

# **Simulation of impact limiter crushing of RAM packages under 9 m drop test conditions - 10090**

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## **ABSTRACT**

The 9m drop test is one of the regulatory mechanical tests for transport packages for radioactive material. Impact limiting devices are attached to the package in order to reduce forces applied on the cask body and closure system due to hypothetical accidents simulated by drop testing. Impact limiters absorb a major part of the impact energy resulting from the 9 m drop. Impact limiters usually consist of three components: stiff inner steel structure, energy absorbing material like wood and outer housing for confining the energy absorbing material. Two different computational methods have been applied widely for simulating the behaviour of impact limiting devices under crushing scenarios: a simplified numerical method based on solving mass-spring system equations and the explicit Finite Element Analysis. The paper explains the application of both methods in detail and shows – with corresponding examples – their constraints and prospects.

The simplified methods are easy to apply, need only little input information and produce quick results. But they premise an appropriate approximation of impact limiter crushing force, which is obtained by combining geometric impact limiter description and a suitable integrated material characterization for wood and metallic components in form of stress-strain curves. The application of simplified numerical methods in the safety assessment is shown exemplary. Limitations for the application of this method are pointed out.

Explicit Finite Element Methods permit a detailed geometrical description of the impact limiter including external and internal metallic components. The required material characterization for energy absorbing and housing material is therefore usually more general and not design-specific. Some aspects of the finite element modelling of the impact limiters are discussed in the paper as well.

## **INTRODUCTION**

The design safety assessment of transport casks for radioactive material in Germany is carried out by the Federal Institute for Materials Research and Testing (BAM). Both experimental and computational (analytical, numerical) methods combined with additional material and/or component tests are the basis for the safety evaluation and assessment concept at BAM according to the state of the art.

The required mechanical tests according to IAEA regulations [1] include, among others, a 9m drop test onto an unyielding target. Impact limiting devices are applied in order to limit the load on cask components in different drop scenarios. Typical constructions of so-called soft impact limiters consist of thin metallic housing filled with wood. They are attached to the casks at the lower and upper ends. The impact limiters absorb the major part of the kinetic

energy as they are relatively soft compared to the cask. The impact intensity on the cask body, closure system and other components of the cask and radioactive content is lowered significantly. In particular, the energy absorption capacity of the impact limiters has a significant influence on package integrity and tightness. The comprehension and physical evaluation of the behaviour of impact limiting components under dynamic loading are essential for the safety assessment. Mode of construction, temperature range and used materials are crucial aspects in regard to the behaviour of the package.

According to IAEA [1], Paragraphs §701 - §702, there are different possible ways to demonstrate safety. Confirmation of compliance with the performance standard required in Section VI of [1] is to be accomplished by any of these methods or a combination thereof.

A combination of drop tests and calculations are common in current typical assessment demonstrations of compliance. On the one hand, due to uncertain parameters and general tentativeness in wood behaviour under large deformation in compression, calculations require verification with suitable experimental results. On the other hand, solitary drop tests are not sufficient to evaluate all aspects of compliance (e.g. resistance to brittle fracture).

Simplified numerical methods like the tool “ImpactCalc“ [2, 3] are often applied in the type assessment of casks for radioactive material in order to determine approximately the rigid body acceleration-time history for 9 m drop test onto an unyielding target. This information is then used to calculate loads for cask components with a “quasi-static” Finite Element (FE) analysis. Questions concerning the applicability of simplified numerical methods in combination with a static FE analysis have to be clarified by the development of calculation procedures for each cask components separately [4].

On the other hand it is possible to simulate the impact limiter behaviour directly in a dynamic FE-calculation. The metallic and wood structure of the impact limiter has to be modelled with finite elements and appropriate material modelling is required.

In the following, the application of both approaches is shown exemplary, advantages and disadvantages are discussed.

## **IMPACT LIMITER MODELLING WITH SIMPLIFIED NUMERICAL TOOLS**

### **Basics**

Typical simplified numerical tools such as ImpactCalc [2, 3] simulate the drop events in terms of single degree of freedom systems. The entire mass of the package is included in a mass point and impact limiter is simplified as a weightless, nonlinear spring. The resistance force of the spring  $F(x)$  due to displacement  $x$  of the mass point is derived from a multiplication of the current effective surface  $A(x)$  with the compression stress on every part of this surface. Depending on the construction features of the package the surface  $A(x)$  can be approximately described as the contact surface between impact limiter and target or impact limiter and cask. For a side drop, as an example, the current, theoretical cut cross section of a cylinder (for cylindrical shaped impact limiter) is usually used:

$$A(x) = 2d\sqrt{(2r-x)x} \quad (1)$$

with  $x$  : deformation,  $d$  : depth and  $r$  : diameter of the impact limiter.

