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ESTIMATION OF CASK DECELERATION AND IMPACT LIMITER DEFORMATION UNDER 9M DROP TEST CONDITIONS USING THE CALCULATION TOOL "IMPACTCALC"

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ABSTRACT

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 include, among others, a 9m drop test onto an unyielding target. In particular, the energy absorption capacity of the impact limiting components has a significant influence on package integrity and tightness.

The comprehension and physical evaluation of the behavior 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 behavior of the package. This paper presents considerations about wood-filled impact limiters. Special features and constructive conditions of impact limiters are shown. The paper focuses on the simulation of cask deceleration and wood-filled impact limiter deformation as they occur during a 9m drop test. For this purpose, the calculation tool "ImpactCalc" was developed. "ImpactCalc" can be used to plan drop tests, simulate the effect of variable special features and constructive conditions of impact limiters, and carry out parametric studies of impact limiting components.

The basis for "ImpactCalc" is the reduction of a complex impact phenomenon to the dynamics of a plain mass-spring-system. The corresponding differential equation of motion describes the time dependent impact process including force-time-, deceleration-time- and deformation-time-dependencies. The governing equations are solved by the computer-algebra-software „MathCAD" [1]. The programmed algorithm was verified by comparison with different current drop tests conducted at BAM. Restrictions concerning the application of "ImpactCalc" arise from its analytical approach. However, if applied correctly, the tool can give an acceptable estimation of the deceleration of the package and deformation of the impact limiter.

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 [3] include, among others, a 9m drop test onto an unyielding target. In particular, the energy absorption capacity of the impact limiting components has a significant influence on package integrity and tightness.
The comprehension and physical evaluation of the behavior 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 behavior of the package.
Simplified numerical methods like the here presented tool "ImpactCalc" [2] often used to be applied in the type assessment in order to determine approximately rigid body accelerations for 9 m drop test conditions onto an unyielding target. These rigid body accelerations were 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 came up in the development of calculation procedures. This article will analyse potential applications and limits for simplified numerical procedures.

IMPACT LIMITING DEVICES OF RAM-CASKS

Impact limiting devices are applied in order to limit the load on cask components in different scenarios. Typical constructions of so-called soft impact limiters consist of thin steel plates filled with wood. They are attached to the casks at the lower and upper ends (Figure 1). The impact limiter absorbs the major part of the kinetic energy as it is relatively soft compared to the cask. The impact intensity on the cask, lid and lid screws is lowered significantly.

Figure 1 Drop Test with the CONSTOR® V/TC

CONCEPT OF PROOF OF SAFETY

According to IAEA [3], Paragraphs §701 - §702, there are different possible ways to demonstrate safety. Confirmation of compliance with the performance standard required in [3], Section VI, is to be accomplished by any of the methods listed below or a combination thereof:

- Performance of tests with prototypes or samples of the packaging
- Reference to previous satisfactory demonstrations of a sufficiently similar nature

- Performance of tests with models of appropriate scale incorporating those features which are significant with respect to the item under investigation when engineering experience has shown results of such tests to be suitable for design purposes
- Calculation, or reasoned argument, when the calculation procedures and parameters are generally agreed to be reliable or conservative.

In the type assessment at the moment demonstrations of compliance are common with a combination of drop tests and calculations. On the one hand, due to uncertain parameters and general incertitude 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).

In the framework of this article the application potential of simplified numerical tools like "ImpactCalc" will be indicated.

DESCRIPTION OF THE DEVELOPED CALCULATION TOOL

In the past simplified or analytical codes mostly provided decelerations of the cask and maximum impact limiter deformation at the end of impact. Time dependencies were often not taken into account. However, this information is necessary for the estimation of the additional dynamic effects in "quasi-static" FE analysis. "ImpactCalc" was developed to calculate time dependent progressions of cask deceleration and impact limiter deformation. The following approach was implemented in the computer-algebra-software "MathCAD" [1].

Theoretical Background

The basic simplification of the considered approach is the idealisation of the cask under the drop conditions by a mass-spring-system. The shock absorber is represented by a non-linear spring loaded with the whole mass of a cask. The corresponding differential equation reads as follows:

$$m\ddot{x} + F(x) = 0 \qquad (1)$$

where m depicts mass, $F(x)$ the spring force characteristic and x compression. Due to non-existing external forces, the particular solution is zero, and the total solution is characterized by the homogenous solution with the drop velocity of the cask as inhomogeneous initial condition.

