Improvements on the numerical structural assessment of a half scale model of a nuclear spent fuel elements transportation package under 9m 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/or 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 (impact absorbers, 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, with emphasis on the impact absorbers behavior, 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. Also, several 9 m drop tests were conducted in a half scale model in different drop orientations. 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.

Mechanics of Solids in Brazil 2011, E.A. Fancello, P.T.R. Mendonça & M. Alves (Editors)
Brazilian Society of Mechanical Sciences and Engineering, ISBN 978-85-85769-46-8

1 Introduction

The radioactive materials transportation is regulated by guides and standards like [1] and [2]. 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.

The packages for the transportation of nuclear research reactors spent fuel elements are classified as type B due the nature of the radioactive content. The applied qualification requirements are very severe including the so-called normal conditions of transport and the hypothetical accident conditions. These conditions are defined in the regulations [1, 2] and it must be demonstrated that the package has to be sturdy enough to resist, among others:

- 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 package 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 package to the upper surface of the bar shall be 1 m. 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 use of shock absorbers is allowed to assure that the resultant deceleration levels in the radioactive content (spent fuel elements) are low enough and to keep the containment functional and structural integrity in the free drop conditions. The shock absorbers are sacrifice devices that must absorb the package kinetic energy in the impact after the drop by means of their deformation. Several materials may be used to fill the shock absorbers such as natural wood, wood composites, low density concretes, metallic foams, polymeric foams, and metallic honeycombs.

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/or 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.). So, the package structural evaluation under the drop test conditions should be conducted by finite element numerical simulations using explicit methods and 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.

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, with emphasis on the impact absorbers behavior, 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. Also, several 9 m drop tests were conducted in a half scale model in different drop orientations. 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 Package description

The package was designed to meet the transportation criteria established by the IAEA (International Atomic Energy Agency) for Type B packages carrying fissile materials [1, 2]. Since no long term storage strategy has been defined in Brazil for this kind of spent fuel, the package is regarded also as a potential storage option. For that reason, some of its features were designed to attend long term storage requirements, such as long-term stability of its constitutive materials and compatibility between them and with the radioactive contents. Also the access to its internal cavity has to be granted for periodical checks through gas sampling.

The package consists of a cylindrical body with internal cavity to accommodate the basket that holds the spent fuel elements. The package body has a sandwich-like shielded wall consisting of stainless steel outer and inner surfaces and lead in-between. A double lid system guarantees the required containment and the internal lid – which is part of the pressure boundary – has a double sealing system. The package is provided with two access ports to the internal cavity, one for pressurization and sampling of the cavity filling gas, embedded in the internal lid, and the other for the cavity draining, located at the lower region of the package wall. Both ports are equally equipped with two concentric seals. All double seals are metallic, whereas external lid seal is elastomeric.

The structure of the basket is made of square tubes. For protection against mechanical and thermal loads, the package is provided with top and bottom external removable shock absorbers. These are structures made of external stainless steel skin and an energy-absorbing filling material. The filling material chosen was an wood composite named Oriented Strand Board (OSB), which 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. A schematic view of the package is shown in Fig. 1. The main dimensions of the natural scale package are: main body, ⌀ 1.000 × 1.400 mm; overall dimension with shock absorbers, ⌀ 2.160 × 2.010 mm. There are also four cylindrical tie bars equally spaced connecting both shock absorbers. These bars are not shown in Fig. 1.

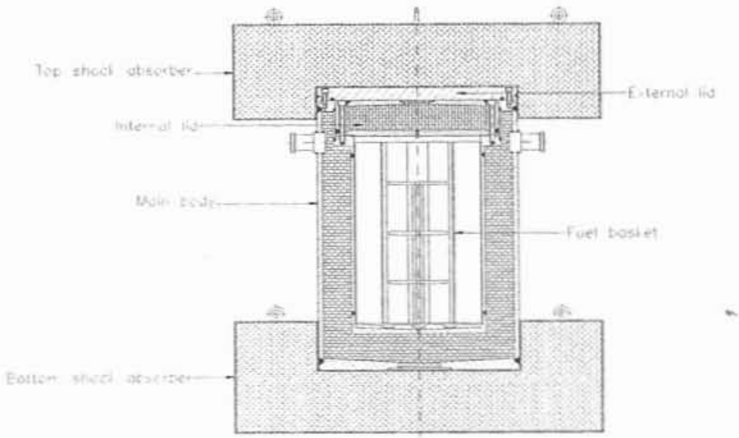


Figure 1: Transport package for research reactor spent fuel.

