APPLYING OPTIMIZATION METHODS AND STOCHASTIC ANALYSIS IN EVALUATING A CASK ACCIDENT

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ABSTRACT

In the following a hypothetical accident scenario is investigated. In this scenario a cask is vertically driven above a structure, elevated above a concrete ground. While driven the cask drops and falls on to the deformable edge of the structure and subsequently into a damped area of the ground. The impact onto the ground will be cushioned by a cavity filled with porous concrete. Should the cask tilt, however, it cannot be excluded that it hits the ground with its top-end outside the damped area made from porous concrete. For this event sequence, the load on the cask needs to be evaluated.

To evaluate realistic impact scenarios, the entire complex drop sequence needs to be simulated. Furthermore, the drop sequence is influenced by numerous parameters, so that the worst scenario in terms of loads cannot be determined by theoretical consideration.

For this matter, the drop sequence was simulated on the one hand as a simplified and physically feasible FE-model which represented the cask as a rigid body. On the other hand, a sensitivity analysis with the program optiSLang identified those parameters which contribute significantly to a high rigid-body deceleration and therefore cause adverse load situations. OptiSLang offers efficient methods for sampling and stochastic analysis. It eases through the high given number of parameters with the lowest possible number of computation runs to arrive at a resilient statistical evidence and further contributes to the automatization of the computation process.

A stress analysis for some selected impact scenarios can be conducted by means of an adequately detailed and sufficiently discretised FE-model. Here, it is possible to position the cask immediately prior to the impact and to initialize the kinematics, which have been determined on the basis of the simplified model, at this point of time.

The complete FE-model is composed of individual partial models which need to be adequately realistic. This is especially important for the partial model of the porous concrete. In order to simulate the energy dissipation of this compressible material, a complex material model had to be used. The material characteristics required for this were calculated with optiSLang. This calculation here means an optimization task in order to minimize the deviations of a test and the test re-calculation.

INTRODUCTION

In the following a hypothetical accident scenario is investigated. In this scenario a cask is vertically driven above a structure, elevated above a concrete ground. While driven the cask drops and falls on to the deformable edge of the structure and subsequently into a damped area of the ground. The impact onto the ground will be cushioned by a cavity filled with porous concrete. Should the cask tilt, however, it cannot be excluded that it hits the ground with its top-end outside the damped area made from porous concrete. To reduce the impact on the cask, an additional temporary wooden impact limiter is dimensioned. For this event sequence, the load on the cask needs to be evaluated.

The falling of a cask is influenced by many parameters and constraints, therefore all variants of the event sequence have to be evaluated in general. Furthermore, the worst case impact scenario for the mechanical exposure of the cask can not be conducted from common assumptions or analytic approaches. In numerical simulations, variants or tolerances of several input parameters like movement speed, falling height, position of mass centre, material behaviour, friction values or dimensioning can be considered. The numerical simulation is based on finite element models in the explicit code LS-DYNA [1]. The calculation of different variants (designs) and the statistical evaluation is done in the context of a sensitivity analysis using optiSLang [2]. The advantage of a global variance-based sensitivity analysis in optiSLang against the deterministic variation of single parameters or parameter combinations is that even with a high number of input parameters nonlinear and multi-variant dependencies of analysis results can be revealed.

ANALYSIS PROCEDURE FOR THE EVENT SEQUENCE

First in the simulation of the event sequence, the simplified FE-model presented in Figure 1 is used. The simplified FE-model contains 5 partial models:

- The cask,
- The abstracted edge of the structure,
- The absorber concrete,
- The temporary wooden impact limiter and
- The ground.

Deformations of the cask are very small in comparison to deformations of the absorber concrete and the temporary impact limiter. That is why the cask is modelled as rigid body. In this FE-model, the ground serves as abutment for the absorber concrete and the temporary impact limiter and therefore it can also be modelled as rigid body. The edge of the structure is simply represented as plastically deformable body and the possible downward deflections of the structure are disregarded. By drastically reducing the numerical analysis procedure, a lot of different variants of the event with different input parameters can be simulated physically feasible. The worst impact scenario is found by means of the rigid body deceleration of the cask. Using a detailed FE-model the stresses and strains are calculated subsequently for the worst impact scenario only.

It is essential for numerical simulations to analyse and assess how numerical parameters (like finite element discretisation and contact stiffness) are influenced by margins of deviation of the material behaviour and how dimension tolerances affect the analysis results. This process is called here qualification of the numerical model. In small, manageable parameter dimensions, this qualification is normally done by a systematic variation of single parameters or parameter combinations. But if dimension or nonlinearity of the parameter dimensions increase, stochastic sampling strategies are important for the model qualification and beneficial for a sensitivity study. Here, the model qualification is done for all partial models with optiSLang by using representative load cases. Each

partial model is verified, if alternative calculation methods or experimentation results are available. For verifying the partial models optiSLang is also used by applying optimization, sensitivity or robustness analysis.
In order to represent nonlinear material behaviour appropriately in the simulation, suitable constitutive material models have to be used. For example, the identification of material parameters of the absorber concrete is done by adjusting the results of a simulated adequacy test to real test results with help of optimization methods as explained in detail in the following.
The analysis procedure for the event sequence can be summarized like this:

