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TOPICAL BAM CASK DESIGN EVALUATION USING DROP TESTS AND NUMERICAL CALCULATIONS: ACCIDENTAL CASK DROP WITHOUT IMPACT LIMITERS ONTO A STORAGE BUILDING FOUNDATION

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ABSTRACT AND INTRODUCTION

In recent years BAM has been performing extensive design and drop test programmes to evaluate the mechanical safety of new transport and storage cask designs from national and international manufacturers like GNS (Gesellschaft für Nuklear-Service mbH), TN International (TNI) and Mitsubishi Heavy Industries (MHI). Although most test scenarios use IAEA test conditions for Type B transport packages, additional investigations are necessary to analyse typical accident scenarios with handling procedures inside storage facilities where casks are moved without impact limiters.

Cask impacts without impact limiters on unyielding targets result in totally different mechanical reactions from those of relatively smooth impacts using impact limiters. During the licensing procedure of the new GNS CASTOR® HAW 28M design for vitrified high activity waste, BAM therefore decided to perform an additional drop test with a 1:2 scale test cask (CASTOR® HAW/TB2). In spite of a small drop height of only 0.3 meters, contact with the unyielding target of the BAM drop test facility, which conservatively covers any storage building foundation, causes considerable stresses to the cask structure with high stress and strain rates.

This paper presents the evaluation strategy of BAM including drop test results and the development and qualification of appropriate finite element modeling to achieve sufficient accordance between test and calculation results. Further steps are mechanical analyses of reduced and full-scale cask designs to determine the most critically stressed areas of the structure, verify scaling factors and demonstrate safety with respect to cask integrity and tightness.

BAM SAFETY ASSESSMENT STRATEGY

Safety assessments for licensing new and complex cask designs for transport and/or storage need challenging strategies with different methods such as full-scale prototype tests, model tests of appropriate scale, calculations, and references to previous satisfactory demonstrations [1]. In the current BAM design test procedures, safety assessments under mechanical IAEA test conditions or storage site specific accident conditions start with preliminary finite element (FE) calculations performed by the applicant and checked by BAM. These are primarily done with the scaled test cask model for verification of the proposed test cask instrumentation and test plan. Based upon the finite element precalculation, extensive test cask instrumentation can be located appropriately and estimates of sensor levels provided. After installation of instrumentation a series of drop tests consisting of different test sequences is performed. The results of the first test and subsequent test sequences are evaluated and reviewed to determine if adjustments to the test plan are necessary.

After completion of the drop tests, numerical post-test analyses are carried out with the finite element method (FEM). These analyses provide a detailed assessment of the entire test cask structure. The evaluations focus on the quality of the correlations between test data and calculated data for all measurement points over the course of impact, and for the different drop test scenarios. These evaluations ensure that all relevant physical effects were considered appropriately by the cask analyses so as to serve as a basis for the following safety assessments. Due to the complexity of the parameters influencing both analysis and testing, validation of experimental boundaries including the material properties and numerical aspects is often a challenging task. Therefore, a detailed analysis of the drop test results is performed after the drop test. Since the desired ideal boundary test conditions often cannot be exactly fulfilled in test practice, post-test analyses are carried out under the real (actual) conditions of the test. A validated finite element model results in successful completion of these steps.

Frequently only one model is developed for all load cases so as to lower the total cost and effort of modeling. Generally, such models are very complex with many material interactions. However, it can be more useful to develop separate reduced scale models to understand physical correlations (boundary conditions, material behaviour etc.) and show the individual aims of the safety analyses.

BAM develops its FE models independently of the applicant and uses alternative FE codes to analyse these models. In some cases, material behaviour can be described with similar material models when equivalent models are missing in the material library of an alternative code. In addition, exact implementation of complex material behaviour may differ. Through the use of different codes, possible errors in the numerical simulation may be found.