The dependency of the stress on lateral position  $y$  inside of cross section can be eliminated by averaging trough integration so that finally:

$$F(x) = \frac{A(x)}{y_{\max}(x)} \int_0^{y_{\max}(x)} \sigma(x, y) dy \quad (2)$$

The stress function  $\sigma(x, y)$  at  $y = 0$  (symmetric line of impact limiter in side drop) corresponds to the global characteristic force-deformation-course from small scale specimen compression tests.

The differential equation of kinetic balance in form of:

$$M \ddot{x} + F(x) = 0 \quad (3)$$

with following initial conditions ( $t = 0 \quad x = 0; \quad \dot{x} = v_0$ , where  $v_0$  is the impact velocity of the 9-m-free-fall of approx. 13.3 m/s) and  $M$  as package mass, can then be solved.

Calculation results are deformation over time:  $x(t)$  and resistance (impact) force over time:

$F(t)$ . From the impact force the rigid body deceleration can be derived by:

$$G(t) = F(t) / M . \quad (4)$$

The maximum rigid body deceleration  $G_{\max}$  will then be used in “quasi-static” FE-calculations for stress and strain analyses of the cask components. In some cases this value has to be increased by additional factor to cover the dynamic effects in the response of components under consideration to impulsive loading [4]. For this purpose the function  $F(t)$  have to be analyzed. A more detailed description is available at [2, 4].

### Calculation of 9m side drop of CONSTOR cask

The CONSTOR<sup>®</sup> V/TC is a full scale model of the GNS (Gesellschaft für Nuklearsysteme mbH, Germany) cask CONSTOR<sup>®</sup> V/69. The CONSTOR<sup>®</sup> V/69 is a spent fuel cask for transport and storage of 69 BWR fuel assemblies. The cask body consists of an outer and inner liner made of forged steel. The space between the liners is filled with CONSTORIT<sup>®</sup>, an iron aggregate frame and hardened cement paste. Two impact limiters are made of a steel structure filled with fir wood of different orientations. After a series of drop tests with a 1:2 model the cask was equipped with a two-part puncture resistant jacket to protect the cask against puncture loads. The key dimensions including component masses are presented in Table 1. For a more detailed description refer to [5].

Table 1 Dimensions and Masses of the CONSTOR<sup>®</sup> V/TC Package

Description	Value
Overall length	7445 mm (24.4 feet)
Diameter cask	2332 mm (7.7 feet)
Outer diameter impact limiter	3510 mm (11.5 feet)
Total mass	181000 kg (399,000 pounds)
Mass per impact limiter	20000 kg (44,000 pounds)
Mass overpack	31000kg (68,000 pounds)

A 9m drop test with the CONSTOR<sup>®</sup> V/TC was performed at the test site of the BAM Federal Institute for Materials Research and Testing in Horstwalde/Berlin, Germany on the occasion of PATRAM 2004. Results are presented in [5]. The drop tower of the BAM is the largest drop tower of its kind in the world and complies with IAEA regulations [1] for drop tests with packages up to 200 Mg. An analysis with high speed cameras showed that the cask impacted the unyielding target at a small slap down angle of around 0.5-1°. Figure 1 presents the acceleration time relations of the experiment and calculation for the lid side of the cask.

