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DYNAMIC FINITE ELEMENT ANALYSES OF A HLW TRANSPORT CASK WITH POLYURETHANE IMPACT LIMITERS IN 9M DROP TESTS

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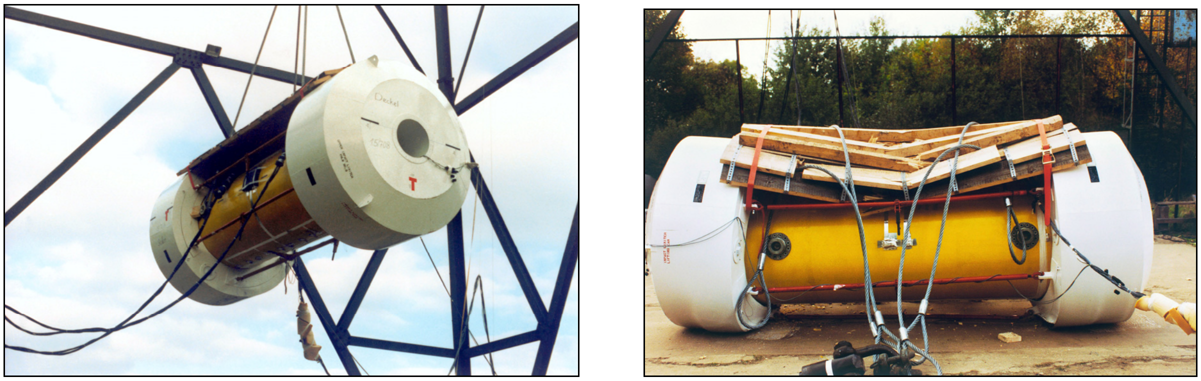
ABSTRACT

Between 1990 and 1992 BAM carried out in cooperation with Sandia National Laboratories a series of drop tests with a HLW transport cask equipped with polyurethane impact limiters. In those days test results were analysed with an analytical method to describe the impact limiter behaviour and deceleration-time relationship, which was state of the art at the time. BAM has studied this former test series with the numerical finite element method once more to develop a new analysis method according to present state of the art. These studies show that the analytical results of 1990 were always appropriate and conservative. However, it is possible to study more crush phenomena of the impact limiters and, thus, understand more details of the test results with modern finite element analyses as opposed to analytic calculations. This paper studies not only the influence of the cask axis impact angle on the rigid body acceleration and strain of the cask, but also the influence of the sheet steel properties of the impact limiter. The latter is not negligible because of the comparatively soft behaviour of the impact limiter material. Furthermore, calculations without a damage criterion for the sheet steel are conservative for 9m drop tests. Since damage of the impact limiters appeared during all of these drop tests, calculations with a suitable damage criterion can describe the tests more correctly. Compared to the analytical method of 1990, the expensive dynamic finite element analyses have some distinct advantages. The finite element model, which was verified using more than one drop test, can now be used not only for the explanation of drop test results but also for the design or approval of new polyurethane impact limiters.

INTRODUCTION

BAM works in the field of materials research and testing with the aim of covering and improving safety and reliability in chemistry and material technology. It is the responsible authority for the technical safety of transport casks for radioactive materials in Germany. In a research project in 1990, BAM carried out a series of drop tests with an original size cask which was evaluated at that time with analytical methods. The advantages and possibilities of modern three-dimensional numerical simulations are shown with the study presented here, particularly with regard to



a) before test b) after test

Figure 1. 9m horizontal drop test of the cask CASTOR® VHLW

impact limiters. The behaviour of an impact limiter, which is a steel sheet construction filled with polyurethane (PU) in this case, can be described now in more detail with dynamic finite element (FE) calculations. The influence of parameters, like impact limiter hardening or impact angle, on the global deceleration of the cask body and on local decelerations at the positions of the accelerometers are discussed and compared with experimental results.

