Proceedings of PVP2008
2008 ASME Pressure Vessels and Piping Division Conference
July 27-31, 2008, Chicago, Illinois, USA

PVP2008-61553

ANALYTICAL AND NUMERICAL EVALUATION OF THE IMPACT LIMITERS DESIGN OF A RESEARCH REACTORS SPENT FUEL TRANSPORTATION PACKAGE HALF SCALE MODEL UNDER 9 M DROP TESTS

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ABSTRACT

Since 2001, under the IAEA (International Atomic Energy Agency) support, some regional projects have been developed in Latin America to assess storage and transportion options for the research reactors spent fuel in the region. One of the projects tasks is the design and testing of a half scale model of a dual purpose (transportation and storage) package for research reactors spent fuel. Considering one of the hypothetical accident conditions, the 9 m drop test, this paper presents the impact limiters design evaluation of the above mentioned half scale model of the dual purpose package based on the impact limiters materials characterization, on the analytical assessment of the impact limiters sizing (dimensions and expected package acceleration levels) and on numerical simulations of the drop tests using a finite element explicit code. Conclusions and comments are addressed based on the obtained results.

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 dual purpose (storage and transportation) package for the research reactors spent fuel elements, following international [1] and national [2] standards, is one of the projects tasks.

As part of the dual purpose package qualification, a half scale model of the dual purpose package was designed and built to be tested under the hypothetical accident conditions in the package qualification. The utilization of the half scale model is justified by economic reasons and the half scale model tests are planned to occur in the middle of this year.

Considering one of the hypothetical accident conditions, the 9 m drop test, this paper presents the impact limiters design evaluation of the above mentioned half scale model of the dual purpose package based on the impact limiters materials characterization, on the analytical assessment of the impact limiters sizing (dimensions and expected package acceleration levels) and on numerical simulations of the drop tests using a finite element explicit code (ANSYS LS-DYNA, [3]).

NOMENCLATURE

E	- Young's Modulus (N/m^2)
E'	- Tangent modulus (N/m^2)
g	- Gravity acceleration
OSB	- Oriented Strand Board
U	- Specific energy (J/m^3)
ε	- Deformation
ν	- Poisson's ratio
ρ	- Density (Kg/m^3)
σ_{ys}	- Yield stress (N/m^2)

THE HALF SCALE MODEL OF THE PACKAGE

Figure 1 shows a cross section of the half scale model of the package. 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 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.

There are two impact limiters, 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 reconstituted wood, has an orthotropic behavior but when confined, as in this project, it behaves as an isotropic material (see next sections).

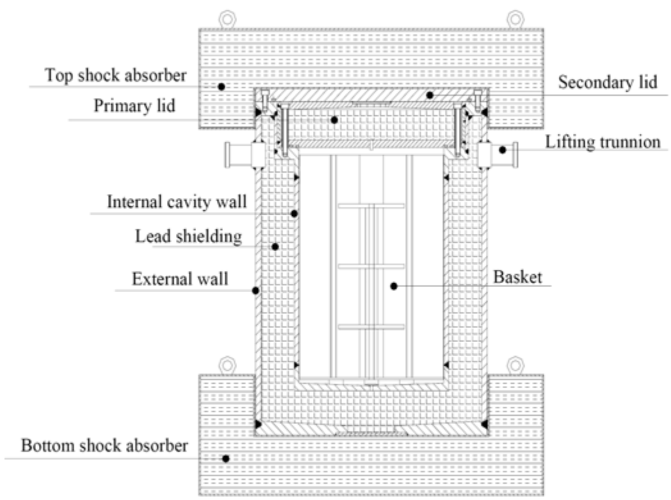


Figure 1: Cross section of the half scale model of the package

The half scale cask model overall dimensions. The external cylinder has a diameter of ≈0.50m and it is ≈0.60m high. With the dampers the overall dimensions are: external diameter ≈0.90m and ≈1.00m high (as depicted in Figure 2).

Figures 3 to 5 show some views of the half scale model of the package and of the impact limiters.