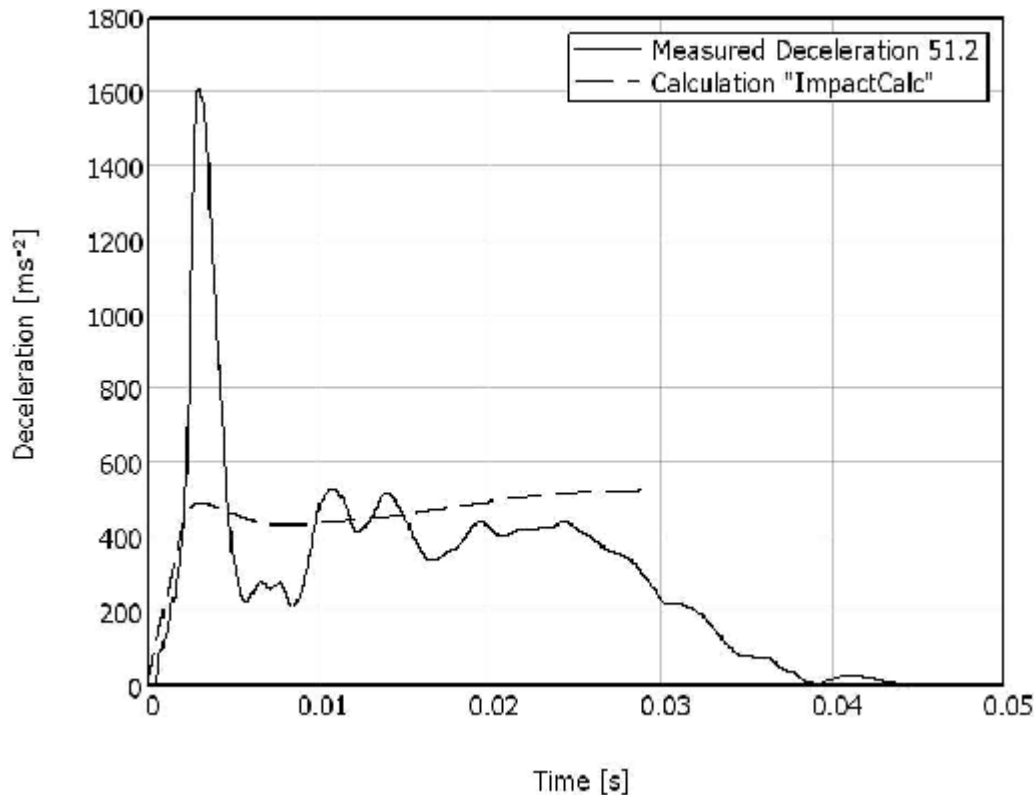


Figure 1 Comparison of the Calculated and Measured Deceleration of the CONSTOR<sup>®</sup> V/TC Package

Apart from the peak at the beginning of the acceleration-time history, “ImpactCalc” is able to calculate adequately the resulting rigid body acceleration (Figure 1). Preliminary analysis indicates, that the peak results from a multiple mass phenomenon including cask, overpack and heavy impact limiter steel structure.

The duration of the impact shock was calculated at 29 ms, which corresponds to the experimentally derived duration of approx. 25 – 30 ms. Since no realistic model for the unloading phase has been implemented in the calculation tool, absolute durations cannot be compared.

The slight slap down angle at impact does not have a major influence on the lid and bottom side impact limiter deformation. Compared to the manual measurement data “ImpactCalc” calculates 27% (lid side) and 17% (bottom side) conservative values for the impact limiter deformation. Taking into account an elastic springback in the wood material of around 30 mm in the unloading phase (estimated from experimental data) “ImpactCalc” calculates 13% and 3% conservative deformation values (Table 2).

Table 2 Impact Limiter Deformation of the CONSTOR<sup>®</sup> V/TC Package in Experiment and Calculation

CONSTOR <sup>®</sup> V/TC	Experiment	Calculation “ImpactCalc”
Maximum deformation lid side incl. elastic springback <sup>1</sup>	150 mm	209 mm
	180 mm	
Maximum deformation bottom side incl. elastic springback <sup>1</sup>	171 mm	208 mm
	201 mm	

<sup>1</sup>(strain reduction according to an elastic “unloading”) of approx. 5%-7.5% in the experiment, according to [2].

### Vertical 9m Drop of the MSF69BG<sup>®</sup>

The cask is a full scale model of the MSF69BG cask by Mitsubishi Heavy Industries Ltd (MHI). It accommodates up to 69 BWR-fuel assemblies. The monolithic cask body is made of forged steel. Neutron shielding is ensured by an epoxy-resin layer between the main body and outer steel surface of the cask. The cask is equipped with two impact limiters of stainless steel, filled with wood of different types and orientations. The main dimensions are shown in Table 3.

**Table 3**

Table 3 Dimensions and Masses of the MSF69BG<sup>®</sup> Package

Description	Value
Overall length	6900 mm (22.6 feet)
Cask diameter	2178 mm (7.2 feet)
Outer diameter impact limiter	3205 mm (10.5 feet)
Total mass	127000 kg (280,000 pounds)
Mass per impact limiter	7000 kg (15,400 pounds)

Figure 2 compares the deceleration-time curves calculated with “ImpactCalc” and measured at the drop test. The calculated curve matches the experimentally derived curve well. The oscillation peaks, which do not represent rigid body accelerations, and the impact of the contents onto the primary lid for 0.019 – 0.025s are covered by “ImpactCalc”, although the code does not treat the contents and cask independently. The calculated impact time corresponds to the experimental impact time reduced by the springback. The difference between measured and calculated impact limiter deformation is small. “ImpactCalc” conservatively estimates around 15% higher results.