DROP TEST WITH THE CASK CASTOR® VHLW

In 1990 a series of drop tests with the original size transport cask CASTOR® VHLW was carried out on the BAM 100 Mg drop test site [1]. One of these tests was the horizontal 9m drop test with impact limiters. Another one was the 15° slap-down test with the same impact limiter construction. The test target was an armoured concrete foundation covered with a steel slab according to IAEA recommendations.

The transport cask consisted of the following main components: cast iron cask body, steel primary lid and protection plate, dummy contents (a coquille filled with glass) and impact limiters on the bottom and lid side which were braced against each other with six steel rods.

Three accelerometers were equipped to the cask body to measure the time-dependent deceleration during impact. Additionally, strain gauges were placed on selected positions. Massive wood blocks were attached on top of the cask body between the impact limiters to stop damage by an impact of the mounting device onto the cask body (Fig. 1). The positions of the accelerometers (measuring points 5, 7 and 9) and some strain gauges (10, 22, 24, 26) are in Figure 2.

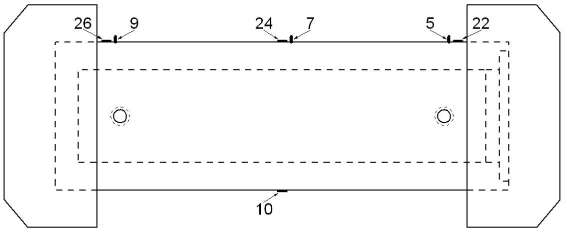


Figure 2. Positions of selected measuring points

MATERIAL BEHAVIOUR

Cask body material behaviour (cast iron, as shown in Fig. 3) depends on temperature as well as loading rate and differs in tension and compression. It was not possible to put tension and compression flow curves for different strain rates separately in the material library of the FE code ABAQUS Version 6.7 [2], which we used here. Therefore, independent material curves for tension and compression were only used at a fixed strain rate of 1/s in the calculations.

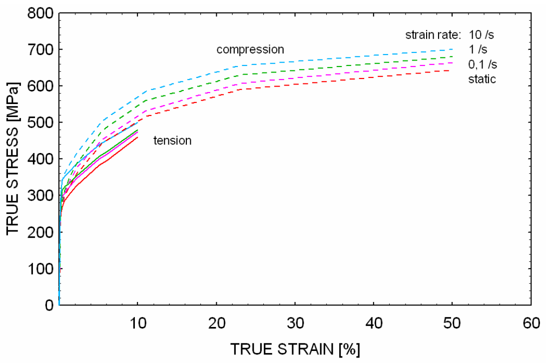


Figure 3. Dynamic flow curves of ductile iron

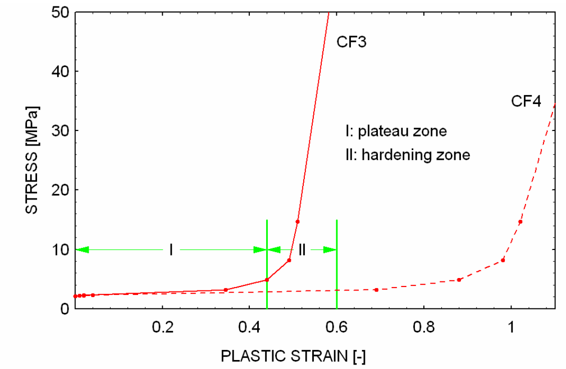


Figure 4. Flow curves of PU-foam

The constitutive equation and material parameters of the PU-foam (Fig. 4) were taken from Sauvé et al. [3] (marked here by CF3, see also ABAQUS 6.7 Example Problems Manual, section 2.1.12, "Cask drop with foam impact limiter"). While this flow curve is not identical with the one in the BAM report [4] for the polyurethane used in the impact limiters, a second flow curve (CF4) with an expanded plateau zone was used in the calculations. Modification of the flow curve may be explained by damage and existing gaps in the impact limiters, which make the behaviour of the construction on the whole softer. The flow rule is the same in both cases. Hence, the ABAQUS material model "crushable foam" describes the material behaviour of the polyurethane foam very well.