Ideal, i.e. worst case, boundary conditions can be scaled up with the validated finite element model to analyse the full-scale cask design and to verify scaling laws. Cask areas and components under maximum stress with respect to, for example fracture mechanics, plastic deformation and leak-tightness of sealed lid systems can be identified and evaluated for final safety assessments. It must be recognized especially that non-linear effects cannot be scaled with simple rules. When scaling is not feasible, investigations must be carried out directly with a full-scale model.

0.3 M DROP TEST REPRESENTING THE STORAGE SITE SPECIFIC ACCIDENT SCENARIO INVOLVING THE CASTOR® HAW 28 M/TB2

Although a drop test series is dominated by IAEA transport regulation requirements that include subjecting the package to different drop orientations, BAM requires additional evaluation of storage site specific accident scenarios where casks are not equipped with impact limiters. These scenarios assume that a cask body may directly hit a very hard foundation, which leads to a totally different mechanical reaction and stress state from the relatively smooth impact using a properly designed impact limiter. BAM has investigated such cask impacts without impact limiters during the last several years in a research project called EBER, which is supported by the Federal Ministry of Education and Research (BMBF) under Contract 02 S 8021 [2]. Amongst others, a procedure using FEM was developed and verified with experimental results for the stress analysis of cubic ductile cast iron containers under mechanical accident conditions. The analysis of highly dynamic stresses was very successful using this procedure. However, it was obvious that impacts from small drop heights could induce highly dynamic stress waves with possible high maximum stresses and strain rates and that the contact conditions and properties of the foundation did significantly influence cask reaction.

With this knowledge BAM took the opportunity to start an investigative program within the framework of the German atomic law licensing procedure for the CASTOR® HAW28M [3] where BAM would perform cask design testing on behalf of BfS (Federal Office for Radiation Protection). In coordination with BfS and GNS an additional drop test including strain and deceleration measurements and a high-speed video recording was performed from 30 cm with the 1:2 scaled test cask (TB2) at the BAM drop test facility. The selected test scenario considered one critical accident situation if a cask drops from the storage building crane during handling operations and hits the ground. The test provided the required test data, especially strain measurements, to validate the finite element model. Figure 1 shows the drop test configuration.

Based on the interpretation of videos and measurement data, the cask hit the ground in an almost perfect orientation, and only a very small angle $< 0.1°$ was observed between the target and bottom of the cask. After the primary impact, the cask inclined visibly and rebounded with an additional slight rotation. Cask inclination during the second impact led to a concentrated load and a visible imprint on the steel plate of the target as shown in the third picture of Figure 1.

Additionally, a comparison of the 0.3 m drop without an impact limiter and the 9 m vertical drop with an impact limiter as per IAEA transport regulations demonstrates the significant differences caused by impact conditions on cask stresses. Figure 2 shows the 9 m drop test configuration before and after impact, and the table lists measurement results from both tests. The test data demonstrates that, despite the different drop height and subsequent impact energy, resulting decelerations and cask stresses do not differ as much as it might be expected. In general, the 9 m drop results in only slightly higher maximum cask stresses, but also in significant differences in stress-strain-histories during the impact.

Figure 1. 0.3 m vertical drop test at BAM with CASTOR® HAW/TB2 onto BAM's 2,600 Mg IAEA target

Drop test data	0.3 m drop	9.0 m drop
Primary impact duration	~ 3 ms	~ 10 ms
Maximum deceleration	~ 350 g	~ 220 g
Max. principal stress [MPa]		
outer cask bottom centre	61	69
outer cask bottom edge	27...47	48...51
inner cask bottom edge	22...30	42...45
inner cask wall: 100 mm above cask bottom	21...75	94...100

