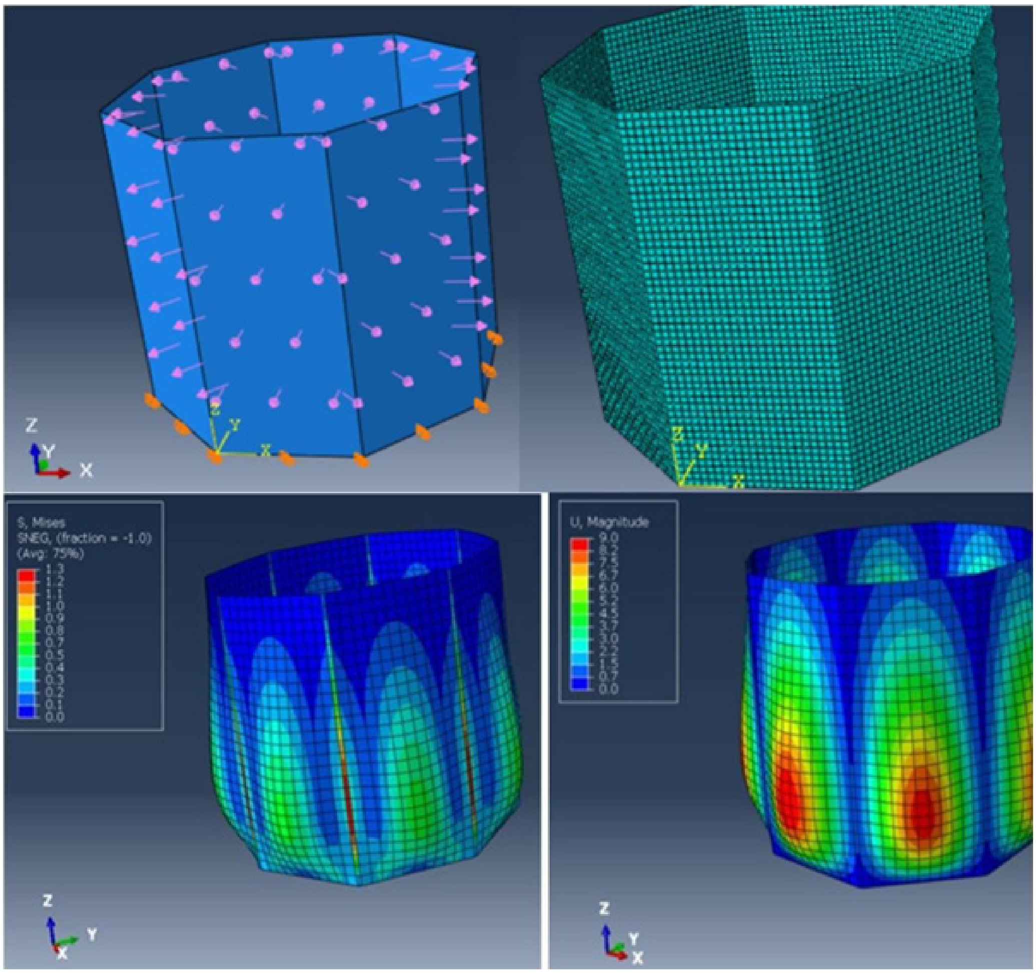

Figure 12. Tensions (left) and deformations (right) of the octabin OCT-455.

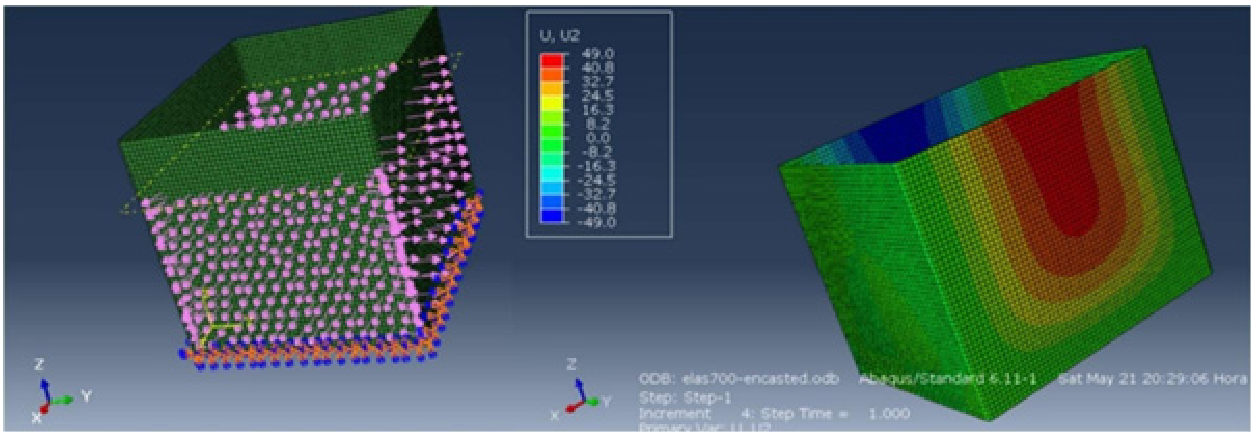

Figure 13. Tensions (left) and deformations (right) of the box C12X10.

