NUMERICAL AND EXPERIMENTAL STRUCTURAL ASSESSMENT OF A HALF SCALE MODEL OF A NUCLEAR SPENT FUEL ELEMENTS TRANSPORTATION PACKAGE UNDER 9 M DROP TESTS

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Abstract. *The applied qualification requirements for the packages used in the transportation of nuclear spent fuel elements are very severe due the nature of the radioactive content. They include the so-called normal conditions of transport and the hypothetical accident conditions. The 9 m drop tests are the most critical hypothetical accident conditions. The package qualification under these conditions shall be conducted using full scale models (prototypes), small scale models, numerical simulations and a combination of physical tests and numerical simulations. The choice of the qualification approach depends on economical and safety aspects. To comply with the nuclear safety functions, as the containment of the internal products and biological shielding, the package itself has several components connected to each other in different ways (welded parts, flanged connections, surface contacts, etc.). This paper presents a discussion on the combination approach with tests and numerical simulations for the structural assessment of a half scale model of a package for transportation of nuclear research reactor spent fuel elements under 9 m drop tests. The numerical simulations of the 9 m free drops over a rigid surface of half scale model of the transportation package under different orientations were conducted using a finite element explicit code considering several nonlinear aspects as the nonlinear materials models and properties, the different package materials stiffness, and the different types of the contacts between the package components and between the package and the rigid surface, including the friction in the contacts. The tests were also conducted for different drop orientations. The half scale model under test was instrumented to assess the deceleration levels and all tests were recorded with pictures, high speed camera movies, size measurements and damage characterization (localization, sizing and type). The numerical and experimental results are compared and comments and conclusions are addressed based on the comparison. Also, some recommendations are issued on the use of the numerical simulations for the full scale tests of the package.*

Keywords*: transportation package; drop test; impact; contact*

1. INTRODUCTION

Since 2001, the International Atomic Energy Agency (IAEA) has supported several regional Latin American projects related to the development of options to the storage and transportation of the spent fuel elements from the nuclear research reactors in the region. The design and qualification of a nuclear research reactors spent fuel elements transportation package is one of the project tasks and this paper describes part of the efforts related to it.

The radioactive materials transportation is regulated by guides and standards like IAEA (2005) and CNEN (1988). The main purpose of these regulations is to protect persons, property and the environment from the effects of radiation during the transport of radioactive material. This protection is achieved by requiring the containment of the radioactive contents, the control of external radiation levels, the prevention of criticality, and the prevention of damage caused by heat.

Based on the applied standard, nuclear research reactors spent fuel elements transportation packages need qualification, which involves the evaluation of some conditions in a given sequence that simulates possible accidents. So, for its qualification, after the sequence of simulated conditions, the cask should maintain its safety functions through its structural and functional integrity. This is achieved if, in any condition, there is the containment of the radioactive products inside it, the integrity of its biological shielding and assurance against criticality of the fuel elements.

The transportation packages must be structurally qualified for the normal conditions of transport and the hypothetical accident conditions which are critical in relation to the cask mechanical sizing. It must be demonstrated that the cask has to be sturdy enough to resist:

- A drop onto a rigid target so as to suffer maximum damage, and the height of the drop measured from the lowest point of the cask to the upper surface of the target shall be 9 m;
- A puncture resultant from drop so as to suffer maximum damage onto a bar rigidly mounted perpendicularly on a rigid target. The height of the drop measured from the intended point of impact of the cask to the upper surface of the bar shall be 1 m and the bar shall be of solid mild steel of circular section, 15.0 ± 0.5 cm in diameter and 20 cm long unless a longer bar would cause greater damage, in which case a bar of sufficient length to cause maximum

damage shall be used. The upper end of the bar shall be flat and horizontal with its edge rounded off to a radius of not more than 6 mm;

- A fire resulting in a temperature of 800 °C for 30 min;
- A submersion to a 200 m depth of water.