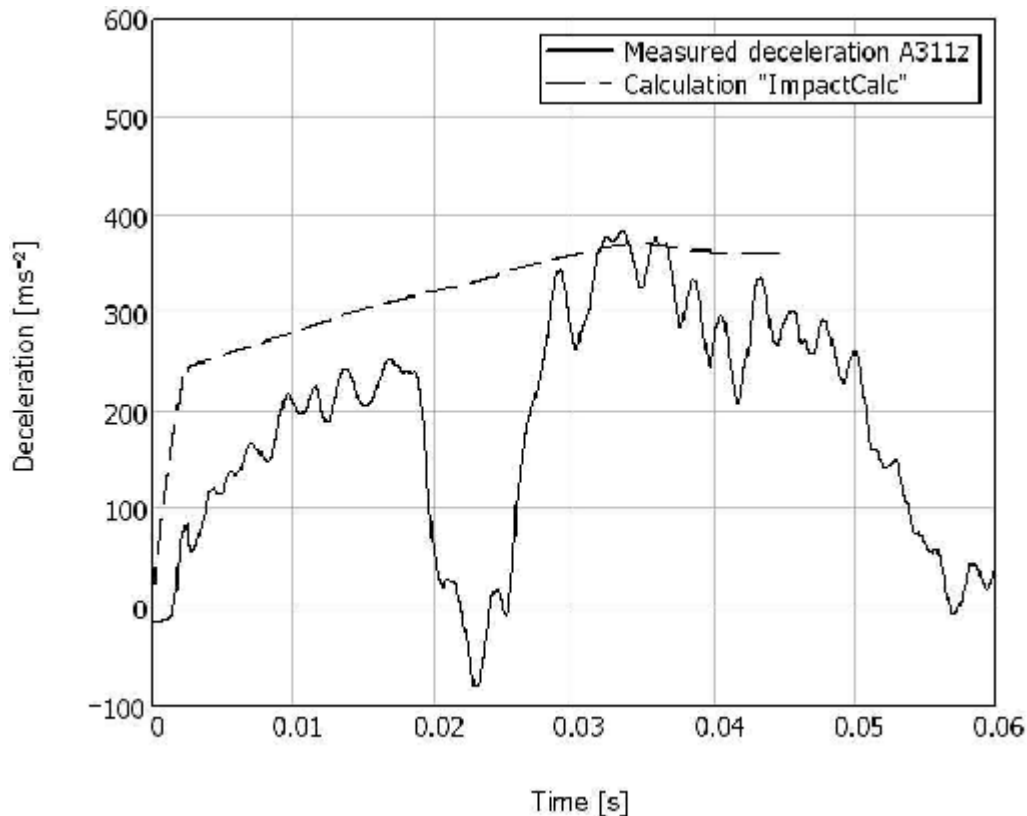


Figure 2 Comparison of the Calculated and Experimentally Derived Deceleration of the MSF69BG<sup>®</sup> Package (400 m/s<sup>2</sup>=1312 ft/s<sup>2</sup>)

### Conclusions for impact limiter modelling with simplified methods

The advantage of this method is that it requires no detailed description of impact limiter geometry and only the global characteristic force-deformation-course from small scale specimen compression tests for specification of material properties. Results are – compared to application of FEM – easier and faster to use. Nevertheless, the small scale specimen compression tests have to be characteristic for the compression of the impact limiter, which can be difficult to prove. Dynamical effects such as multiple mass phenomena and interactions between different package parts can not be calculated. Changes in the compression mechanisms already result from small changes in the design and boundary conditions. These uncertainties have to be accounted for by a corresponding safety or uncertainty factor. It should be noted that the results of this method give only the input information for further quasi-static analysis of the cask components.

### IMPACT LIMITER MODELLING WITH FEM

In comparison with analytical methods that were used for a long time, the dynamic FE-analysis has a clear advantage [6, 7, 8]: The impact limiter is not simplified to a one-dimensional mass-spring-system. Different phenomena (like load transfer, impact limiter weak points, definition of critical impact angles, influence of the impact limiter hardening, friction, etc.) which are not ascertainable with the analytical method, can be examined and explained satisfactorily. The accuracy of the FE analysis depends on the detail of the modelling, the chosen of material definitions, and the replication of all relevant conditions of the drop test.