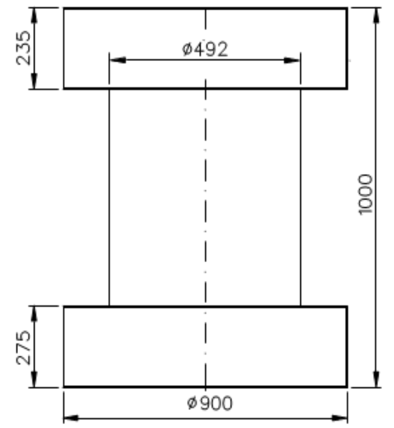


Figure 2: Overall dimensions of the half scale model of the package (in mm)

Figure 3: Lateral view of the package half scale model

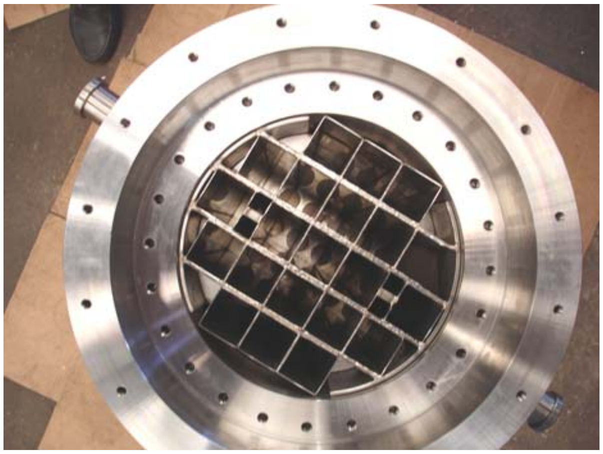


Figure 4: Internal view of the package half scale model

Figure 5: Lower impact limiter partial assembling

IMPACT LIMITERS MATERIALS CHARACTERIZATION

The material chosen for the package impact limiters is the wood composite named Oriented Strand Board (OSB). As the properties of this material 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.

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.

Impact tests

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 [4]. 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 Figures 6 and 7.a (all curves were filtered at 500 Hz, low pass filter). 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 constraining condition.

This behavior can be seen clearly in Table 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%.

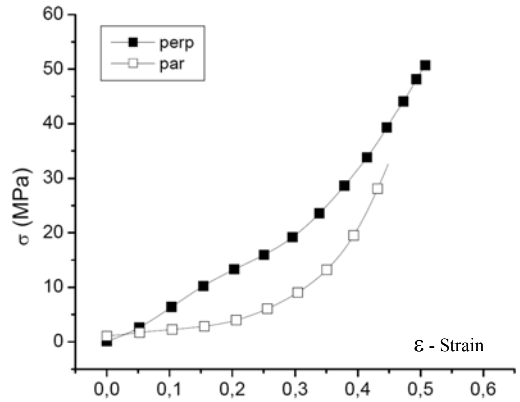


Figure 6: Impact stress-strain curves for different directions – Non-encased specimens

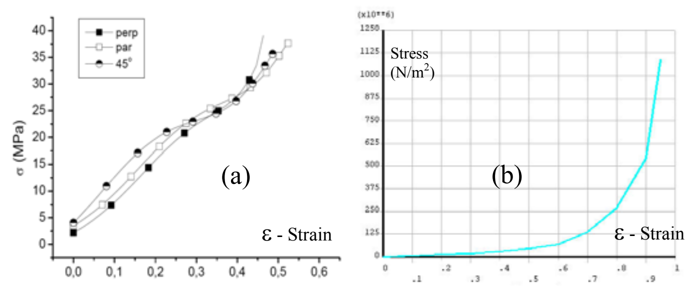


Figure 7: Impact stress-strain curves for different directions (a) encased specimens, (b) adopted in analyses

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 impact limiters.

- According to [5], 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.