3 The half scale model of the package

Considering the scale 1:2, the model 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.

Regarding the half scale model, Fig. 2 to 5 show, respectively, the overall dimensions , a lateral view, an internal view, and the bottom shock absorber partially assembled.

The half scale package model materials are indicated in Tab. 1.

Table 1: 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

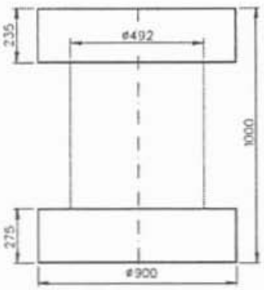


Figure 2: Overall dimensions of the half scale model of the package (in mm).

Figure 3: Lateral view of the package half scale model.

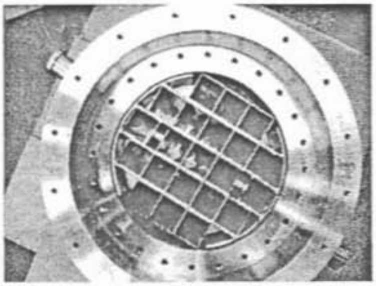


Figure 4: Internal view of the package half scale model.

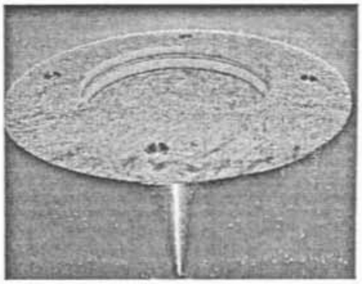


Figure 5: Bottom shock absorber partial assembling.

4 Shock absorbers material characterization

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 [3]. 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 direction, whereas the glued surfaces define the specimen parallel 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. 6 (all curves were filtered at 500 Hz, low pass filter) [3]. As can be seen, from Fig. 6, 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 (encased) condition.

This behavior can also be seen clearly in Tab. 2, 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

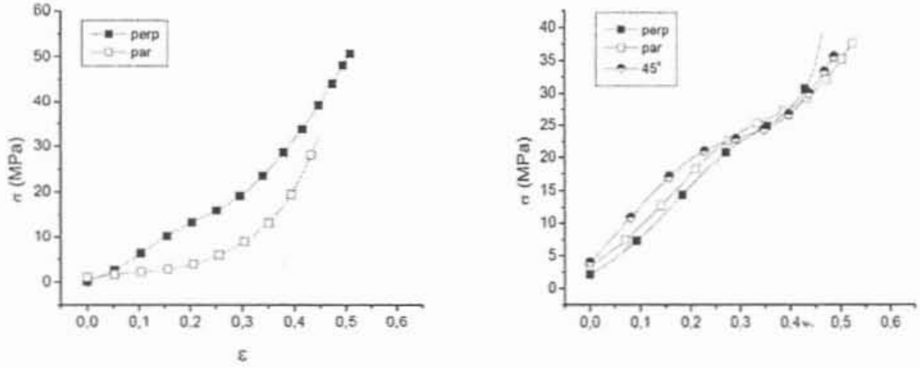


Figure 6: Shock absorbers material stress-strain curves for different directions.

the unconstrained situation is 47% (7.0 to 3.7 $\mathrm{MJ/m^3}$), while the average difference for the encased specimens between the three test directions is less than 10%.

Table 2: Specific energy absorbed (U) @ $\varepsilon = 0.45$.

		U ($\mathrm{MJ/m^3}$)
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 [4], 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.

5 Numerical simulations of the package half scale model 9m drop tests

The half scale model of the package structural evaluation under the drop test condition was 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 the finite element explicit code ANSYS LS-DYNA [5].