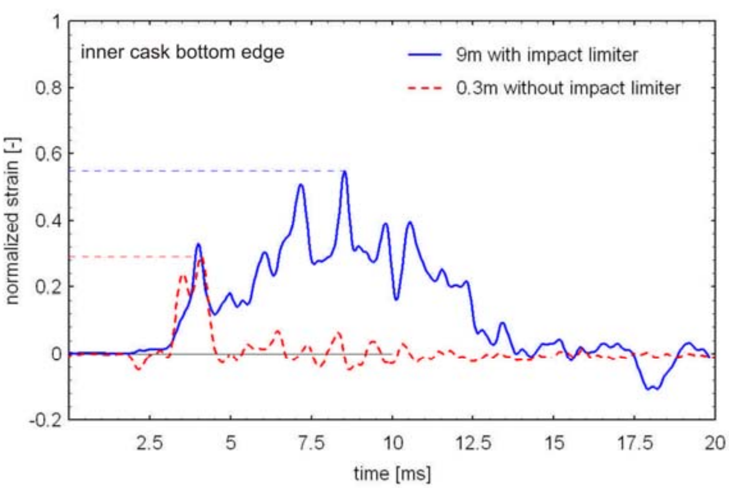


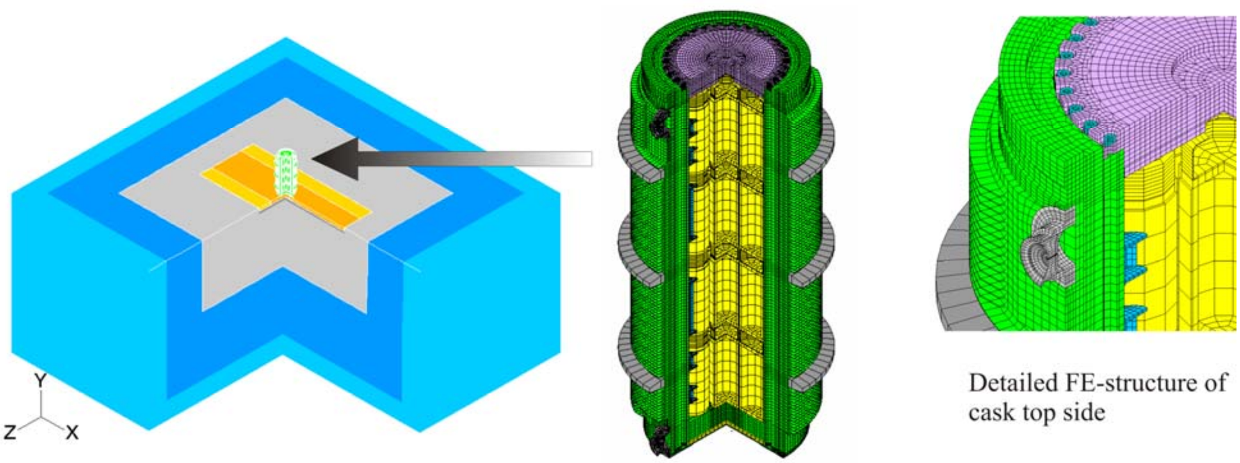
Figure 2. Test results of 0.3 m drop without impact limiter compared to those of 9.0 m drop with impact limiter

DEVELOPMENT AND VERIFICATION OF THE FINITE ELEMENT CASK MODEL

For a re-analysis of the drop test, BAM developed a detailed finite element model of the test cask and its main components including those inside the cask as shown in Figure 3. The modeling and following dynamic calculations were performed with the ABAQUS/Explicit finite element code, which has been used very successfully at BAM for several years for physically similar analyses in various research projects. Since slight impact angles in combination with selected strain measurement points have to be considered during the evaluation, it was essential to construct a complete, three-dimensional cask model. A segment model using symmetry conditions was not able to capture the response of the unsymmetrical impact. The impact zone at the cask bottom was meshed comparatively fine by using 3d solid elements with a linear shape function and reduced integration for a dynamic calculation. All free surfaces were defined for contact conditions without friction except for the cask bottom area, where a friction parameter of 0.15 was used. Total mass of the cask model was about 14 Mg.

Due to the hard impact contact conditions without any energy absorption by additional impact limiters, the mechanical properties of the foundation also have a large influence on the cask response. Transmissions and reflections of stress waves generated by the cask impact are mainly influenced by structural transitions between different materials or components. Therefore, it was necessary to build a detailed foundation model with dimensions large enough to avoid unrealistic reflections of stress waves and their possible influence on the cask reaction during calculation time: see Figure 3. The modeled foundation consists of a 14m x 4m x 5m reinforced concrete block (B25) covered by a 50cm concrete layer (B35) with three 22cm steel plates for an impact area of 10m x 4.5m. The steel plates are connected to the concrete block by 40 steel cylinders 36mm in diameter and about 2m long.

