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Validation of Numerical Simulation Models for Transport and Storage Casks using Drop Test Results

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Abstract

The safety assessment of new designs for transport and storage casks for radioactive materials is a challenging task by using different methods like prototype tests, model tests, calculations and analogy reflections. At BAM (Federal Institute for Materials Research and Testing), the test procedures for the mechanical IAEA (International Atomic Energy Agency) test conditions often start with preliminary finite element calculations mostly with a small-scale cask model for verification of the proposed test cask instrumentation and test plan. On that basis the extensive test cask instrumentation is applied and checked. After that, a drop test series consisting of different test sequences is performed. Under test conditions according to the IAEA transport regulations, casks are usually equipped with impact limiters and dropped onto a so-called unyielding target. In general, it is difficult to verify a complex finite element (FE) model by using results from only one drop test because of the complex impact process and the complex structure of such packages. After each drop test, numerical post-analyses should be carried out. Only if all drop tests were simulated successfully by using the same FE model under different test conditions, it is possible to get a validated numerical model for further investigations. In this case the results of the numerical simulations meet satisfactorily the experimental results. In this paper a study is presented, where the influence of different components on the cask loading is investigated systematically.

Keywords: transport and storage cask, drop test, finite element model, dynamics, simulation, validation.

1 Introduction

In recent years numerical analysis has played a growing role in the safety assessment of new designs for transport and storage casks for radioactive materials. The verification and validation of the used numerical model for a correct analysis is a challenging task because there are many factors which strongly influence the accuracy of a numerical analysis like modelling of cask body and its components, used material models, used finite element code with default or adjusted parameters and definition of contact conditions. At BAM (Federal Institute for Materials Research and Testing), the test procedures for the mechanical safety assessment often start with preliminary finite element calculations mostly with a small-scale cask model for verification of the proposed test cask instrumentation and test plan. On that basis the extensive test cask instrumentation is applied and checked. After that, a drop test series consisting of different test sequences is performed.

Following the drop tests, numerical post-analyses are carried out. These analyses offer the possibility of a detailed calculation and assessment of stresses and strains in the entire test cask construction. The calculation results have to be carefully compared with the measurement data over the impact history to find out all relevant parameters for a realistic simulation of the impact scenario. Sometimes the desired ideal test conditions according to the regulations cannot be met exactly in practice. Therefore, numerical post-analyses are carried out by using the real boundary conditions of the drop tests. It is the objective to find a validated model, for which the results of the numerical simulations meet satisfactorily the experimental results. Under test conditions according to the IAEA transport regulations [1], casks are usually equipped with impact limiters and dropped onto a so-called unyielding target. In this paper a study is presented, in which the influence of different impact positions on the cask loading is investigated. The results of the numerical simulations are compared with drop test results of the half-scale cask model CASTOR® HAW/TB2 [2].

BAM carried out the drop test series and studied the test scenarios with sophisticated finite element models using ABAQUS/Explicit [8]. Results from basic research of crush phenomena of impact limiters are presented. Hence it is possible to interpret the test results in detail by means of modern finite element analyses.

2 Drop test program

For transport and storage of vitrified High Level Waste (HLW) from reprocessing a new cask design was developed by German company Gesellschaft für Nuklear-Service mbH (GNS), Essen [2, 3]. BAM as part of the competent authority system in Germany is responsible for the assessment of mechanical and thermal safety analyses and quality assurance measures within the complete evaluation of the Safety Analysis Report (SAR). An extensive drop test program with an instrumented half-scale model was carried out on the 200 metric tons BAM drop test facility [4, 5].