5.1 Contacts modeling

The following discussion is based on some recommendations from the LS-DYNA manual [5]. A contact is defined by identifying (via parts, part sets, segment sets, and/or node sets) what locations are to be checked for potential penetration of a slave node through a master segment. A search for penetrations, using any of a number of different algorithms, is made every time step. In the case of a penalty-based contact, when a penetration is found a force proportional to the penetration depth is applied to resist, and ultimately eliminate, the penetration. Unless otherwise stated, the contacts discussed here are penalty-based contacts as opposed to constraint-based contacts. Rigid bodies may be included in any penalty-based contact but in order that contact force is realistically distributed, it is recommended that the mesh defining any rigid body be as fine as that of a deformable body.

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 package and of the the half scale model of the package (see Fig. 1 to 5), it was used the so-called AUTOMATIC SURFACE TO SURFACE contact option of the ANSYS LS-DYNA code.

This type of contact is a two way contact allowing for compression loads to be transferred between the slave nodes and the master segments. Tangential loads are also transmitted if relative sliding occurs when contact friction is active. A Coulomb friction formulation is used with an exponential interpolation function to transition from static to dynamic friction. This transition requires that a decay coefficient be defined and that the static friction coefficient be larger than the dynamic friction coefficient. The constraint algorithm used in the LS-DYNA program is based on the algorithm developed in [6].

This involves a two-pass symmetric approach and allows for compression loads to be transferred between the slave nodes and the master segments. The definition of the slave surface and master surface is arbitrary since the results will be the same.

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.

In ANSYS LS-DYNA the default procedure to compute the time-step and the contact stiffness is based on the maximum value of the Young's Modulus E, the maximum slope from the stress-strain curve (Ecurve). This default approach is conservative to ensure that the computed time-step is stable for all compressive strains. The default value of the modulus from this approach could either be too small (if E is greater than E_{curve}) or too large (if the E_{curve} is greater than E). ANSYS LS-DYNA allows the overriding of this default logic. Suppose a case where the Ecurve is 10 MPa and E is 50 MPa. Consequently, the E value of 50 MPa was used in the time-step and contact stiffness calculations which is roughly 0.025% of the modulus of steel (200.000 MPa). This huge disparity in stiffness values between the impacting bodies is naturally going to cause instabilities in contact. The alternative approach is to use a penalty contact using soft-constraint algorithm. However, ANSYS LS-DYNA always uses a penalty based approach based on material stiffness for contact between a rigid body and deformable bodies. Therefore, it is recommended to alter the modulus to a value at least 1% of the modulus of the impacting material (which, in this case, is steel).

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. ANSYS LS-DYNA follows strictly the stress-strain curve to the last input stress-strain point. 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. 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.

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.

5.2 Materials modeling

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 $\varepsilon = 0.95$ 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 'calibrated' to reproduce the mass predicted to fill the package. This was done to capture the package overall behavior. 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	units
E – Young's modulus	200e9	14e9	2e9	200e9	200e9	N/m^2
ν – Poisson's ratio	0.3	0.42	0.0	0.30	0.30	—
ρ – Density	7500	11500	600	7500	7500	Kg/mm^3
σ_{ys} – Yield stress	310e6	14e6	—	310e6	—	N/m^2
E' – Tangent modulus	7.6e8	1.0e7	—	7.6e8	—	N/m^2

5.3 Finite element model

A 180° finite element model, showed in Fig. 7, 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).