A third main focus was the implementation of material properties. In this case elastic-plastic stress-strain curves determined by test cask material investigations were used for the cask material (ductile cast iron) as function of temperature and strain rate. Elastic material properties from given material specifications were used for all other cask and foundation components.



Detailed FE-structure of cask top side

FE-model of BAM drop test target

FE-cask model with canisters

Figure 3. BAM finite element model of CASTOR® HAW/TB2

The main criteria for sufficient correspondence between test and calculation results are the correlations of a set of representative measurement points over the cask structure during the whole significant impact period. In this case, there were at first seven measurement points on the bottom area of the cask. The time period considered was 20 ms, which is more than four times the duration of the primary impact. Figure 4 shows two representative strain histories, one for the center of the cask bottom and one on the inner side wall. The evaluation considered a very small impact angle of 0.05°, which was observed during evaluation of the video recordings. Additional analyses with different angles of 0°, 0.05° and 0.1° showed a significant influence on the results. Another analytical verification performed included the canisters inside the cask. Differences between dotted and continuous lines in Fig. 4 show that the canister responses were captured sufficiently. The oscillations after 5 ms represent stress waves running through the cask body which were influenced by the interaction of the canisters amongst themselves and with the cask. Further verification evaluated finite element modeling of cask (e.g. FE mesh refinements), foundation and contact conditions.

The graphs in Figure 4 show reasonable correspondence of test data and calculational results, which means the physical test response was sufficiently captured by the numerical model. With the last correlation, an appropriate basis for further strain and stress analyses of the whole cask structure under worst-case conditions without an impact angle has been demonstrated.

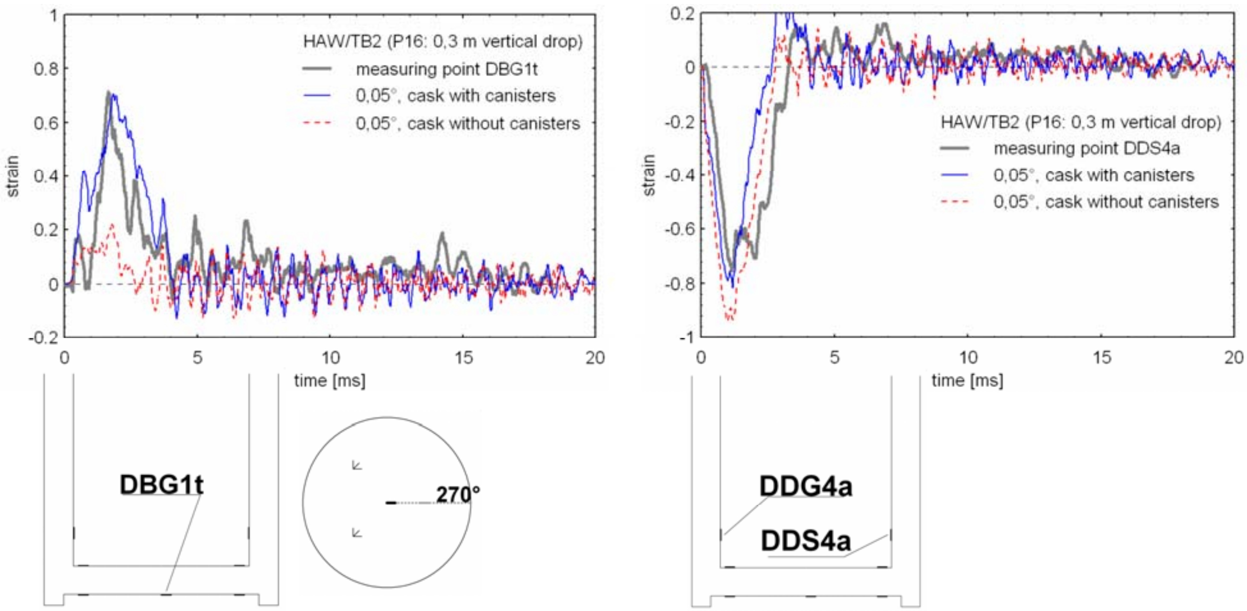


Figure 4. Comparison of normalized FE-calculation results and strain measurement data