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As it can be observed in Figures 11, the deformations obtained in the CAE model are similar to those measured in the test. The error is less than 15%, which is quite approximate considering the variations in resistance that corrugated cardboard usually suffers. The maximum deformations are reached with a stress value of 1.3*N/mm*^{2} for the octabins, and 1.4*N/mm*^{2} for the square boxes. The stress determined in the simulation is smaller than $S_{y,ECT}$ for the cardboard. The CAE model gives deformation results similar to those of the test, at a height of 470*mm*, with a difference in environment at 10%. Taking into account the variations registered in the samples C12X10 and C8X6 (tested twice), the CAE tool can provide deformation results compatible with those observed using low values of the modulus of elasticity (smaller than 200*N/mm*^{2}), which can be determined from the formula E = 60 ·ECT/h.

In the case of the billets, a C3D8R mesh with 3600 elements and 4805 nodes is used. Likewise, the Riks algorithm is used to increase the loads and the deformations are obtained from the first 20 buckling modes. In this case, a voltage limit equal to the value of ECT/h is added. From this point it is assumed that the material plasticizes. In this way the deformation of the mesh is closer to reality.

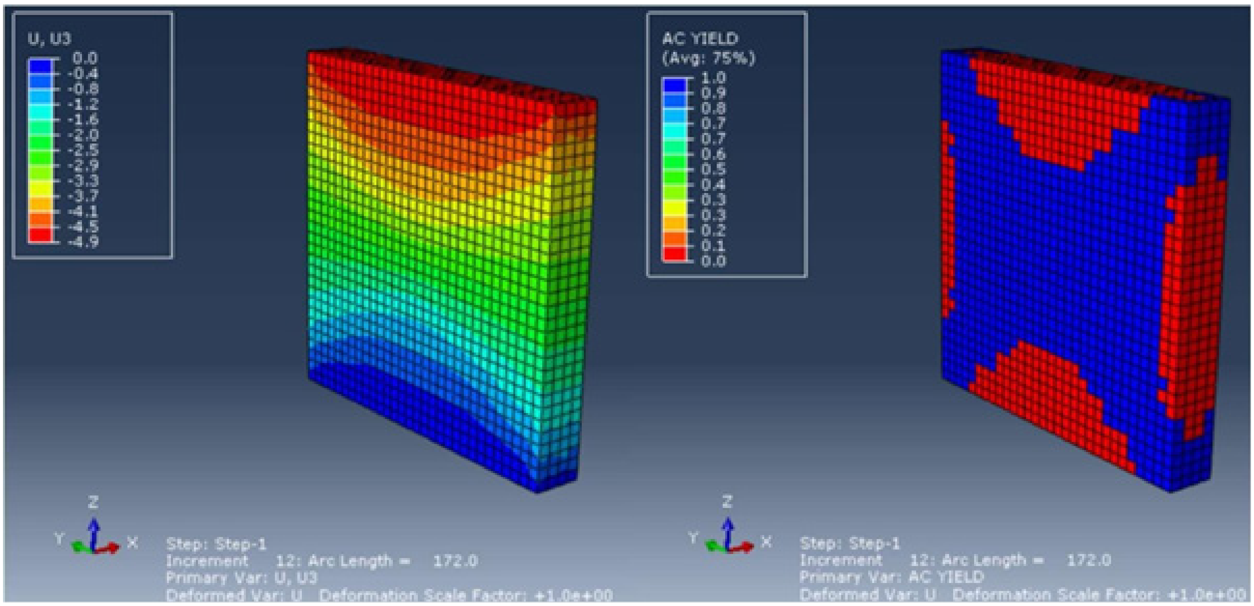

Figure 14. Tensions (left) and deformations (right) of the box C12X10.