The 9 m drop test is considered the most critical hypothetical accident condition. The package qualification under these conditions shall be conducted using full scale models (prototypes), small scale models, numerical simulations and a combination of physical tests and numerical simulations. The choice of the qualification approach depends on economical and safety aspects.

Considering only the 9 m drop tests, this paper presents a discussion on the combination approach with tests and numerical simulations for the structural assessment of a half scale model of a nuclear research reactor spent fuel elements transportation package.

The numerical simulations of the 9 m free drops over a rigid surface of half scale model of the transportation package under different orientations were conducted using a finite element explicit code considering several nonlinear aspects as the nonlinear materials models and properties, the different package materials stiffness, and the different types of the contacts between the package components and between the package and the rigid surface, including the friction in the contacts. It is important to mention that, to comply with the nuclear safety functions, as the containment of the internal products and biological shielding, the package itself has several components connected to each other in different ways (welded parts, flanged connections, surface contacts, etc.).

The tests were also conducted for different drop orientations and followed by representatives from IAEA and the participating countries (Argentina, Brazil and Chile). The half scale model under test was instrumented to assess the deceleration levels and all tests were recorded with pictures, high speed camera movies, size measurements and damage characterization. The numerical and experimental results are compared and comments and conclusions are addressed based on the comparison. Also, some recommendations are issued on the use of the numerical simulations for the full scale tests of the package

2. THE HALF SCALE MODEL OF THE TRANSPORTATION PACKAGE

Figure 1 shows a cross section of the package half scale model constructed to be tested. Its main parts are: Internal Basket to accommodate the spent fuel elements, one internal and one external stainless steel cylinder connected by two flanges (internal and external) with lead located between the lateral and lower parts, an upper closure (Primary lid) constituted by a shell surrounding a plate of lead, located on the internal flange. The lead constitutes the biological shield against the radiation. There is, also, a plate connected to the external flange by bolts to fix the upper closure (Secondary lid).

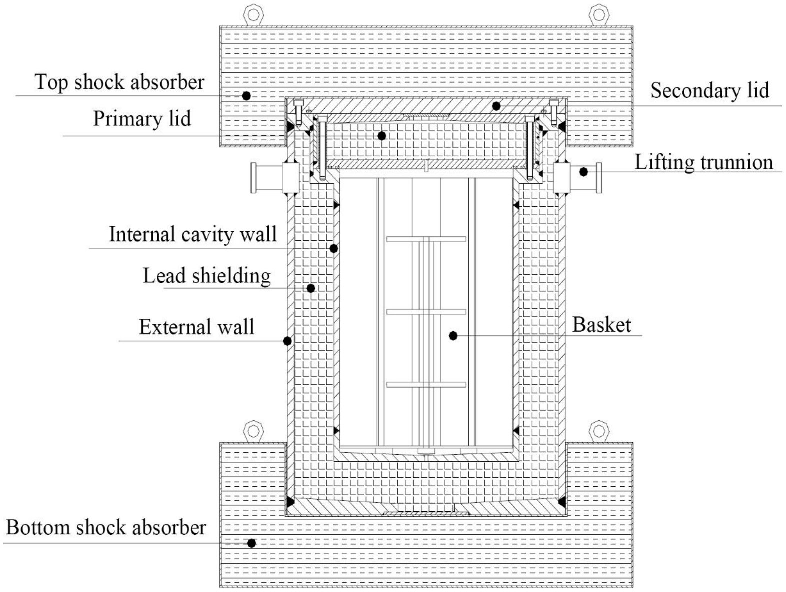


Figure 1. Cross section of the half scale model of the package

There are two shock absorbers, each one surrounded by a thin stainless steel shell. They are connected by four round bars, and are constituted by Oriented Strand Board (OSB) glued plates. Usually, the OSB, a kind of composite or reconstituted wood, has an orthotropic behavior but when confined, as in this project, it behaves as an isotropic material (see next sections).

The external cylinder has a diameter of ~ 0.50m and it is ~ 0.60m high. With the shock absorbers the package overall dimensions are: external diameter ~ 0.90m and ~ 1.00m high.