Non-linear spring characteristics for impact limiters are very difficult to obtain. Therefore, they have to be replaced by an adequate characterization. The spring force $F(x)$ can be - when translated in the context of a compressed object of e.g. constant cross section and constant height - replaced by $A \times \sigma(x)$. Here, A specifies the cross section area and $\sigma(x)$ the stress perpendicular to the area as function of the compression. In order to obtain a unit-free result, the compression is replaced by the strain ε according to $x = x_0\varepsilon$, where the variable x_0 represents the initial height (thickness) of the compressed object. The resulting differential equation is depicted as follows:

$$m \times x_0\ddot{\varepsilon} + A \times \sigma(\varepsilon) = 0 \qquad (2)$$

The solution of this differential equation sets the basis for further investigations. For common designs the effective thickness and effective area depend in more complex manner on the current compression of the shock absorber than in equation (2). In the case of a vertical drop, the area remains constant, but the effective thickness can vary for different points on this area. In the case of a horizontal drop (compare with Figure 2), the deformed area increases and the effective thickness changes as well.

In the general case, the impact limiter reaction force can be determined by the following integral:

$$F(x) = \int_{A_O} \sigma(x, y, t)\, dA \qquad (3)$$

In special cases, this can be transformed into:

$$F(x) = \sigma(x)A(x) \tag{4}$$

In order to calculate the reaction force, the cross section function $A(x)$ and the stress function $\sigma(x)$ have to be derived.

Modeling of the Geometry

The cross section function $A(x)$ can be deduced by calculating the cross section area and referring all variables to x. In case of a circular shaped impact limiter, the cross section area at a horizontal drop can be written as:

$$A(x) = 2 \cdot y_{\max}(x) \cdot f \tag{5}$$

where $A(x)$ depicts the cross section function, $y_{\max}$ the maximum width of the impact limiter, and f the effective depth of the impact limiter.

A second possibility is to relate all variables of the cut volume V to x and differentiate the volume $V(x)$. The advantage is that volumes of cut geometrical objects are easily available, e.g. [4].

$$A(x) = \frac{dV(x)}{dx} \tag{6}$$

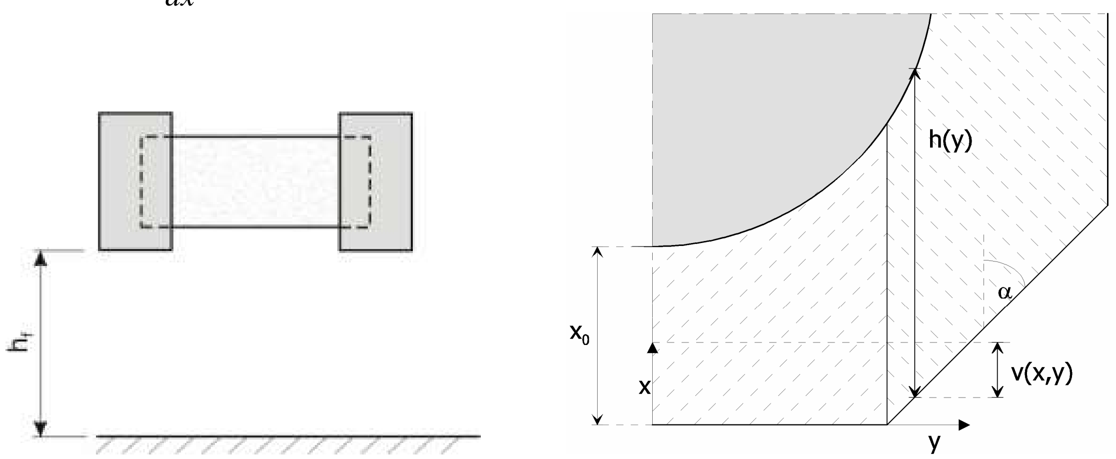

Figure 2 Schematic Sketch of a Section of an Octagonal Impact Limiter

Modeling of the Material

The stress function $\sigma(x)$ of equations (2) and (4) is often deduced from compression tests with wood specimens. These tests are usually carried out with handy size specimens, so the results should be transferred to the geometrical conditions in the impact limiter:

$$\sigma(\varepsilon[x, y]) = \sigma\left[\frac{v(x, y)}{h(y)}\right] \tag{7}$$

Symbols are explained in Figure 2. The assumption is thereby the compression of the impact limiter from the foundation in the positive x-direction. After elimination of the dependency of σ from y, the stress function $\sigma(x)$ and the area function $A(x)$ can be applied to equation (8):

$$m \times x_0 \ddot{\varepsilon} + A(\varepsilon)\sigma(\varepsilon) = 0 \tag{8}$$