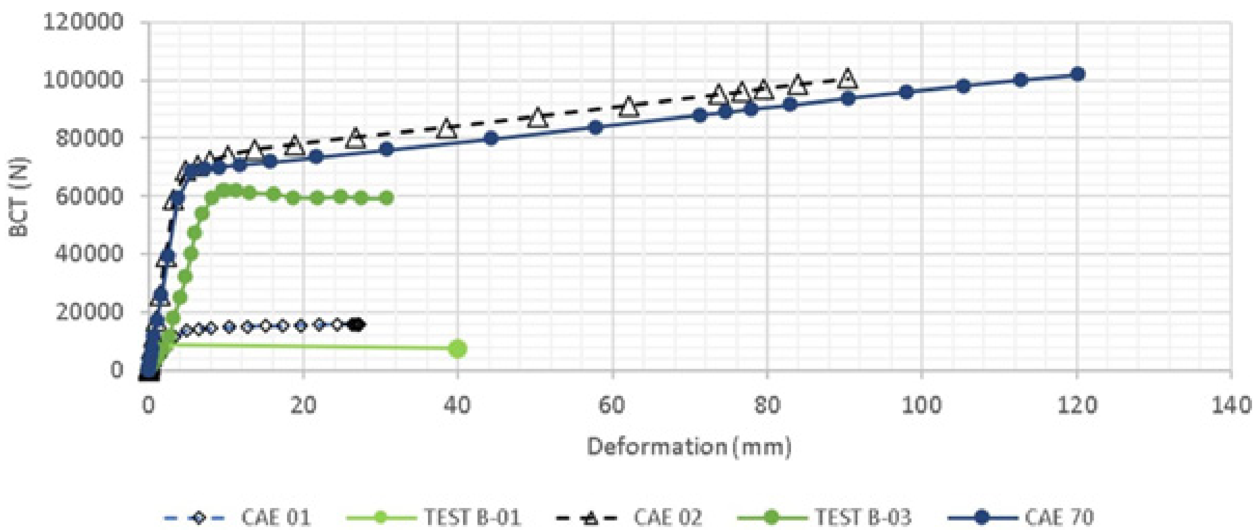

Figure 15. Tensions (left) and deformations (right) of the box C12X10.

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The proposed methodology can be applied with all FEFCO shapes of boxes as long as the dimensions of the faces are at least 5 times greater than the thickness of the cardboard. Figure 16 summarizes the application of the CAE model to a FEFCO 0423 cover of dimensions 600x400x100mm^3 with an opening of 60x60mm^2. A BC channel board made with 250g/m^2 kraft paper and 160g/m^2 semi-chemical paper has been used. The ECT is 12N/mm.

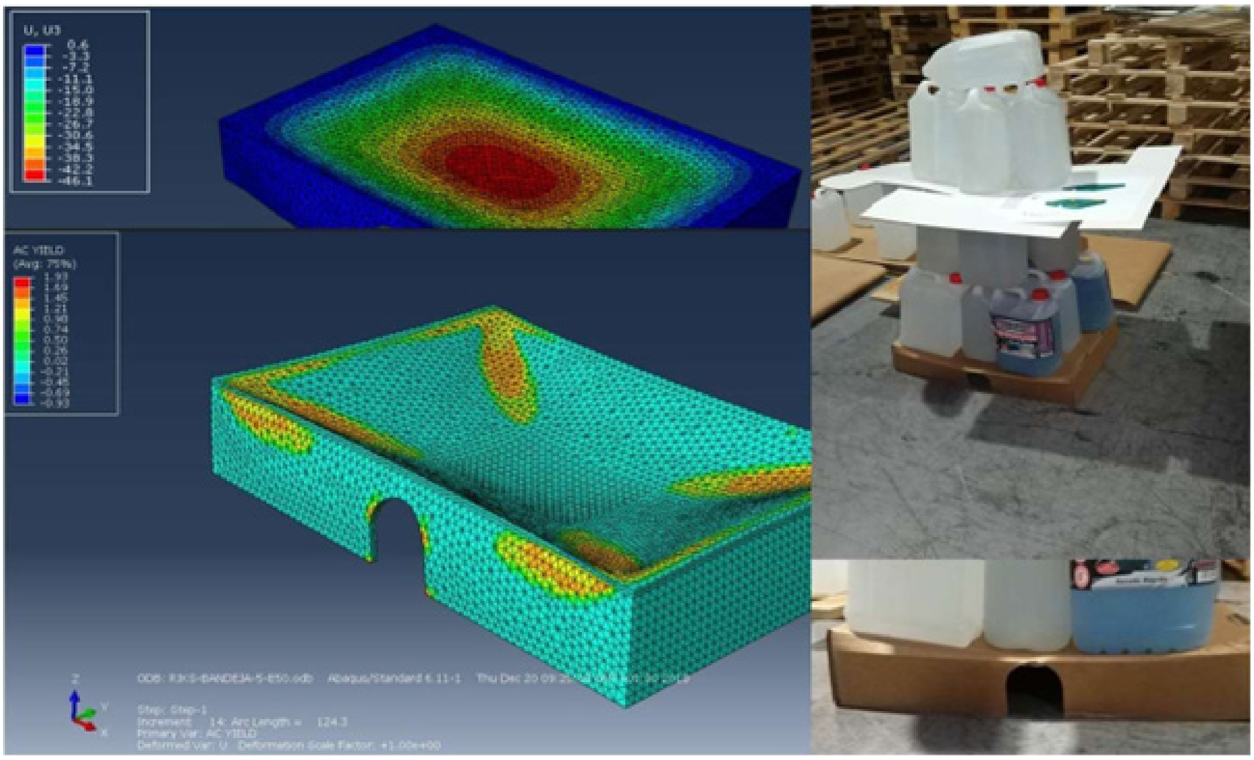

Figure 16. Example of application in a cover type FEFCO 0423 subjected to vertical load in its center.

CONCLUSIONS

The deformations obtained with the CAE model have a difference of less than 15% with respect to the results of the tests or the filling tests. Therefore, the model can provide good precision for its application in the study of real cases, providing good precision in the case of complex geometries where the Mckee equation cannot be used.

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CONFLICTS OF INTEREST

The author declares no conflict of interest.

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