## Simulation model

The explicit dynamical calculation code LS-DYNA [9] was used for the calculations described here. The simulated 9 m drop test is a side drop of a dummy cask equipped with two impact limiters in the scale 1:2. Aim of the test was analysis of impact limiter behaviour under drop conditions and not loading of the cask.

Basic model information is shown in Table 4. Lid and cask and impact limiter and cask are connected with bolts. The bolts are modelled as truss-elements (1-d-rod-elements with tension-compression-characteristics). Elastic material laws were applied for the cask and lid, since the experimental results showed that only elastic loads occurred for these parts of the cask. Hexahedron-elements with 8 nodes and reduced integration scheme were used. Reduced integration was applied because fully integrated elements and larger element length/width ratios lead to an overestimated stiffness [9].

Table 4: Basic FE-model-information

Model component	Nodes	Elements	Material law
full model	153046	136922	
cask	32830	25104	3 (elastic)
cask body	29124	22080	3 (elastic)
primary lid	3706	3024	3 (elastic)
bolts	0	24	3 (elastic)
impact limiter	127368	111794	
steel structure	36974	29520	3 (elastic)
inner steel sheets	14064	18768	24 (piecewise_linear_plasticity)
outer steel sheets	44804	44994	24 (piecewise_linear_plasticity)
wood	31526	18512	26 (honeycomb)

The impact target is modelled as rigid wall (rigidwall\_planar\_id). The rigidwall prevents any penetration of nodes into or behind the rigidwall and does not absorb any energy, except for friction. This reproduces to a large degree the situation at the drop test facility of BAM, where mass of impact target is about 200 times higher than cask mass. The target is covered by a thick steel plate [10].

## Impact limiter modelling

The steel structure of the impact limiter can be modelled with shell elements with an elastic-plastic material law. Here material model 24 of LS-DYNA was used. Yield curves have been derived by tensile tests.

The wood was modelled by solid hexahedron elements with 8 nodes and reduced integration. Material model 26 (honeycomb) of LS-DYNA was used. It was developed for honeycomb materials [11], but is among the material models coming with LS DYNA together with material model 126 with its independent orthotropy one of the most appropriate to simulate wood behavior.

Wood exhibits under axial compression a softening after reaching compression strength. This softening is a function of lateral strain restriction [2] and is difficult to simulate due to the local nature of the FEM. For reasons of numerical stability a non-softening yield curve has to be applied. This yield curve was then altered to average the specific energy absorption capacity under the lateral strain restrictions occurring for the specific construction of the impact limiter.

## Results

Quality of calculation was assessed by comparing locally measured and calculated cask-decelerations and impact limiter deformations on lid- and bottom side of the dummy cask.

Figure 4 shows local deceleration-time-plots from experiment and calculation. They correspond, apart from some deviations of deceleration and impact duration.