CALCULATION RESULTS USING REDUCED- AND FULL-SCALE CASK MODEL

With prior demonstration of sufficient correlation between test data and calculation results the qualified 1:2 scale FE-cask model was used for calculation of the most critical, i.e. exactly flat, cask impact (impact angle = 0°). Additionally, a cask model only geometrically enlarged to full-scale with otherwise no modification was used to investigate consequences of different cask scales on stress and strain analyses. Figure 5 shows representative results for the high stressed area at the outer cask bottom centre. The graphs show that the primary impact duration is nearly doubled whereas maximum strains and stresses remain the same level. This correlates well with analytical expectations if linearity dominates. Complemented by similar results for other cask regions, the principle applicability of the reduced scale cask model for safety analyses could be demonstrated. Nevertheless, the full-scale cask model is essential for detailed stress analyses and safety assessments of the complete cask design.

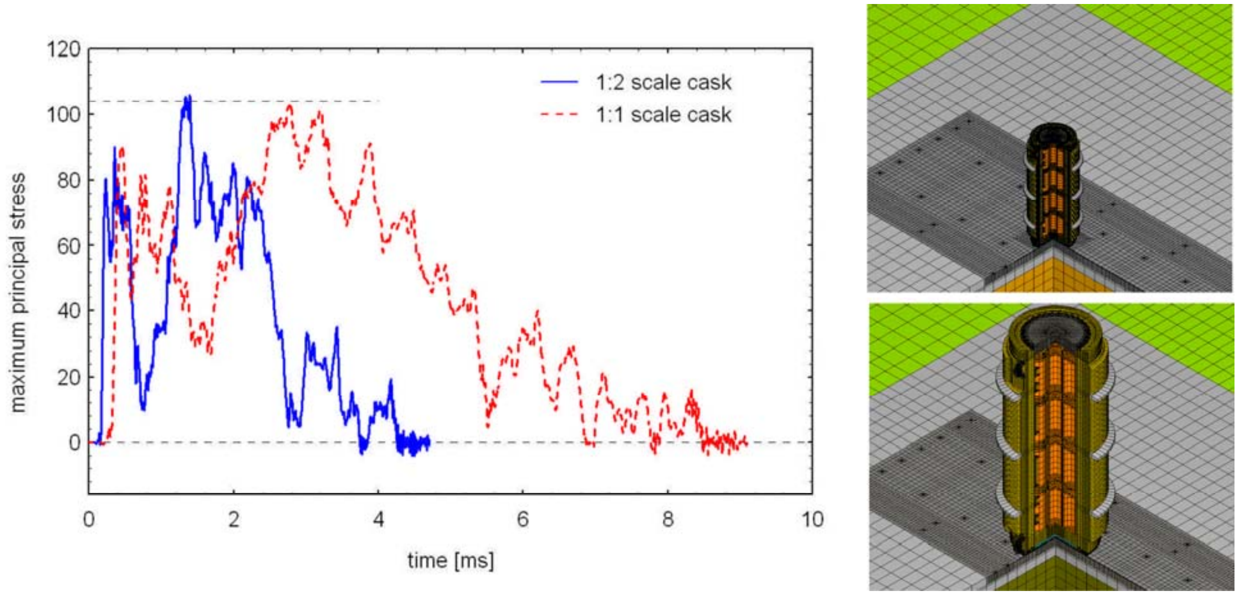


Figure 5. Exemplary comparison of 1:2 scale and full-scale FE-calculation results (Impact angle = 0°; outer cask bottom centre)

Figure 6 shows maximum principal stresses over the cask structure at four different times during the 0.3 m impact. Most stressed areas are largely direct impact zones and adjacent areas. The type of stress there is mainly pressure, which reaches local plasticity only in very small areas. On the other hand, the pictures illustrate the stress wave initiated by the impact moving through the cask from the bottom to the top until the cask lid is finally reached.