Figures 2 and 3 show, respectively, an internal view of the half scale model of the package and the bottom shock absorber partially assembled.

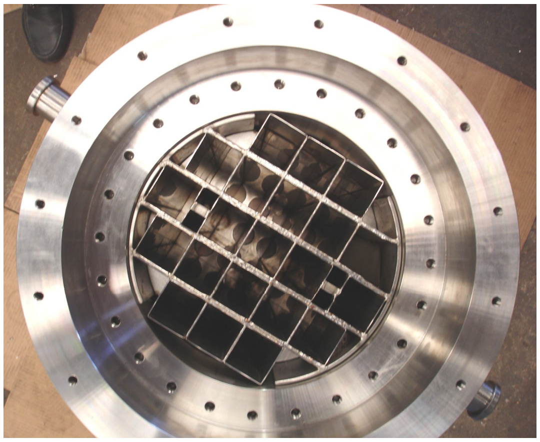


Figure 2. Internal view of the package half scale model

Figure 3. Bottom shock absorber partial assembling

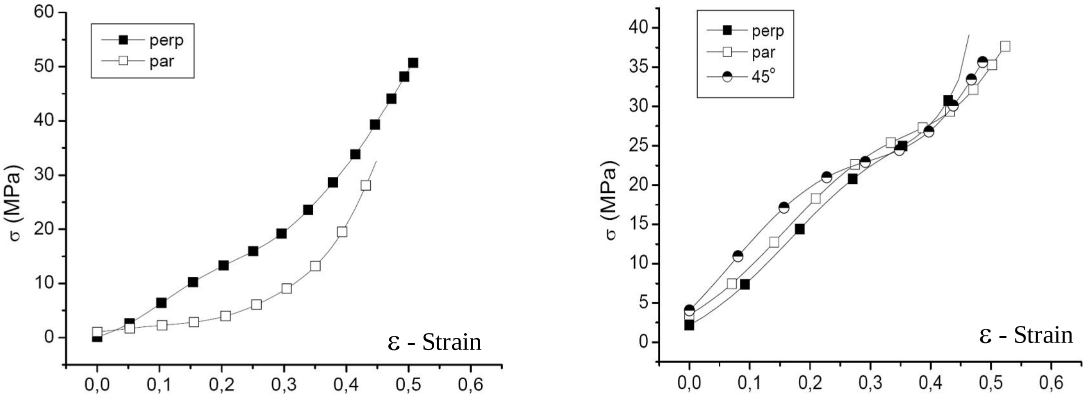
3. SHOCK ABSORBERS MATERIAL CHARACTERIZATION

The material chosen for the package shock absorbers is the wood composite named Oriented Strand Board (OSB). The OSB is an engineered, mat-formed panel product made of strands, flakes or wafers sliced from small diameter, round wood logs and bonded with a binder under heat and pressure. Its commercially available dimensions range from 6 mm to 40 mm in thickness and up to 5,000 mm x 2,800 mm in length and height.

As the properties of the OSB are not well known, especially its response to dynamic loads, a testing campaign was conducted to determine the parameters of interest for the intended use.

To study the effect of the lateral constraint in the dynamic response of the OSB, both encased and non encased specimens were submitted to impact tests (Mourão, 2007). The specimens, also made of glued layers of OSB, consisted of cylinders with 60 mm in diameter and 30 mm height. The direction normal to the glued surfaces was defined as the specimen perpendicular (perp) direction, whereas the glued surfaces define the specimen parallel (par) directions. Besides the perpendicular and parallel directions, the specimens were also tested at 45° angle. The encased specimens were surrounded by a 0.5 mm thick metallic shell.

The averaged stress-strain curves obtained are shown in Fig. 4 (all curves were filtered at 500 Hz, low pass filter) (Mourão, 2007). As can be seen, from Fig. 4, the non encased specimens respond as an anisotropic material. On the other hand, the OSB behaves as a nearly isotropic material when tested under lateral constraint condition.