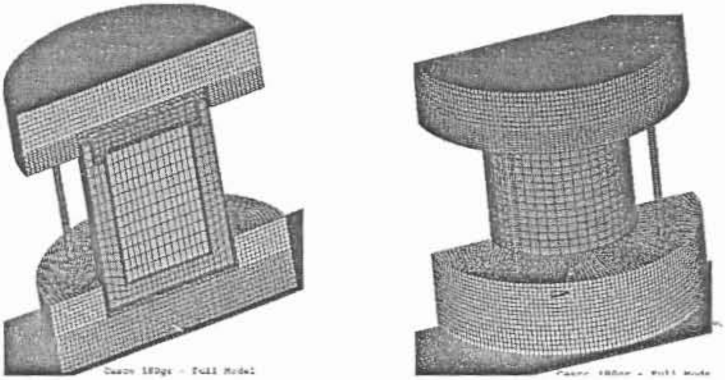
5.4 Numerical simulations

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

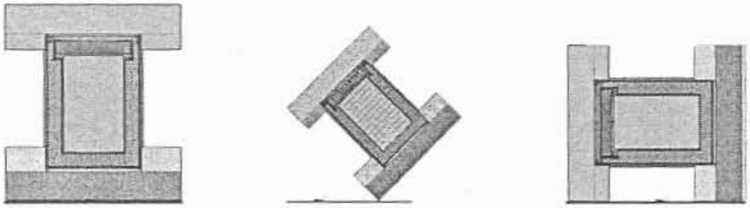
Three analyses were performed simulating the vertical, the horizontal and the corner impact. In general, the results in terms of displacements along the time are smooth while in terms of accelerations a filter like Butterworth-type should be adopted due to the noise introduced by the successive integrations [7].

5.5 Deformed shapes

In Fig. 8, the contact modeling does not include the improvements discussed in section 5.1 above related to time-step and contact stiffness and increased solid element thickness in contact while in Fig. 9 all improvements were included in the contact modeling.



Front view Back view



Vertical drop Corner drop Horizontal drop

Figure 7: 180° finite element model and drop orientations.

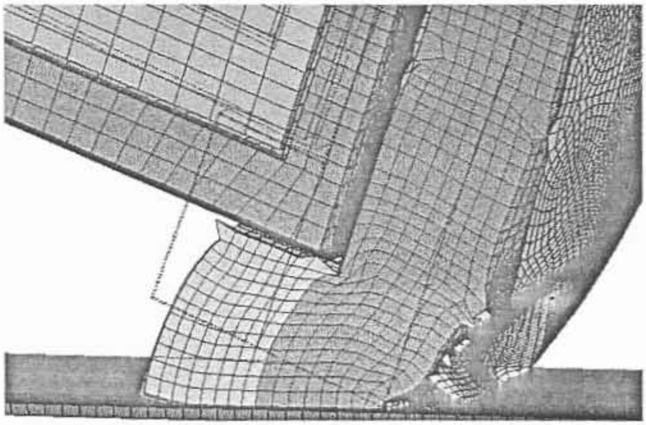


Figure 8: 180° finite element model deformed shape without improved contact modeling.

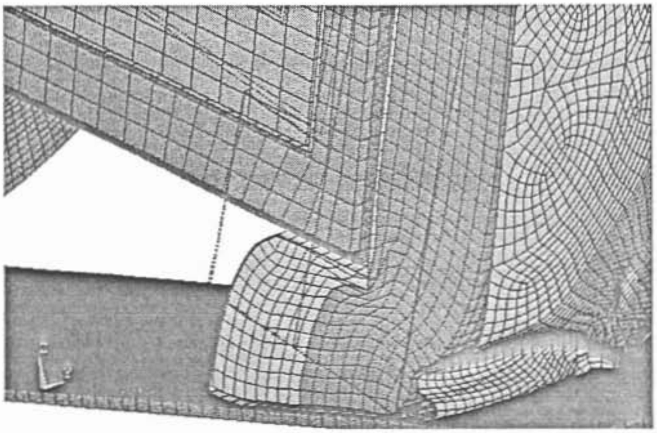


Figure 9: 180° finite element model deformed shape with improved contact modeling.

6 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 10 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. Some deformed shapes after tests are showed in Fig. 11.

Vertical drop Corner drop Horizontal drop

Figure 10: Tests drop orientations.