Figure 1: Model cask without impact limiter before drop test

The drop test program according to transport and storage test conditions consisted of 17 drop tests with different drop orientations, drop heights and temperatures. In this study seven different drop tests were used for the investigation of cask body and impact limiter behaviour. At first the basic 0.3 m vertical drop test without impact limiter directly onto the unyielding target (test P16) was carefully analysed for the validation of the cask body mesh, foundation behaviour and evaluation procedure (Figure 1). The other six tests with equipped impact limiters, which include the vertical drop tests on the lid side of the cask (P05) and the bottom side of the cask (P14) for testing of the lid and bottom impact limiter made of wood, the 0.3 m horizontal drop test (P01) and 9 m horizontal drop test (P04) for testing of jacket impact limiters made of aluminium, the 5° slap-down drop test (P10) and 20° slap-down drop test (P12M) for testing of the combined behaviour of lid, bottom, jacket impact limiters and trunnions, are shown in Figure 2 just before the drop test.

P05

P14

P01

P04

P10

P12M

Figure 2: Model cask with impact limiter shortly before different drop tests

3 Finite element model

The competent authority BAM developed a finite element model (FE model) for mechanical design assessment independently of the applicant. Thereby the different test scenarios were considered. The FE model (Figure 3) of the drop test cask CASTOR® HAW/TB2 was built in a detailed manner to get reliable and accurate results. These numerical results were compared with test data to validate the FE model. The model consists of the following main components:

- cask body made of ductile cast iron,
- moderator boreholes,
- primary lid and lid screws,
- four trunnions,
- model canisters,
- model graphite columns,
- moderator plate at cask bottom,
- closing plate at cask bottom,
- bottom end and lid end impact limiter filled with wood,
- three jacket impact limiters made of aluminium.

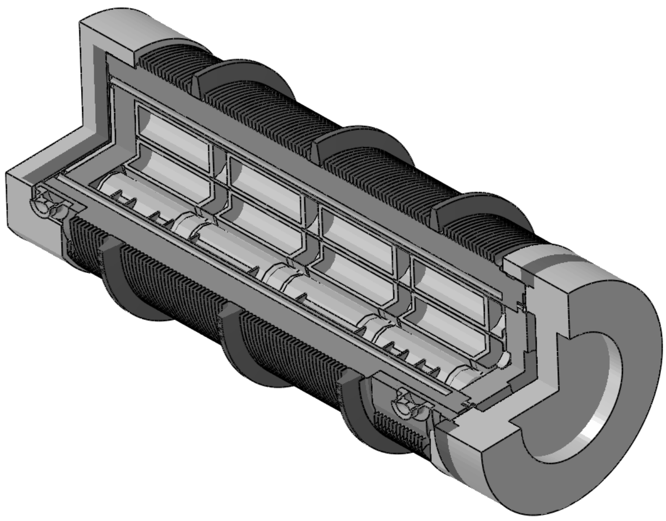


Figure 3: FE Model of the half-scale cask model CASTOR® HAW/TB2

The gross weight is approximately 14.5 Mg. The complete FE model has about 300,000 elements and 400,000 nodes. It was built up with 3D solid elements of ABAQUS type C3D8R with linear interpolation and reduced integration for the dynamic simulation. All free surfaces (between cask body and canisters, cask body and primary lid, cask body and impact limiter as well as between impact limiter and foundation) were defined by using ABAQUS option "general contact". One-dimensional truss elements with a very small cross section area were attached along the strain gauge direction at the measuring points on the model surface to get directly the local strains. Both signals of local decelerations from drop test and simulation were filtered with the same Butterworth function with a cut-off frequency of 1 kHz resulting from a modal analysis of the cask body.

4 Simulation of vertical drop test without impact limiter

Figure 4 shows the used model for the simulation of the 0.3 m vertical drop test without impact limiter directly onto the unyielding target of BAM drop test facility. In addition to the modelling of the cask it is also important to model the test site foundation precisely. Due to the impact without impact limiter the target absorbs a significant part of the impact energy. Stress waves are transmitted into the target and their transmission and reflection is mainly influenced by structural transitions between different materials or components. An over-simplified model, e. g. with a rigid target, would neglect the energy absorption of the target. For that reason it is necessary to build a detailed foundation model with all components and dimensions large enough to avoid unrealistic reflections of stress waves and their possible influence on the cask reaction during the calculation time. The test site target has a base of 14 m x 14 m, is 5 m deep and consists of reinforced concrete. This block is covered by three 0.22 m thick steel plates forming a 10 m x 4.5 m impact area. The steel plates are fixed with the concrete block with 40 steel rods (2 m long with a diameter of 33 mm). Additionally, there is a 0.5 m thick concrete transmission layer between steel plate and reinforced concrete block. The soil around and below the reinforced concrete block was built up with so-called infinite elements which avoid unwanted stress wave reflections from boundaries.