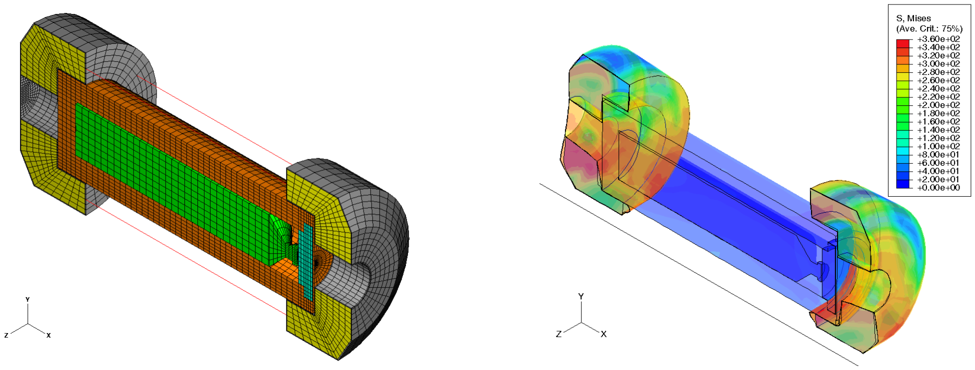
Table 1. Linear-elastic material parameters

component	primary lid	protection plate	dummy contents	steel sheet	pull rod	PU-foam	cast iron
Young's modulus [GPa]	210	200	70	200	200	0.18	164
Poisson's ratio	0.3	0.3	0.1	0.3	0.3	0.125	0.275
mass density [kg/m³]	7900	7900	2690	7900	7900	350	7200

The sheet metal is defined as elastic-plastic with damage criteria. Material behaviour must be considered adiabatic because of heat generated during plastic deformation of the steel construction at impact. The effect is taken into account by modified "adiabatic" flow curves in an uncoupled isothermal calculation. All other components are defined as linear-elastic (Table 1).

FINITE ELEMENT MODEL

The FE model for the CASTOR® VHLW with impact limiters is shown in Figure 5. It consists of the cask body, primary lid, protection plate, contents (coquille), impact limiters (steel sheet construction filled with PU foam) and impact limiter fasteners (pull rods). Total mass with impact limiters amounts to approx. 23 Mg. Due to prevailing symmetry conditions, only half the cask was modelled. Therefore, the influence of rotation around the cask axis cannot be studied with this model. The foundation was prescribed as a so-called analytical rigid body. The 9m drop height is given by the initial velocity at the moment of impact. All free surfaces (between cask body and coquille, cask body and impact limiter, sheet construction and PU foam, impact limiter and foundation) were modelled by means of the "general contact" option in ABAQUS/Explicit.



a) Finite element mesh **b) Stress distribution at 25 ms after impact**

Figure 5. Cask model with impact limiters for horizontal drop test

The finite element mesh consists of 8-node 3D solid elements with reduced integration (ABAQUS element type: C3D8R). The material parameters of elastic parts are in Tab. 1, and the cask body material is shown in Figure 3. Both crushable foam material definitions (CF3, CF4) for the impact limiters were used in different calculations for comparison purposes (Fig. 4). The material model of the sheet metal is explained above.

CASK BODY DECELERATION

In analysing the drop test of a "hard" cask with "soft" impact limiters the cask body may be simplified as rigid. Cask deceleration is then a measure of its load. Deceleration is normally indicated as a multiple of g (9.81 m/s^2). However, in a real drop the cask is always stimulated into oscillations so that the rigid body prerequisite is more or less violated. Therefore, the accelerometers show, strictly speaking, local decelerations. The rigid body deceleration cannot be measured directly. Therefore, oscillations are normally removed by signal filtering. These physically based oscillations also appear in the numerical simulation of a drop test with a deformable cask body. In addition, the contact algorithm of the FE code produces high-frequency numerical oscillations in many cases. However, the calculation has a great advantage: if the cask body is modelled as rigid, the rigid body deceleration can be calculated directly.