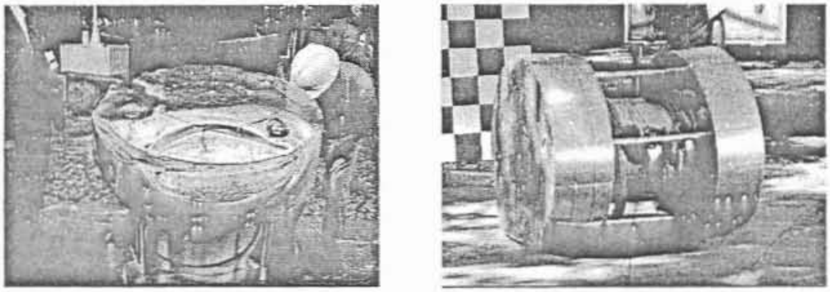

Corner drop Horizontal drop

Figure 11: Final deformed shapes for two impact orientations from tests.

7 Results comparison

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.

As an example, Fig. 12 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.

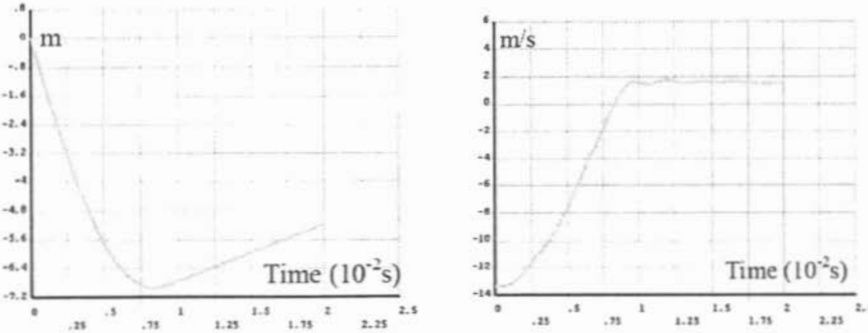
The maximum deceleration can be observed in Fig. 12 (c). In this case, the value is $\approx 280g$ (g is the acceleration of the gravity) (as mentioned before, it should be applied a Butterworth-type low pass filter [7]).

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 displacements from numerical simulations and tests.

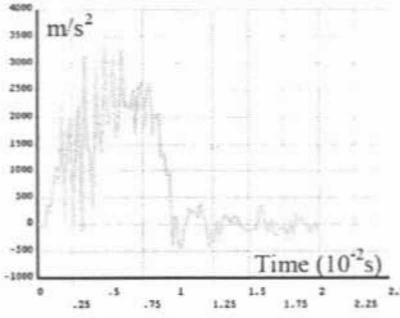
	Numerical simulations		Tests		Error	
	Decel. (g)	Disp. (mm)	Decel. (g)	Disp. (mm)	Decel. (%)	Disp. (%)
Corner drop	138	46	116	51	+19	-10
Horizontal drop	237	28	280	23	-15	+22
Vertical drop	299	13	273	16	+10	-19

g – gravity acceleration



(a) Displacement × time

(b) Velocity × time



(c) Acceleration × time

Figure 12: Movement curves of the 180° finite element model central node under 9 m drop test in the horizontal orientation.

8 Comments and conclusions

At a first glance, there is a reasonable agreement between the numerical and experimental results with errors [(numerical-experimental)/experimental] around ±20%. Nevertheless, with a deeper look on the results, it is clear that the drop orientation has an important influence on the results comparison and this influence is related to the shock absorbers behavior.

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

For the corner and vertical drops, the observed maximum displacements in the tests were greater than that obtained from the numerical simulations. Also, the correspondent decelerations were smaller. On the other hand, for the horizontal drop the opposite situation occurred.

Also, during the tests, some rebound of the model was observed in an extension not reproduced in the numerical simulations, especially in the vertical orientation. 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 more with respect to wood fiber/grain orientation than it is considered in the material modeling used for the OSB.

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 further assessments must be done in the future numerical simulations such as:

- Review of the shock absorbers material characterization.
- Review of the shock absorbers material model used in the numerical simulations.

Acknowledgements The work presented in this paper was supported by the International Atomic Energy Agency (IAEA) Latin American Projects RLA/4/020 and RLA/3/008 on Engineering of Casks for the Transport of Spent Fuel from Research Reactors.

Responsibility notice

The authors are the only responsible for the printed material included in this paper.

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