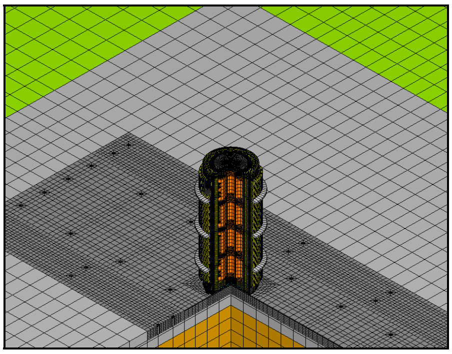


Figure 4: FE model of the cask on top of the BAM drop test facility target.

Figure 5 shows strain histories for the cask bottom centre. The small differences between the dotted and the continuous line in Figure 5 show that the canisters are considered in a sufficient manner. The oscillations after 5 milliseconds (ms) represent cask bottom vibrations which are influenced by the interaction of the canisters among themselves and with the cask. Other verifications were conducted referring to finite element modelling of the cask (e. g. FE mesh refinements), the foundation and contact conditions. The final results represented by Figure 5 show a good correlation of test and calculation data. Therefore, the numerical model can be considered as a sufficient description of the physical reality. With that an appropriate basis for further strain and stress analyses of the whole cask structure is given. More details can be found in a prior work [6].

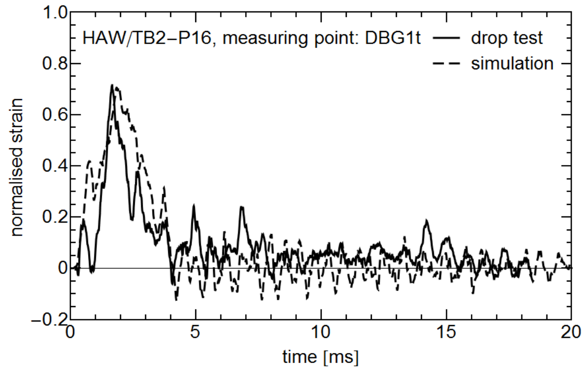


Figure 5: Strain histories from calculation and measuring at cask bottom centre

5 Simulation of vertical drop test with bottom and lid impact limiter

In this section the simulations of the drop tests P05 (Figure 6a) with lid impact limiter and drop test P14 (Figure 6b) with bottom impact limiter are discussed. Both the lid and bottom impact limiter have a similar structure and use the same wood filling in a surrounding aluminium shell. In a prior work [7], a simple crushable foam plasticity material model from ABAQUS [8] combined with a modified Hankinson equation from Yoshihara [9] was used to describe the integrated wood behaviour under impact loading with different fibre orientations. The stress-strain curve of the model was estimated from test data [10]. During the vertical drop the integral wood behaviour follows dominantly the flow curve for 90° fibre orientation. The model canisters were positioned directly on the primary lid at the beginning of drop P05 and directly on the cask bottom at the beginning of drop P14. The recorded data of the accelerometers and strain gauges were used for comparison of drop test and simulation results.

a) b)