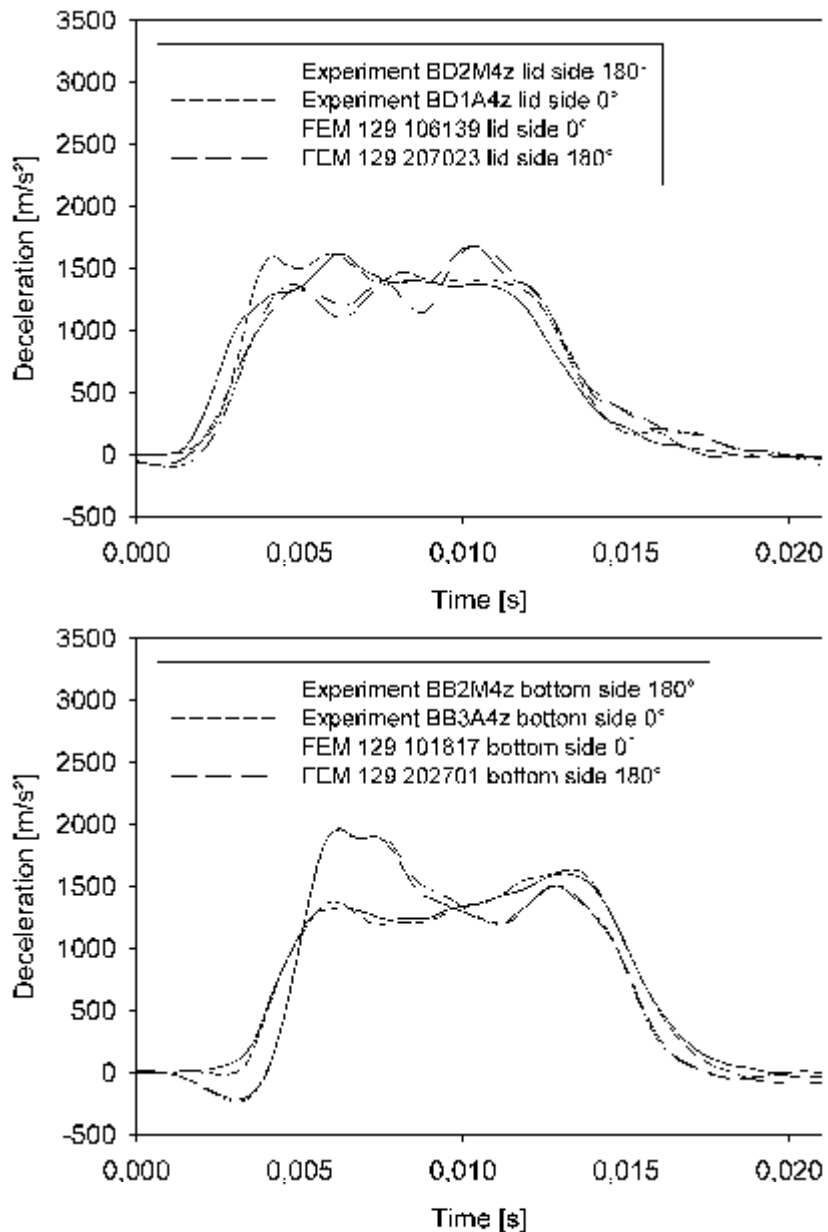


Figure 4: Comparison of local deceleration-time-plots (lid and bottom side, 0 and 180°) from experiment (impact limiter component drop test from 9 m height) and calculation (material law 26 of LS-DYNA with a non-softening yield curve for wood) (1500 m/s<sup>2</sup> equals 4921 ft/s<sup>2</sup>)

Table 5 shows a comparison of deformations measured after drop test and in calculation. On bottom side deviations are very small (2%) while they are higher but still acceptable at lid side (9%).



Table 5: Deformations in experiment and calculation, taking into account an elastic springback of 5%<sup>1</sup>

Impact limiter deformation	Experiment	Finite Element calculation	Deviation
bottom side	68.3 mm	69.8 mm	2.2 %
lid side	62.2 mm	67.9 mm	9.2 %

<sup>1</sup>(strain reduction according to an elastic “unloading”) of approx. 5%-7.5% in the experiment, according to [2].

### Summary for FEM-simulation of drop test

The calculation results show that with appropriate modelling the drop test results can be simulated acceptably. The consideration of compression mechanisms in wood is precondition for a purposeful simulation. Yield curves have to be adapted in dependence of lateral strain restriction occurring at the impact limiter in experiment. Presented procedures can only be applied in connection with verification. Drop tests with sufficient similar designs (in particular impact limiter construction) are obligatory for verification.

### CONCLUSIONS

This paper presents two possibilities to simulate the behaviour of impact limiters of RAM casks under 9m drop test conditions.

It was shown that simplified numerical tools are in general able to calculate rigid body acceleration-time history of transport casks with wood filled impact limiters, as long as certain limitations are taken into account: compliance of the cask components and the impact target compared to the impact limiter must be negligible. Multiple mass phenomena, as occurred on the CONSTOR V/TC and MSF69BG packages, are usually not included in such approach. The most influential part is the implemented wood strength curve, which has to be integrally representative for compression in the whole shock absorber. Changes in the compression mechanisms already result from small changes in the design and boundary conditions. Therefore, comprehensive verification including drop tests and compression tests is essential.

An FE simulation of a drop test with a dummy cask equipped with two impact limiters in the scale 1:2 was carried out. Behaviour of the absorbing material (wood) could not be simulated universally including influence of lateral strain restriction; nevertheless loading of the cask by crushing of impact limiters could be simulated purposefully. Verification with experimental results is compulsory. If significant changes between verification and calculation occur, the predictability of the calculation method is small. Only if compression mechanisms in the impact limiter can be determined by analysis of impact limiter wood, a certain predictability can be expected.

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