Non-encased specimens

Encased specimens

Figure 4. Shock absorbers material stress-strain curves for different directions

This behavior can also be seen clearly in Tab. 1, which shows the values for specific energy U absorbed at 0.45 of strain. The difference in U values in parallel and perpendicular directions for the unconstrained situation is 47% (7.0 to 3.7 MJ/m^3), while the average difference for the encased specimens between the three test directions is less than 10%.

Table 1. Specific energy absorbed (U) @ ε = 0.45.

		U (MJ/m^3)
Non-encased specimens	Perpendicular	7.0
	Parallel	3.7
Encased specimens	Perpendicular	7.5
	Parallel	8.2
	45°	8.4

For the encased specimens, the values of Young modulus determined in the three impact test directions are: E_{perp} = 68 MPa (perpendicular direction), E_{par} = 65 MPa (parallel direction) and E_{45} = 81 MPa (45° angle).

Although having the OSB mechanical properties characterization in two conditions obtained from tests with non encased and encased specimens, the choice for the use of the properties of the later may be justified by three reasons:

- The encased behavior of the OSB is not given only by the surrounding steel shell but also from the self lateral constraining without splintering.
- The deformed configurations of the non encased specimens after the impact tests show splintering in outer parts that are not expected to occur in the shock absorbers.
- According to Diersch et al. (1994), only a minor increase in the compression forces can be observed due to the influence of the steel casing with thicknesses of 0.5 mm in wood specimens of diameter of 100 mm, avoiding the specimens lateral splintering in the impact tests.

4. NUMERICAL SIMULATIONS OF THE PACKAGE HALF SCALE MODEL 9 M DROP TESTS

The half scale model of the package structural evaluation under the drop test condition may be conducted by finite element numerical simulations considering several nonlinear aspects as the nonlinear materials models and properties, the different package materials stiffness, and the different types of the contacts between the package components and between the package and the rigid surface, including the friction in the contacts.

In this paper, the numerical simulations of the 9 m free drops over a rigid surface of half scale model of the described transportation package under different orientations were conducted using a finite element explicit code ANSYS LS-DYNA (ANSYS, 2007).

In high velocity impact analysis, the deformations can be very large and predetermination of where and how contact will take place may be difficult or impossible. For this reason, the automatic contact options are recommended as these contacts are non-oriented, meaning they can detect penetration coming from either side of an element.

Due to the impact condition and due to the geometric features of the half scale package showed in Fig. 1, it was used the so-called AUTOMATIC SURFACE TO SURFACE contact option of the ANSYS LS-DYNA code.

Modeling the contact between the OSB material (soft) and other steel package parts (rigid) poses several challenges in impact conditions. This is due to its relatively low stiffness of the first when compared with other structural materials which has an indirect effect on its contact-impact interactions with other materials.

An important point in contact modeling of the impact between materials with large differences in their stiffness is the procedure to avoid the collapse of the first row of soft materials, due to large compressive strains, that leads to an abnormal run ending with negative volumes issues. For strain magnitudes larger than the last input point in the curve, the code extrapolates using the last slope. This may yield small stress values and fails to model the bottoming out effect that occurs at large compressive strains. Following the recommendations from Bala (2006) verified by numerical tests (Miranda et. al, 2008), the fix to this is to manually provide an exponentially increasing curve to cover compressive strains to a minimum of 95-99%. It must be noticed that the manual curve must be smooth. The modified curve used in this paper is showed in Fig. 5.