It should be mentioned, that only the compression phase and not the elastic spring back of the impact limiter during the drop event can be described using the stress function derived from wood specimens tests.

The presented equations are applied to the commercial algebra tool MATHCAD® [1]. The solution is based on a Runge-Kutta method with 500 nodes. Results are presented as deformation-time-, acceleration-time- and force-time-dependencies.

VERIFICATION

Verification is performed by comparing experimentally derived and calculated acceleration time dependencies and the impact limiter deformation, since force as the optimal verification criterion is not directly measured in the experiment. This comparison assumes an averaging out of local decelerations onto the whole cask and, therefore, results in a rigid body approach.
The prerequisite for this procedure is that the cask except for an impact limiter can be treated as a rigid body. The impact limiter mass must be small compared to the cask mass, because parallel to deformation, the mass of the package will be reduced by the mass of the already decelerated impact limiter parts.
The calculated and experimentally derived deformation of the impact limiter is a further criterion for verification. It has to be taken into account that the deformation measured after the experiment is normally smaller than the maximum deformation at impact. The difference is due to the elastic springback of the impact limiter. The calculation result does not take the springback into account, while the deformation measured after the experiment is smaller than the maximum amount of deformation and has to be adapted. Consideration of the maximum deformation is important to prevent excessive deformation of the impact limiter and stop other parts of the cask (e.g. handling devices) from touching the ground.
In order to compare measured and calculated results, deformation phenomena which occur on cask parts other than the shock absorber (e.g. ovaling or bending oscillations of the cask body) have to be eliminated. These phenomena are not crucial as long as the above presented boundary conditions (rigid body, no multiple mass phenomena) are met. If oscillations coming from these phenomena have small cycle durations compared to impact time, they can be eliminated by low pass filtering. IAEA Advisory Material §701.9 [5] recommends the application of a low pass filter: "When acceleration sensors are used to evaluate the impact behaviour of the package, the cut-off frequency should be considered." A suggestion for the cut off frequency of the low pass filter for packages up to 100 Mg is then given by:

$$f_f = [100Hz...200Hz]\sqrt[3]{\frac{100Mg}{m}} \qquad (12)$$

where f_f describes the low pass filter frequency and m depicts the mass of the package. Whether extrapolation above 100 Mg is possible is not stated. For the CONSTOR® V/TC with a mass of 181 Mg a cut off frequency of 150 Hz is suggested as a conservative approach.

Horizontal 9m Drop of the CONSTOR® V/TC

The CONSTOR® V/TC is a full scale model of the GNS (Gesellschaft für Nuklearsysteme mbH, Germany) cask CONSTOR® V/69. The CONSTOR® V/69 is a cask for spent nuclear fuel containing 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®, an iron aggregate frame and hardened cement paste. The impact limiting devices 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 [6].

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

Description	Value
Overall length	7445 mm
Diameter cask	2332 mm
Outer diameter impact limiter	3510 mm
Total mass	181 Mg
Mass impact limiter	20 Mg each
Mass overpack	31 Mg

A 9m drop test with the CONSTOR® V/TC was performed at the test site of the Federal Institute for Materials Research and Testing in Horstwalde/Berlin, Germany on the occasion of PATRAM 2004. Results are presented in [8]. The drop tower of the BAM is the largest drop tower of its kind in the world and complies with IAEA regulations [3] for drop tests with packages up to 200 Mg. Further information can be obtained in [7].
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 3 presents the acceleration time relations of the experiment and calculation for the lid side of the cask.