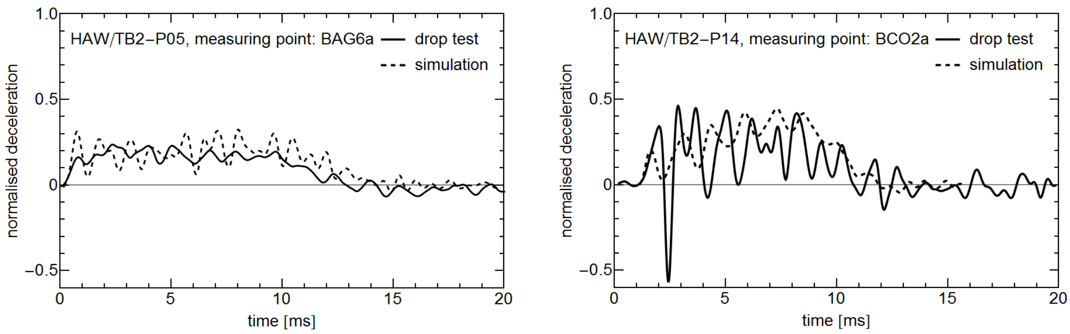
Figure 6: FE model for simulations P05 (a) and P14 (b)

Figure 7 illustrates the simulated stress distribution during the impact phase at the same time of t = 5 ms and with the same displacement scaling factor. The stress on the cask body at drop test P14 is slightly larger than at drop test P05 because of the different construction of lid and bottom impact limiter.

a) b)

Figure 7: Calculated stresses at time t = 5ms for drop tests P05 (a) and P14 (b)

In Figure 8 the local decelerations from drop tests and from corresponding simulations are compared. Both signals from drop test and simulation were filtered with the same Butterworth function with a cut-off frequency of 1 kHz resulting from a modal analysis of the cask body.



a) b)

Figure 8: Comparison of decelerations from drop tests and simulations of a) drop P05 with lid impact limiter and b) drop P14 with bottom impact limiter

At these two drop tests the cask body showed only elastic deformation and the impacts were almost ideally flat. The mean deceleration of the plateau zone at drop P14 is twice as high as the corresponding value at drop P05. The higher impact force is the reason for higher cask body stresses during drop P14 compared with drop P05, although the drop height was 9 meter in both tests.

6 Simulation of horizontal drop tests with jacket impact limiter

The ring-shaped jacket aluminium impact limiter around the cask body absorbed the major part of the impact energy during the 9 m horizontal drop. The presented dynamic calculation of this drop test was done without thermo-mechanical coupling. The numerical analysis considered isothermal conditions by using the adiabatic stress-strain curves of aluminium with the test temperature of -40°C. In a prior work [11] a more sophisticated simulation was carried out with consideration of thermo-mechanical coupling. Thereby the heat generation inside the aluminium material was considered and isothermal dynamic stress-strain curves for different temperatures were used. The comparison of the calculation results showed that for the investigated drop tests both computational approaches lead to comparable results.

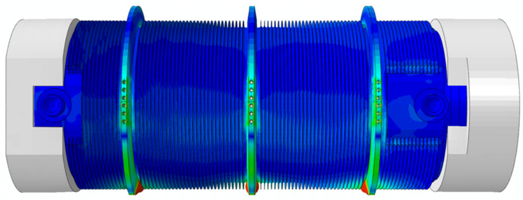


Figure 9: Simulation result of drop test P04

Figure 9 shows the global result of the numerical simulation. The cask body remained undamaged as shown by the drop test. The deformed shape of the aluminium ring was just a so-called "elephant foot". The behaviour of aluminium in this case was dominated by plastic deformation up to about 60% strain. Postulation of failure for aluminium would have only a small influence in this case. Hence, the consideration of a failure criterion for aluminium is not necessary here. Figure 10 shows the deformation of the aluminium impact limiter more clearly. In case of P01 (0.3 m drop) the deformation was comparatively small. The temperature change was negligible. In case of P04 (9 m drop) there was large deformation and the temperature change was significant.