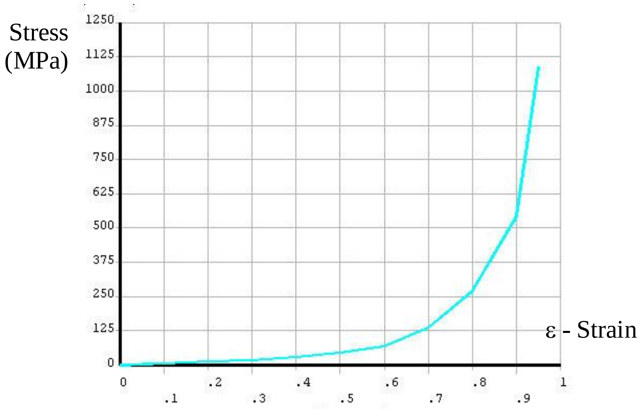
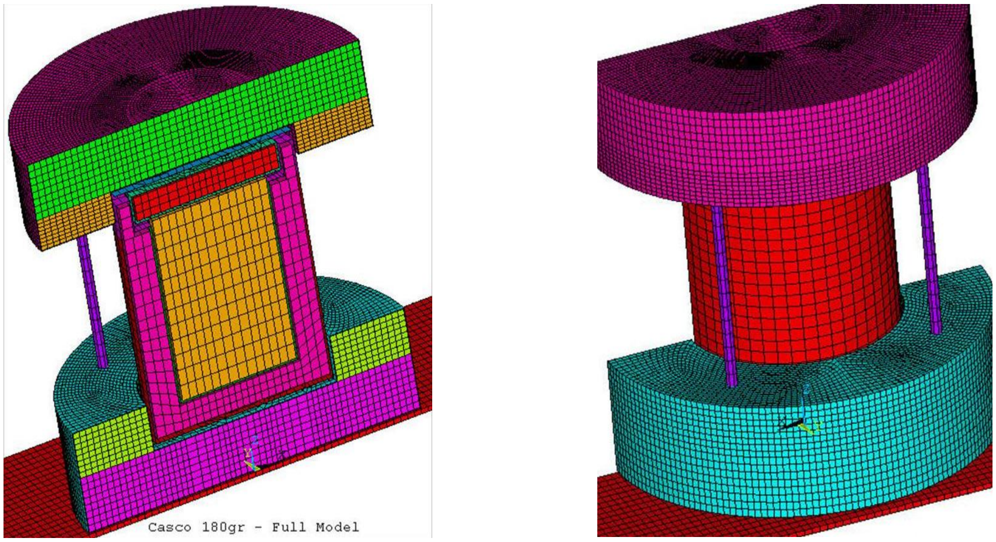


Figure 5. Modified shock absorbers material stress-strain curves used in the analyses.

Some penetration between soft and rigid materials can be found during the maximum compressive strain. This may be attributed to the way the segment thickness is computed for solid elements. Much like shell elements, in which the mid-surface is offset in both directions of the segment normal, the solid segments maximum allowable thickness is also computed. The amount of maximum allowable thickness is based on a small percentage (5%) of the solid element diagonal which, based on the element geometry, could be very small making it vulnerable to nodal release. So, it is recommended to increase the offset thickness to a value adequate to ensure that no nodes are released from contact.

4.1. Finite element model

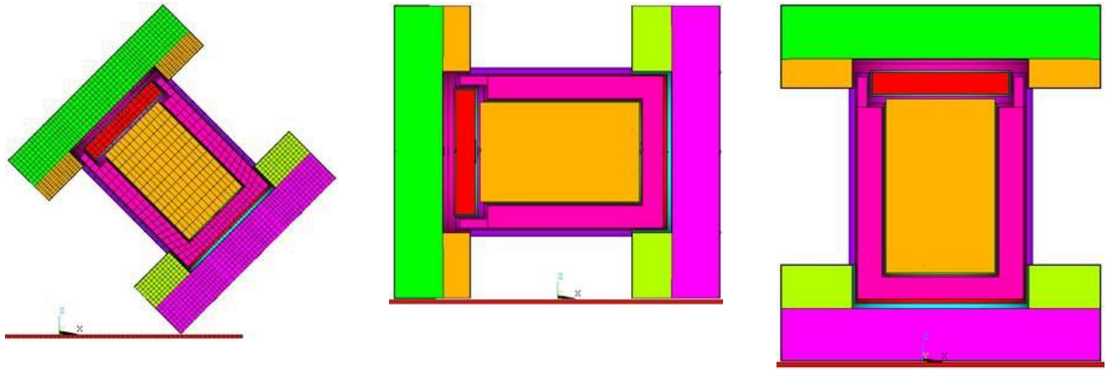
A 180° finite element model, showed in Fig. 6, was developed using solid and shell elements and considering the symmetries in the structures. Parts as trunnions, bolts and threads were not modeled. This model can be rotated to cover all drop orientations that must be simulated (see Fig. 7)..