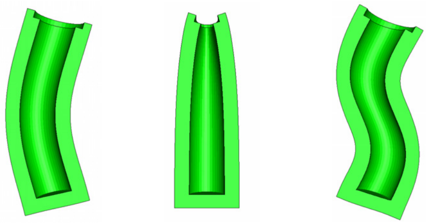


Figure 6. Cask body vibrations from modal analysis (deformation enlarged)

The filtering cut-off frequency depends on the cask construction. In this case, a modal analysis is always required to find the base frequency. If the chosen cut-off frequency is too high, local decelerations are interpreted erroneously as global load. Figure 6 illustrates some vibrations of the cask body. As an example, Figure 7 shows the directly calculated rigid body deceleration (dotted line) and filtered calculated deceleration of the body (heavy line; Butterworth filter with cut-off frequency of 348 Hz). Obviously, the derived curve oscillates a little bit stronger and, therefore, also shows a higher maximum value on the whole.

A quasi-static calculation was carried out with the external force (mass*72g). Figure 8 compares the calculation result with the fully-dynamic calculation at measuring points 10 and 24. The maximum strain values agree very well. Hence, signal filtering with the base frequency from the

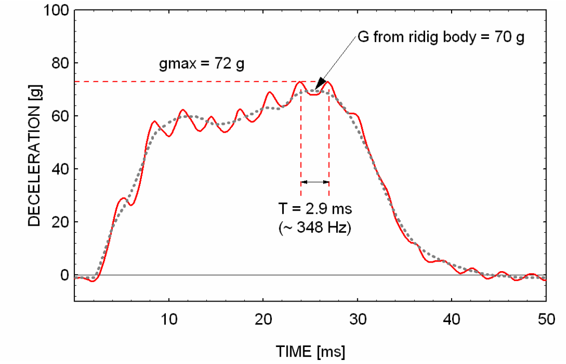


Figure 7. Calculated decelerations: rigid body (dotted line), deformable body with signal filtering (heavy line)

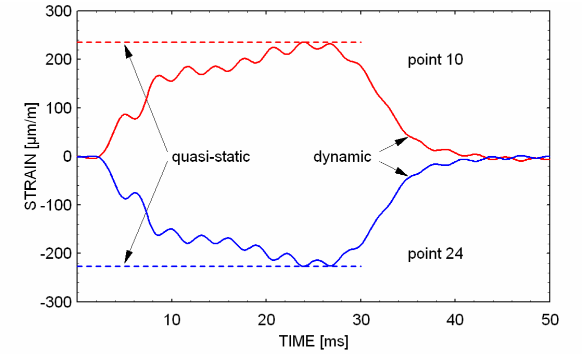


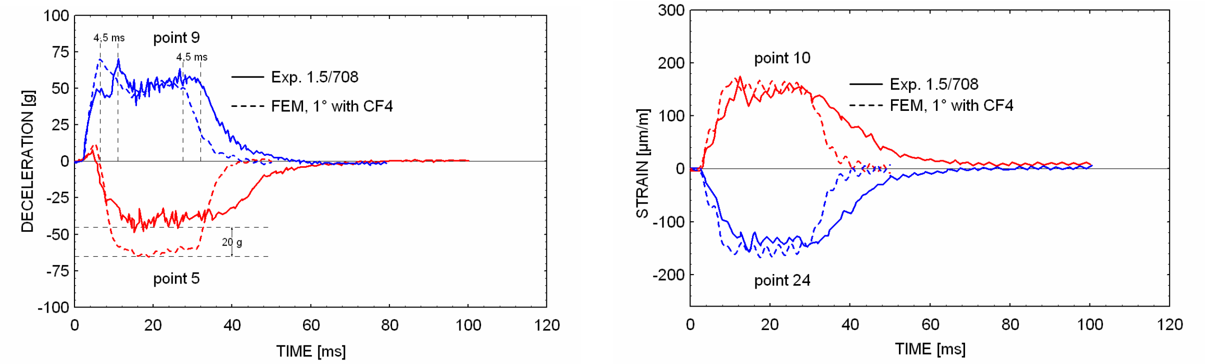
Figure 8. Strain from dynamic and quasi-static calculations

modal analysis provides a basis to assess maximum value of a time-dependent strain from a quasi-static calculation if the cask body can be described approximately as a rigid body.