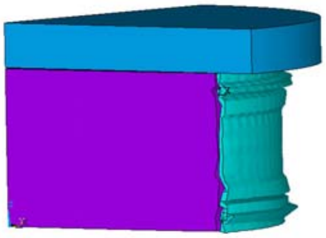
NUMERICAL SIMULATION OF THE IMPACT LIMITERS MATERIAL DYNAMIC TEST

In order to get feeling and to check the available software (ANSYS LS-DYNA [3]) ability to perform the 9 m drop test evaluation, a numerical simulation of the impact limiters material dynamic test in the encased specimen in the perpendicular direction was conducted.

The aim of this simulation was to test the software regarding the elastic and plastic deformations, the material models with different deformation behavior, the materials with different stiffness, the frictional interfaces between two deformable materials, and the frictional interfaces between deformable materials and rigid bodies.

Figure 9 shows the deformed shapes of the encased specimen obtained from the test and from the numerical simulation (the rigid base was not shown). The final specimen deformation in the test was 9.0 mm and from the numerical simulation, 12.5 mm. The finite element model of this simulation is shown in Figure 10(a) with the rigid base (red) in the bottom, the OSB (purple) in the middle, the rigid hammer (light blue) in the top and the encasing shell surrounding the OSB.

(a) Test



(b) Numerical simulation

Figure 9: Material test and numerical simulation results comparison

IMPACT LIMITERS SIZING VERIFICATION

Considering that the deformation behavior of the OSB encased specimens showed in Fig. 7 is practically isotropic and linear until the deformation of 0.50, a linear deformation analysis was performed in order to check the impact limiters sizing for the 9 m drop. Three aspects were verified: the available thickness of the impact limiters, the resulting linear deformation of them and the resulting maximum deceleration in the content.

Table 2 shows the obtained results for the three impact directions, i.e., vertical impact, side impact and corner impact.

Table 2: Results from the impact limiters sizing verification

	Vertical Impact	Side Impact	Corner Impact
Available thickness (mm)	152	204	123
Minimum thickness (mm)	44	69	(*)
Impact limit deformation	0.32	0.35	0.51
Maximum deceleration (g)	370	238	440

g – 9.806 m/s^2
(*) – not calculated

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

In the 9m drop test simulation, all the existing non-linearities related with the several contacts, material mechanical properties and geometry are considered in the numerical analysis performed with an explicit code. Initially, a 90^o Finite Element (FE) model was developed, with one round bar at 45^o position to simulate the vertical impact, Figure 10, applying adequate symmetries.

As the most damaging position is not known "a priori", some skewed positions will also be analyzed, as the horizontal impact, also called side impact, Figure 11.a, and the 45^o impact, Figure 11.b, duplicating the 90^o FE model and rotating it adequately.

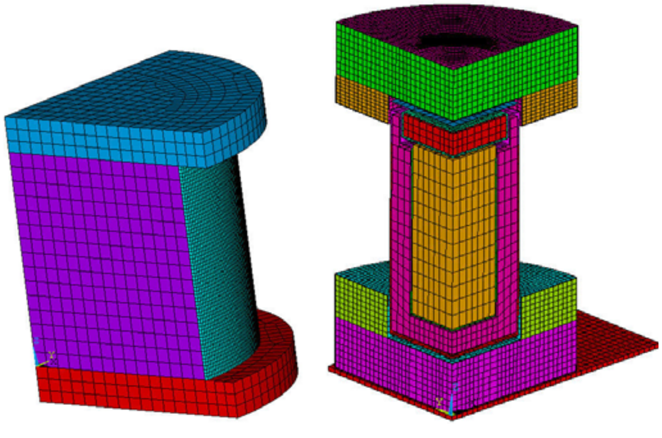
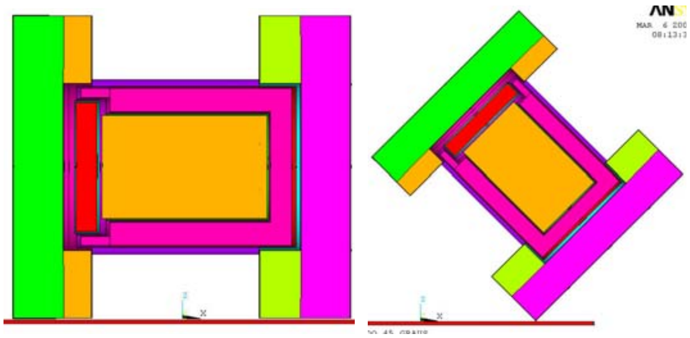