Front view

Back view

Figure 6. 180° finite element model



Corner drop Horizontal drop Vertical drop

Figure 7. Numerical simulations drop orientations.

4.2. Materials modeling

The half scale package model materials are indicated in Tab. 2.

Table 2. Half scale package model materials.

Cask Part	Material
Lower shell	stainless steel
Bottom shock absorber	wood (OSB)
Inner shell	stainless steel
Shielding	lead
Outer shell	stainless steel
Top shock absorber	wood (OSB)
Upper shell	stainless steel
Tie bars	stainless steel

The shock absorbers filling material (OSB) was modeled as crushable foam with its correspondent curve following an isotropic linear behavior until a strain of $\varepsilon = 0.45$, extended until $\varepsilon = 0.95$, as per Fig. 5, to avoid numerical instabilities. The rigid surface was modeled with the ANSYS LS-DYNA RIGID option. The steel parts, including the round bars, as well as the lead ones were modeled as Bilinear Isotropic Material (BISO). The basket was modeled in a simplified way as a continuous mass with fictitious values and a density value that reproduces the mass predicted to fill the cask. All adopted material properties, except OSB, can be seen in Tab. 3.

Table 3. Materials properties adopted in the analyses.

	Steel	Lead	Mass	Bar	Rigid Surface
E - Young's modulus (N/mm^2)	200e9	14e9	2e9	200e9	200e9
υ - Poisson's ratio	0.30	0.42	0.0	0.30	0.30
γ - Density (kg/m^3)	7500	11500	600	7500	7500
σ_{ys} - Yield stress (N/mm^2)	310e6	14e6	-----	310e6	-----
E - Tangent modulus (N/mm^2)	7.6e8	1.0e7	-----	7.6e8	-----

4.3. Numerical simulations

The analysis starts as the model touches the rigid surface, so the applied initial velocity (13.3 m/s) corresponds to the 9m free drop. Additionally the gravity acceleration was applied to the model.

Three analyses were performed simulating the vertical, the side (horizontal) and the 45° (corner) impact. In general, the results in terms of displacements along the time are smooth while in terms of accelerations a low pass filter like Butterworth-type should be adopted due to the noise introduced by the successive integrations (IAEA, 2008).

5. HALF SCALE TRANSPORTATION PACKAGE 9 M DROP TESTS

The half scale transportation package 9 m drop tests were performed in the following sequence: corner drop, horizontal and vertical orientations. The shock absorbers were replaced from one test to other. Figure 8 shows the model prepared to 9 m drop in the three orientations.

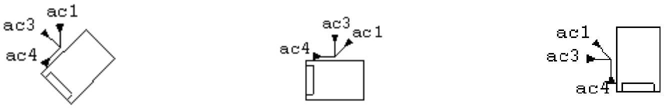
Before the drop itself the model, suspended by a crane, was carefully positioned to assure the desired position and angle.

Corner drop Horizontal drop Vertical drop

Figure 8. Tests drop orientations.

The accelerations were measured by three accelerometers (ac1, ac2, ac3), fixed in the external wall, and the respective data acquisition and conditioning system fixed to the model according the Figure 9.

All procedures was approved and followed in details by the present representatives of the participating countries and IAEA.



Corner drop Horizontal drop Vertical drop

Figure 9. Accelerometers positioning in the model.