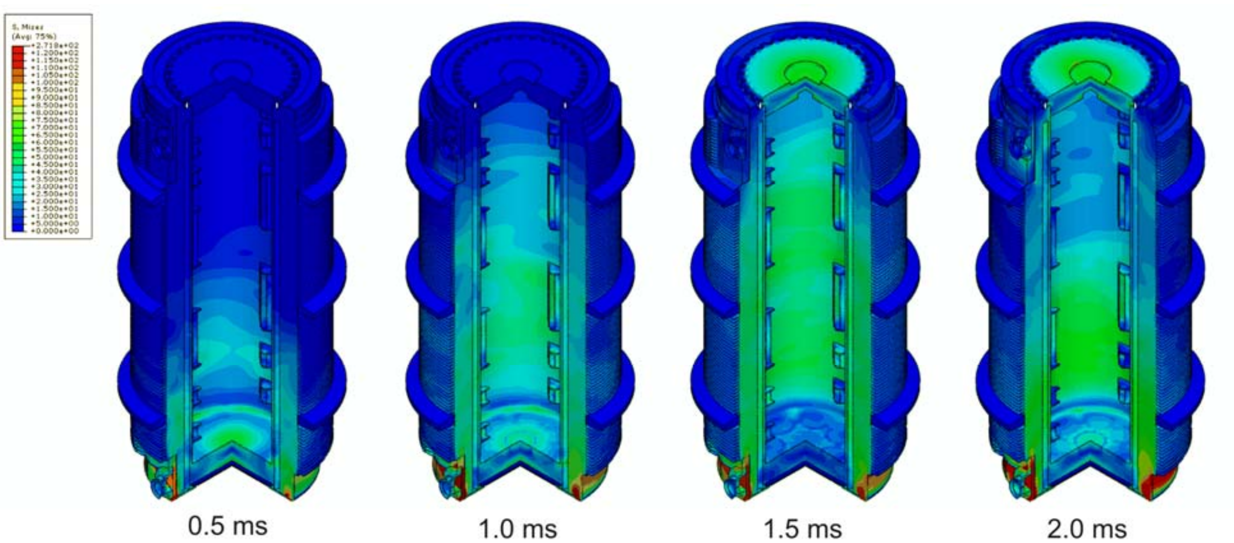


Figure 6. Full-scale cask FE-calculation; principal cask stresses at different times after the 0.3 m drop impact

CONCLUSIONS

The accident scenario inside a storage facility was investigated by a cask without impact limiters dropped from 30cm onto an unyielding target. The test scenario with a 1:2 scaled test cask and the related experimental results were shown and compared to those of a 9m drop test with impact limiters. In general, the two test scenarios lead to completely different dynamic stress states and histories over the cask structure with slightly higher maximum stresses in the case of the 9m drop but not as much as it might be expected considering the much larger drop height and impact energy.

For a complete safety analysis it was necessary to develop a comprehensive 3-dimensional finite element computer model of the cask and foundation. Good accordance between experimental and numerical results could be achieved and demonstrated for the 1:2 scaled test cask configurations with this calculation model. However, a large effort was needed for foundation modeling in geometry and materials as well as for an appropriate definition of contact conditions for the finite element structures. One important result of the investigations was identification of a very small impact angle (<0.1°) between cask bottom and foundation in the drop test with significant influence on cask stresses. With this knowledge calculations could also be performed for an exactly flat impact, and most critical test conditions could be demonstrated for this scenario.

Finally, the validated computer model was scaled up to full-scale cask size to check analytical scaling laws and calculate stresses and strains over the entire, full-scale cask structure. Since maximum stresses and deformations can be determined at the most stressed cask areas together with corresponding stress and strain rates, the safety assessment can be completed which considers elastic-plastic and brittle fracture failure criteria for the cask material.

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