CALCULATION RESULTS

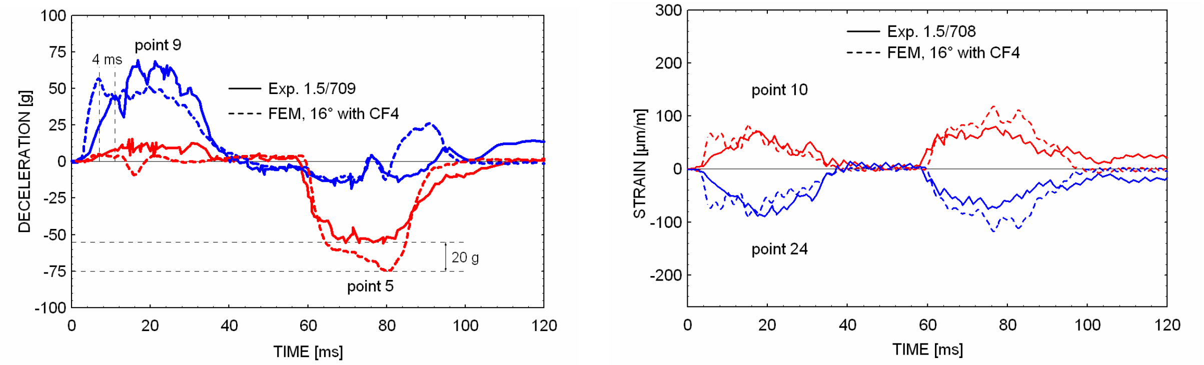
Referring to recently published parameter studies [5, 6], we find more realistic impact limiter behaviour with the parameter combination CF4 (extended plateau zone of the PU-foam flow curve, steel sheet with damage, contacts with friction, real target). Test results are compared with calculation results for the 9m horizontal drop in Figure 9.

Hereafter, the slap-down test was simulated with exactly the same set of physical parameters. According to the test report, the cask was dropped at an angle of 15°. The angle was slightly changed to 16° in the calculations, as indicated by comparison with the experimental results (Fig. 10). Deviations between the curves are comparable with the horizontal drop test case. It can be inferred from calculations of different test scenarios with the same physical parameters that deformation behaviour of VHLW impact limiters is well-known and adequately modelled. Small differences in the decelerations remain at measuring point 5 near the lid system. Further investigation is needed here with a more detailed model of the lid system and bolts including pre-tension.



a) deceleration **b) strain**

Figure 9. Test and calculation results for parameter combination CF4 with impact angle of 1°