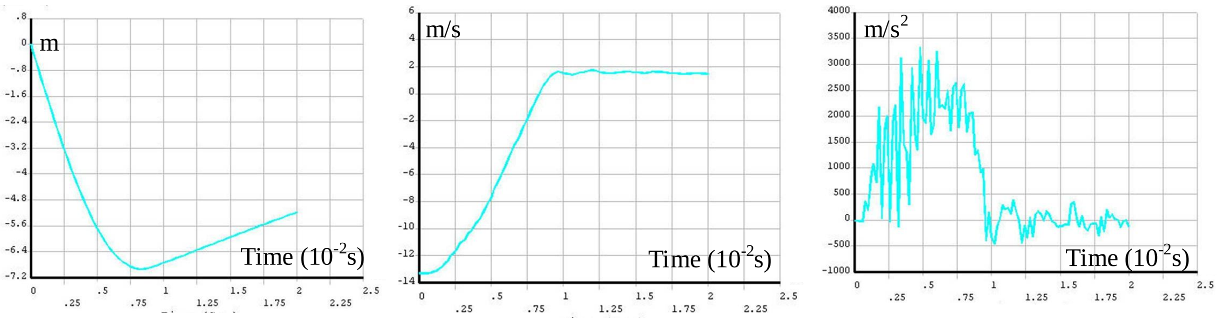
6. RESULTS

The main results of numerical simulations and tests are related to the displacements, velocities and accelerations of some chosen points, the maximum decelerations in the internal content of the package and the deformed shapes of the structures in the time of their maximum deformation.

First, as an example, Figure 10 shows the typical curves of displacement versus time, velocity versus time and acceleration versus time of the finite element central node for the horizontal 9 m drop test.

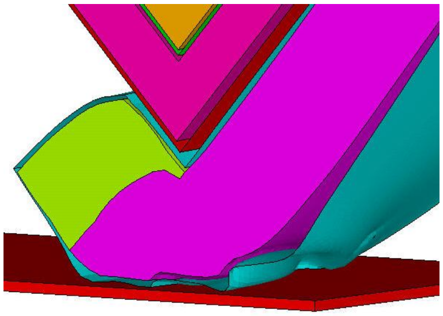
The maximum deceleration can be observed in Fig. 10 (c). In this case, the value is ~ 250 g (g is the acceleration of the gravity) (as mentioned before, it should be applied a Butterworth-type low pass filter (IAEA, 2008)).

Figure 11 shows some aspects of the deformed configurations for the three impact directions already analyzed at the moment of their maximum deformation: vertical, side or horizontal and corner impact. Figure 11.b shows only the “lower” shock absorber once the “upper” one has an almost identical behavior (they don’t behave identically because their projects are slightly different – their maximum individual deformations are, respectively, 66.1 mm and 69.1 mm). Also, in the vertical and side impact figures one can see the almost uniform deformation in the shock absorber impact under and due to the external cylinder. This viewing is allowed by the dark lines representing the (initial) non deformed situation.

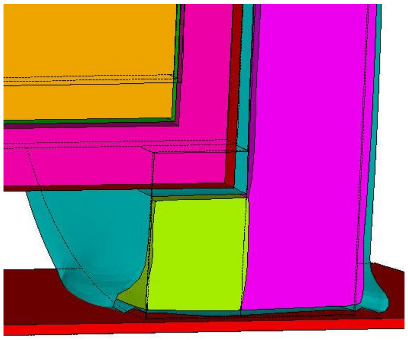


(a) Displacement X time (b) Velocity X time (c) Acceleration X time

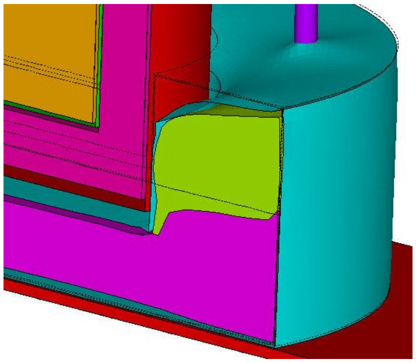
Figure 10. Movement curves of the 180° finite element model central node under 9 m drop test in the horizontal orientation.