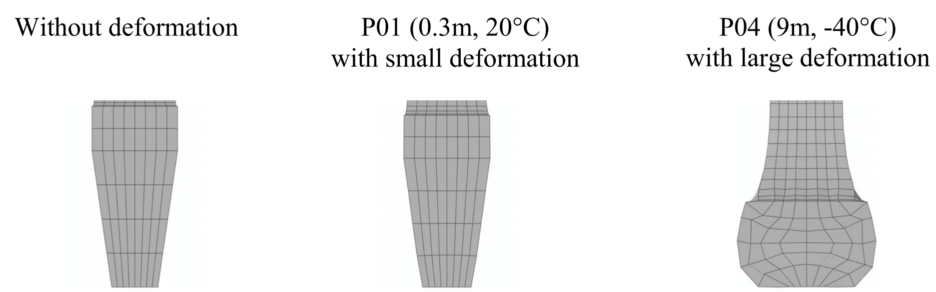


Figure 10: Schematic presentation of deformation of aluminium impact limiter

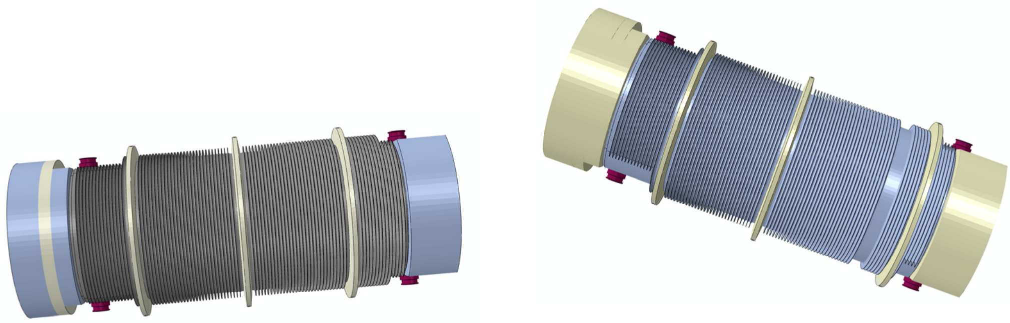
Table 1 shows the comparison of the normalised maximum cask body deceleration at measuring point BMA6t and normalised maximum local strain at measuring points DKM4a and DKM4t gained from simulation and drop test. The comparison shows a good correspondence.

Measuring point	BMA6t		DKM4a		DKM4t	
	P01	P04	P01	P04	P01	P04
Measuring	0.2	0.75	0.08	0.23	0.14	0.42
Simulation	0.2	0.79	0.06	0.21	0.15	0.51

Table 1: Normalised maximum deceleration and strain at drop tests P01 and P04

7 Simulation of slap-down drop test with lid, bottom, jacket impact limiter and trunnions

In this section two drop tests with combined behaviour of lid, bottom and jacket impact limiters as well as trunnions are simulated. The selected drop tests are P10 with an impact angle of 5° (Figure 11a) and P12M with an impact angle of 20° (Figure 11b).



a) b)

Figure 11: FE model of a) with impact angle of 5° and b) with impact angle of 20°

The contact duration of drop test P10 was about 10 ms. It showed almost no slap-down effect. That means both the first impact onto the unyielding target at the lid side and the second impact at the bottom side appear almost in one impact process. Hence, during the impact the lid and jacket impact limiter at lid side were at first in contact with the unyielding target. After that, the bottom and the jacket impact limiter at bottom side came into contact with the target. In this drop test the trunnions were also in contact with the steel target. Due to the initial impact angle, there was shear load on the jacket aluminium impact limiter. In this case the shear failure of aluminium must be considered [12]. FE simulation results with and without aluminium shear failure definition at measuring point BTG6t (local deceleration) are shown in Figure 12. The calculated maximum deceleration without failure definition of aluminium gives the highest maximum deceleration because the material is modelled too hard in this approach compared to reality. The simulation with aluminium failure definition shows similar results compared with the drop test because of the more realistic description of material behaviour in this case. The consideration of a failure criterion for aluminium is necessary here.