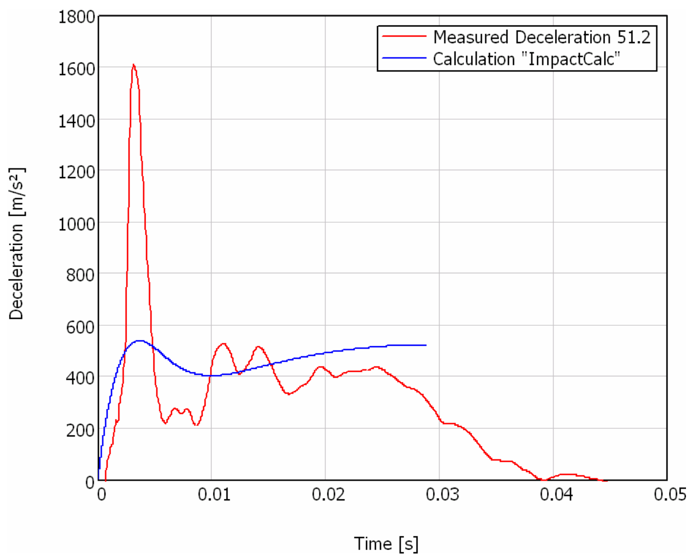

Figure 3 Comparison of the Calculated and Measured Deceleration of the CONSTOR® V/TC Package

Apart from the peak at the beginning of the acceleration-time history, “ImpactCalc” is able to calculate adequately the resulting rigid body acceleration (Figure 3). 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® V/TC Package in Experiment and Calculation

CONSTOR® V/TC	Experiment	Calculation “ImpactCalc”
Maximum deformation lid side	150 (180) mm	209 mm
Maximum deformation bottom side	171 (201) mm	208 mm

Vertical 9m Drop of the MSF69BG®

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 limiting devices of stainless steel, filled with wood of different types and orientations. The main dimensions are shown in Table 3.

Table 3 Dimensions and Masses of the MSF69BG® Package

Description	Value
Overall length	6900 mm
Cask diameter	2178 mm
Outer diameter impact limiter	3205 mm
Total mass	127 Mg
Mass impact limiter	7 Mg each

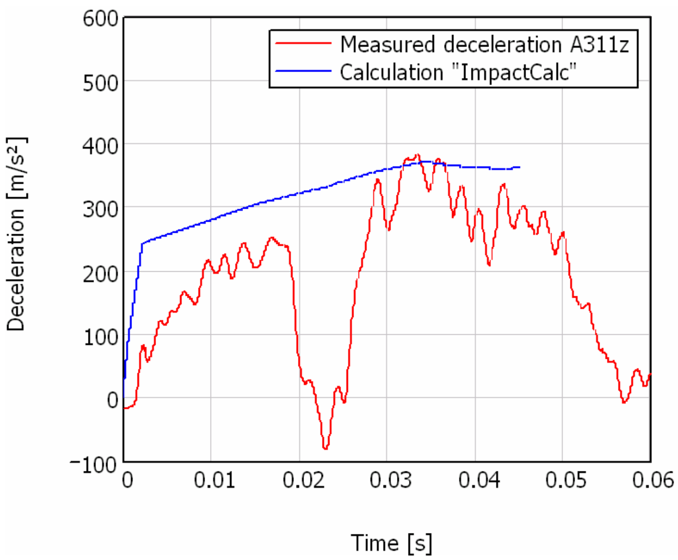

Figure 4 Comparison of the Calculated and Experimentally Derived Deceleration of the MSF69BG® Package

Figure 4 compares the deceleration-time curves calculated with “ImpactCalc” and measured at the drop test. The calculated curve matches the experimentally derived curve well. Small 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.

CONCLUSIONS

This paper presents the basic assumptions of the calculation tool "ImpactCalc". Its calculation results are compared to experimental results of full scale drop tests. It was shown that the tool is in general able to calculate rigid body accelerations 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 not taken into account.
The most influential part is the implemented wood strength curve, which has to be integrally representative for compression in the whole shock absorber. Of course, 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. Due to uncertainties regarding further changes in boundary conditions, which may affect the energy absorbing capacity, results from simplified numerical tools should be treated as a rough estimate of rigid body accelerations and impact limiter deformation. In a type assessment of RAM-casks these limitations should be carefully considered, but tools like "ImpactCalc" are, in general, suitable for small sensitivity and parameter analysis or for first estimates of rigid body acceleration and impact limiter deformation.

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