(a) Corner drop



(b) Horizontal drop

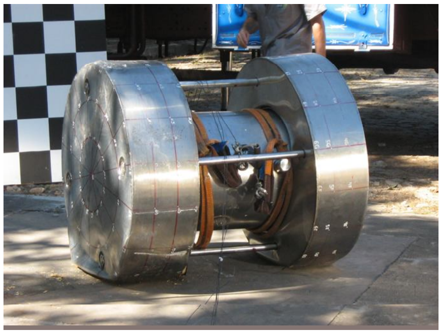


(c) Vertical drop

Figure 11. Final deformed shapes for three impact orientations from numerical simulations.

Similar deformation shapes can be observed from the tests. Figure 11 shows them.

(a) Corner drop



(b) Horizontal drop

(c) Vertical drop

Figure 12. Final deformed shapes for three impact orientations from tests.

Some important results for the package project are those related to maximum decelerations and deformations. Table 4 presents some of the obtained results in terms of the package maximum decelerations (after a filtering operation) and deformation in the shock absorbers from the numerical simulations and from the tests.

Table 4. Internal content maximum decelerations and shock absorbers maximum deformations from numerical simulations and tests.

	Numerical simulations		**Tests**		**Error**	
	Deceleration (g)	**Deformation (mm)**	**Deceleration (g)**	**Deformation (mm)**	**Deceleration (%0**	**Deformation (%)**
Corner drop	130	60,7	115,9	50.5	+12,7	+20,2
Horizontal orientation	250	40,3	277,8	32.3	-10,0	+24,8
Vertical orientation	310	20,5	272,7	15.8	+13,7	+29,8

g – gravity acceleration

7. COMMENTS AND CONCLUSIONS

At a first glance there is a good agreement between the results from the numerical simulations and from tests if one looks at the deceleration values once an error around 10-15% is acceptable. However, the maximum shock absorbers deformations have differences up to 30%.

The observed maximum deformations in the tests were smaller than that obtained from the numerical simulations but the tests maximum decelerations were closer than the numerical simulation ones.

Although the numerical and experimental maximum deformation values have differences, the final shock absorbers deformed shapes are quite similar.

It can be noticed that during the tests the shock absorbers shells failed in several positions (see Fig. 12). This unexpected behavior indicates a lower than expected weld strength. Evidence includes possibly inadequate weld penetration based on visual inspections. Also the design incorporates 'sharp edges', which concentrate stress at the joints where failure occurred. So, a new testing campaign will be conducted after the shock absorbers design modifications to correct the detected problems.

Also, during the tests, some rebound of the model was observed in an extension/value not reproduced in the numerical simulations, mainly in the 9 m vertical drop. This indicates that the energy absorption of the shock absorbers in the vertical orientation (impact load perpendicular to the OSB fiber/grain) appeared to be less than expected. The OSB energy absorption characteristics appear to vary significantly with respect to wood fiber/grain orientation. Evidence supporting this includes package 'bounce' especially in the vertical orientation as opposed to the observed energy absorption in drop tests in the horizontal orientation.

As one of the main objectives of the comparison between the results from numerical simulations and from tests is to establish a qualified methodology to simulate the 9 m drop tests of a package prototype some improvements must be done both in the numerical simulations and in the new testing campaign such as:

- Design improvements are recommended to the shock absorbers shells weld joints, shock absorbers shell shapes and shock absorber energy absorbing material (material selection and/or OSB orientation).
- Review of the shock absorbers energy absorbing material characterization.
- Review of the shock absorbers energy absorbing material model used in the numerical simulations.

As a first approach the obtained numerical results can be evaluated as good ones. As the activities will continue in a new IAEA project and test campaign, to correct some aspects as the shock absorbers design, the new analyses will be done considering the improvements above mentioned.

8. ACKNOWLEDGEMENTS

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