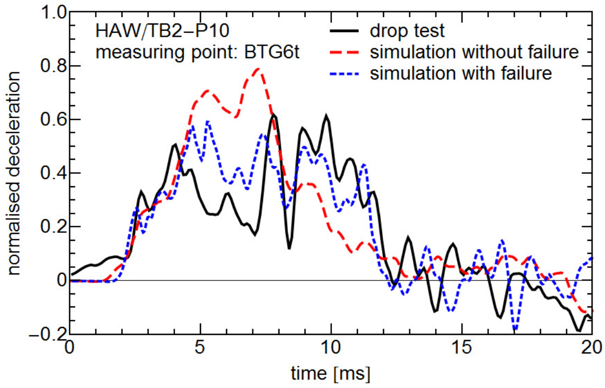


Figure 12: Comparison of local decelerations from drop test and simulations of P10

The drop test P12M was more complex than all the other drop tests. At the first impact with 20° drop angle, the bottom impact limiter, jacket aluminium impact limiter at bottom side and a trunnion at bottom side below the cask body were in contact with the unyielding target combined with a large shear load almost at the same time. The first impact took about 10 ms, and then the cask suffered a free rebound for about 45 ms. After that phase it came to the second impact at lid side for about 10 ms with a very small impact angle. During the second impact the impact limiter at lid side, jacket aluminium impact limiter at middle of cask body and at lid side and a trunnion at lid side below the cask body were in contact with the unyielding target under pressure and shear load. Hence, the full model with all components can be checked with this complex impact scenario.

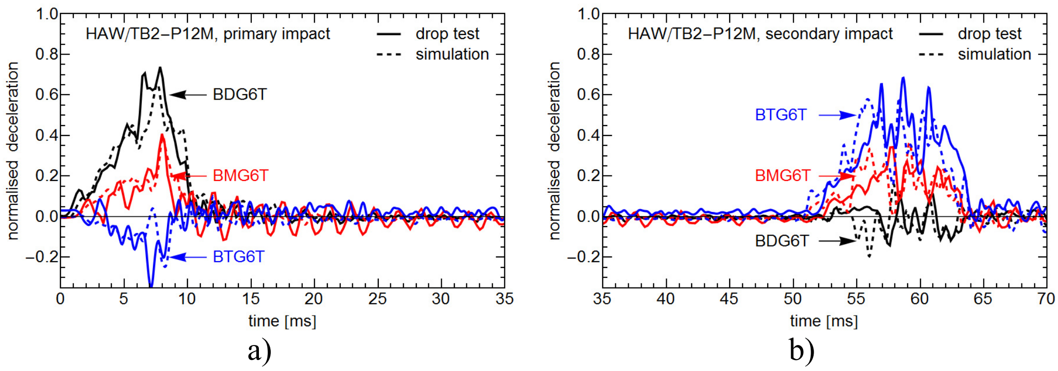


Figure 13: Comparison of local decelerations from drop test and simulations of P12M for a) first and b) second impact

With the prior defined parameters the simulation of P12M was carried out only with a change of impact angle from 5° to 20°. A detailed comparison between drop test results and simulation results for local decelerations at bottom side (BDG6T), in the middle (BMG6T) and at lid side (BTG6T) of the cask body is shown in Figure 13. The comparison shows a good correspondence between drop test and simulation results.

8 Conclusions

In this paper, seven drop tests of a half-scale cask model equipped with and without impact limiters under different drop test positions were selected to investigate the cask behaviour during 9 meter drop. At first, a drop test from a height of 0.3 m without impact limiter directly onto the unyielding target was carried out. A suitable FE model was developed, and the test could be simulated successfully. After that, the FE model was extended by impact limiters and their connections to the cask body to simulate other drop tests with impact limiters. All drop tests were simulated with the same FE mesh. Material models of all components were developed independently by separate material tests. The results of these simulations were presented.

It can be concluded that it is difficult to validate a complex FE model of a cask including additional components by using only results from one drop test because of the complex impact process and the complex structure of such packages. After each drop test, numerical post-analyses should be carried out. Separate component tests are necessary without having the results of a drop test series available. Only if all drop tests (or component tests) were simulated successfully by using the same FE model under different test conditions, it is possible to get a validated numerical model for further investigations. In this case reliable calculation results can be expected as shown here by comparison with experimental results and their good correspondence.

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