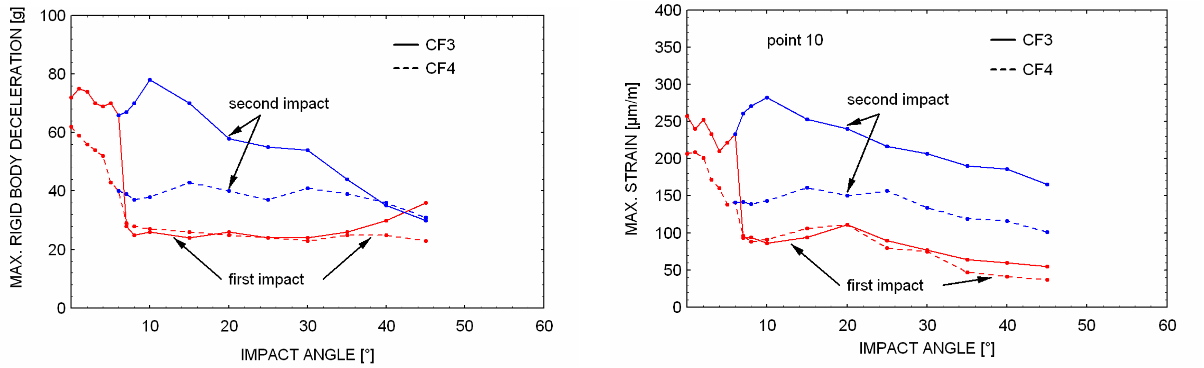
a) deceleration **b) strain**

Figure 10. Test and calculation results for parameter combination CF4 with impact angle of 16°

SLAP-DOWN EFFECT

The so-called slap-down effect can appear at large impact angles, i.e. impact velocity can be higher at the secondary impact because of cask rotation. This can result in a higher load on the cask body and lid system. The slap-down effect on the cask body will now be examined up to an impact angle of 45° in 5° steps. However, influences on the lid system will not be discussed here. The calculations were carried out for a rigid target and elastic cask body. Figure 11a shows the maximum values of rigid body deceleration at different impact angles. The relation of strains to impact angle at the measuring point 10 in the middle of the cask is represented in Figure 11b. The course of the strains resembles the one for rigid body deceleration.

Two ranges can be distinguished. No secondary impact appears up to an impact angle of 7°, and the impact limiters only deform. The calculations show for a primary impact angle in the range of 7° to 45° nearly constant and almost identical rigid body decelerations for both parameter sets CF3 and CF4. Maximum strains are hardly different too. Maximum rigid body deceleration rises for CF3 between 7° and 10° first at the secondary impact and then falls continuously. The curves are also slightly angular-dependent for CF4 with angles above approximately 10°.



a) rigid body deceleration **b) strain**

Figure 11. Maximum values in the middle of the cask at different impact angles

Higher loads appear at secondary than primary impact. The material CF4 leads on the whole to lower decelerations and strains. The load is always smaller than for a horizontal impact. However, if the impact limiters are deformed up to their limits or lock, a situation like case CF3 occurs. The secondary impact leads to much higher loads than the primary impact, and the load can be even higher than at the impact angle 0°. Thus, we find a small slap-down effect at the calculation CF3 for an impact angle of 10°. No slap-down effect occurs at the calculation CF4 like in the CASTOR® VHLW cask test.

In practice, a scenario as in calculation CF4 should dominate for the 9m horizontal drop since impact limiters may not lock. Impact limiters must be regarded as a whole because not only filling material but also dynamic crack initiations, gaps in the filling, and large plastic deformation with simultaneous heating of the material will influence impact limiter behaviour.

CONCLUSIONS

Dynamic finite element calculations for impact angles of 1° and 16° with otherwise identical parameter sets show similar results to the test. The calculation results are always conservative. The influence of impact angles on the cask load was examined by parameter studies, which is of special interest for defining test conditions. A slap-down effect cannot be expected in the real drop test investigated here because of damage to the impact limiters.

Rigid body deceleration is a very important value when assessing the load on the cask. It differs from the locally measured deceleration of an elastic body. However, rigid body deceleration can be derived from local decelerations near the centre of a cask with appropriate signal filtering if the cask body can be described approximately as a rigid body.

FE analysis accuracy strongly depends on details of the modelling, chosen material models and replication of all relevant boundary and initial conditions of the drop test. The expanded plateau zone in the flow curve of the impact limiters filling material can be explained mainly by unknown gaps between different components from slight manufacturing deviations. These gaps are not contained in the FE model. Additionally, dynamic crack initiations and large plastic deformation with simultaneous heating of the material may occur. In this case, the complicated deformation behaviour of the impact limiters has been described approximately by carefully modifying the flow curve of the filling material. Modelling of the impact limiters has been checked by simulating real drop tests with different impact angles. Based on these studies of comparatively simple impact limiter constructions (homogeneous isotropic filling material), the development of an anisotropic model for wood-filled impact limiters has been planned.

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