Figure 10: Finite element models – (a) impact limiters material dynamic tests, (b) 90º FE Mesh (Vertical impact)



(a) Horizontal (side) (b) 45º corner impact

Figure 11: Some positions to be analyzed with the 180º model

Some parts, like the impact limiters, were divided in two parts and their contacts are defined properly. So, the model has eighteen parts defined as Components that can be in contact, including the rigid surface were the package should impact from the 9m drop.

There are twenty six contacts, some of them defined as TIED as those between the dampers volumes/elements with their neighbors, due to their glued assembling. One other example of TIED contact is between the plate and flange connected by bolts (not modeled). All the others contact were defined as ASTS (Automatic Surface-to-Surface Contact) with static and dynamic friction coefficients set to 0.3 and 0.2 respectively.

The dampers filling material (OSB) was modeled as crushable foam with its correspondent curve following an isotropic linear behavior until $\varepsilon = 0.45$, extended until $\varepsilon = 0.95$, as per Figure 7.b, to avoid numerical instabilities. The rigid surface was modeled with the RIGID option. The steel parts, including the round bars, as well as the lead ones were modeled as Bilinear Isotropic Material (BISO) while the internal dummy mass was modeled with fictitious values and a density value 'calibrated' to reproduce the mass predicted to fill de cask. All adopted material properties, except OSB, can be seen in table 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	0.30	0.42	0.0	0.30	0.30	---
ρ - Density	7500	11500	600	7500	7500	Kg/m^3
σ_{ys} - Yield stress	310e6	14e6	-----	310e6	-----	N/m^2
E' - Tangent modulus	7.6e8	1.0e7	-----	7.6e8	-----	N/m^2

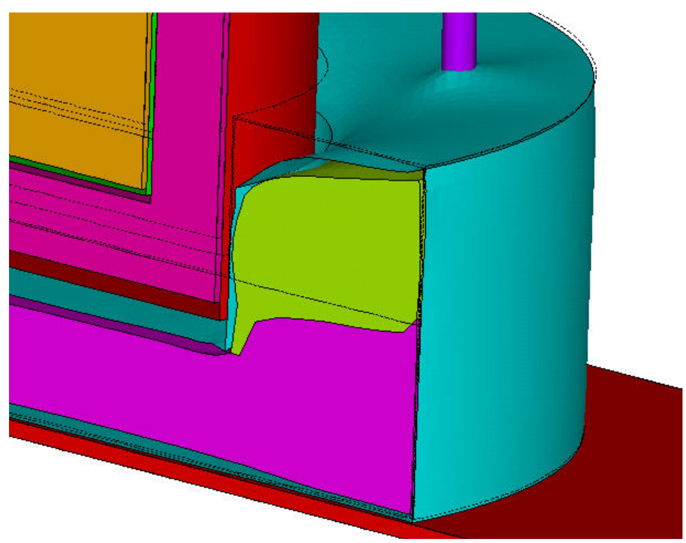
The analysis starts as the model touches the rigid surface, so the applied initial velocity (13.3 m/s) corresponds to the 9m free drop. Additionally the gravity acceleration was applied to the model.

Three analyses were performed simulating the vertical, the side (horizontal) and the 45^o (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. Table 4 presents some of the obtained results in terms of the package maximum deceleration (after a filtering operation) and deformation in the impact limiters.

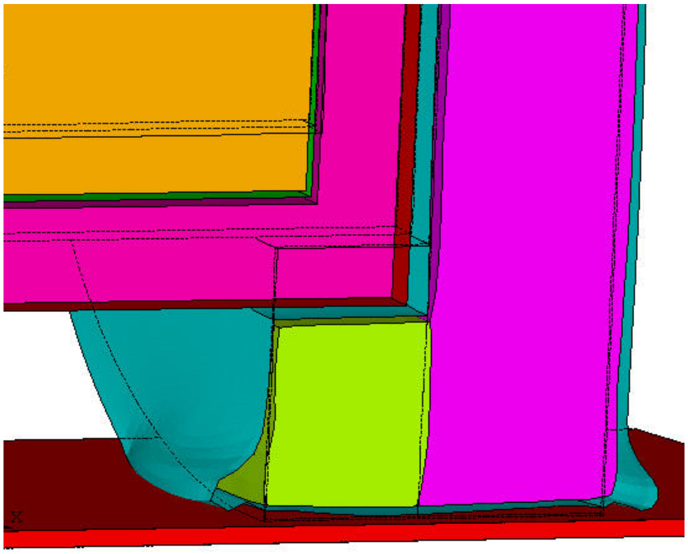
Table 4: Results from numerical simulation

	Deceleration (g)	**Deformation (mm)**
Vertical	430	45.5
Side (Horizontal)	250	67.6
Corner (45°)	130	153.6

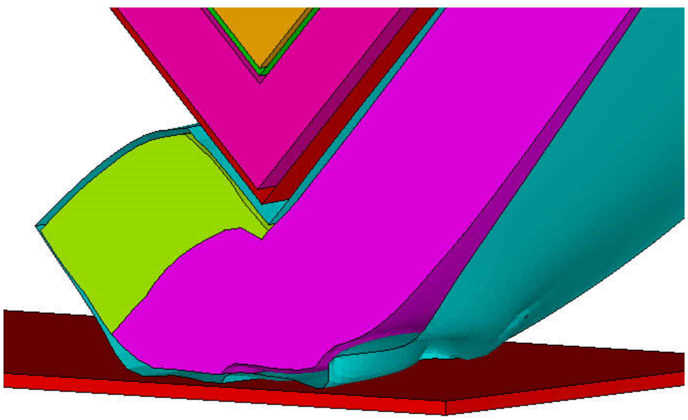
Some other parameters, like the final deformed configuration, could be used to compare the numerical simulations results with the experimental ones. Figure 12 shows some aspects of the 'final' deformed configurations for the three impact directions already analyzed: vertical, side or horizontal and corner impact (45°). Figure 12.b shows only the "lower" limiter once the "upper" one has an almost identical behavior (they don't behave identically because their projects are slightly different – their individual deformations are, respectively, 66.1mm and 69.1mm). Also, in the vertical and side impact figures one can see the almost uniform deformation in the limiter impact under and due to the external cylinder. This viewing is allowed by the dark lines representing the (initial) non deformed situation.



(a) vertical



(b) side (or horizontal) – 'lower' limiter



(c) corner (45º)

Figure 12: Final deformed for three impacts

OBTAINED RESULTS ASSESSMENT

One important thing to take in mind is that due to the scale factor (1:2) between the analytical (and numerical) simulations 1:2 scale model and the package prototype some corrections should be done in the numerical results to find the expected ones in the prototype. In this particular case in study accelerations should be divided by two.

In principle, results presented in tables 2 and 4 should agree. However their differences in the deceleration values can be explained once the table 2 has average (analytical) values over the entire model while table 4 has results obtained in a specific point – the center of the dummy mass. This point was chosen because its results are naturally smoother than in any other point in the model.

CONCLUSIONS AND COMMENTS

The standards [1,2] stress the need of experimental qualification for this type of package. The 9 m impact tests usually are done in the vertical and side directions and at least one corner direction.

The numerical simulations have additional importance to define which corner direction is the most damaging. The comparison among decelerations obtained in the numerical simulations and the ones in the experiments could be done. However, the final deformed configuration is one of the most important parameter to characterize the damage produced in the package and in the impact limiters.

Both, analytical and numerical results, however, show the possibility to have decelerations values greater than 200g which is a 'target' value due to estimates in the fuel elements strength. This 'target' value can be reached by modifying the limiters project.

ACKNOWLEDGMENTS

This work was partially sponsored and granted by the International Atomic Energy Agency (IAEA).

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