1. Reduction of the task by using a simplified, physically feasible FE-model
2. Qualification and verification of the partial models
    - exemplary parameter identification of the absorber concrete
3. Sensitivity study of the event sequence simulation
4. Analysis of impact for decisive variants with a detailed FE-model
5. Evaluation of stresses and strains or fracture-mechanical investigations in case of deep temperatures with regard to integrity of the cask

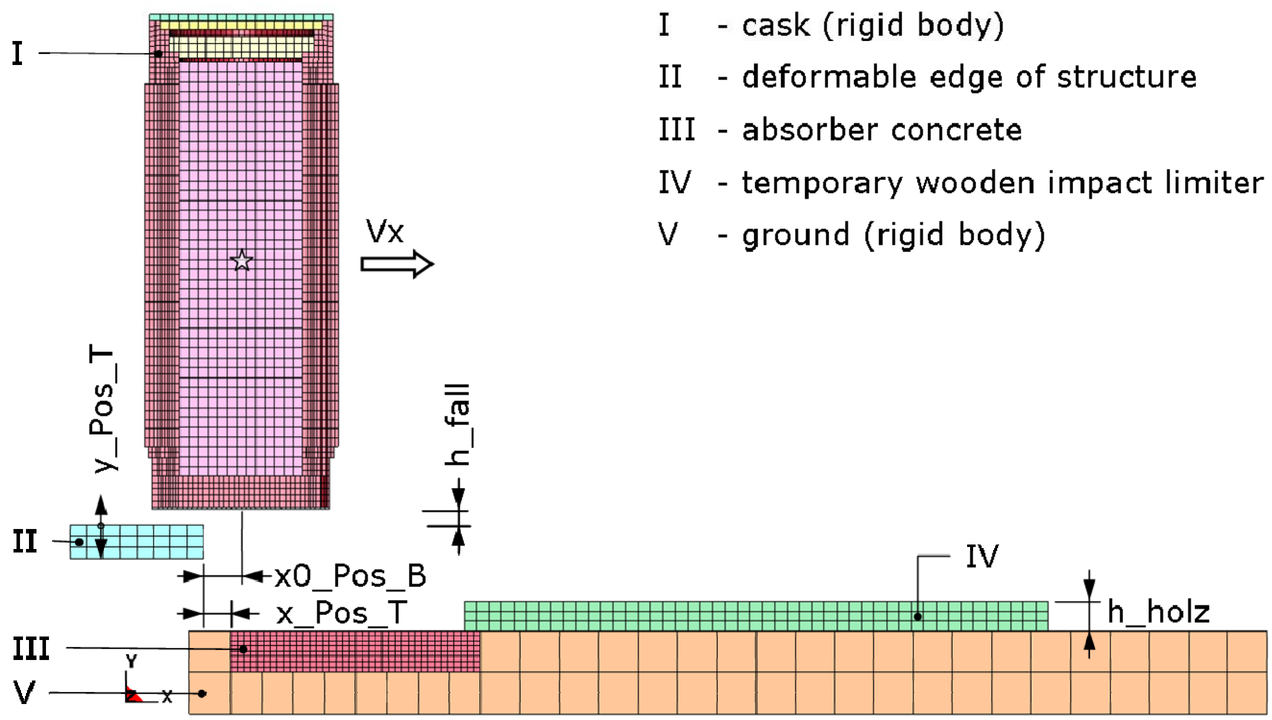

Figure 1. FE-model, component description, most important measures

IDENTIFICATION OF MATERIAL PARAMETERS OF THE ABSORBER CONCRETE

Absorber concrete is a mixture of sand and polysterol balls in a matrix of cement. The required results for parameter identification were taken from a drop test [3] of HOCHTIEF AG, Germany.
In the test, a drop body (steel bar) with a mass of 212 kg and a cross section area of 12 x 12 cm² fell from a height of 3.3 m onto a cylindrical body (Ø60 cm, height 35 cm). Figure 2 shows the time variation of velocity and penetration of the drop body from the test.
For simulation, the LS-DYNA material model *MAT_SOIL_AND_FOAM is chosen. Therefore, 9 material parameters have to be determined. Within parameter identification, the test results and simulation results are compared. The search for the best possible agreement of analysis and test

results is formulated as optimization problem. Thus, deviations between measured values and analysis results have to be described as objective function. The objective function for the optimization task consists of three equally weighted terms regarding the adjustment of penetration depth, velocity and time of maximal penetration.
The adjustment with the 3 test results was done with a deviation less than 0.30%. The excellent agreement to the test results is confirmed by the calculated signals of penetration depth and the velocity of the drop body in comparison to the test results, as shown in Figure 2. The best design, from which material parameters for further calculations are taken, is marked red.

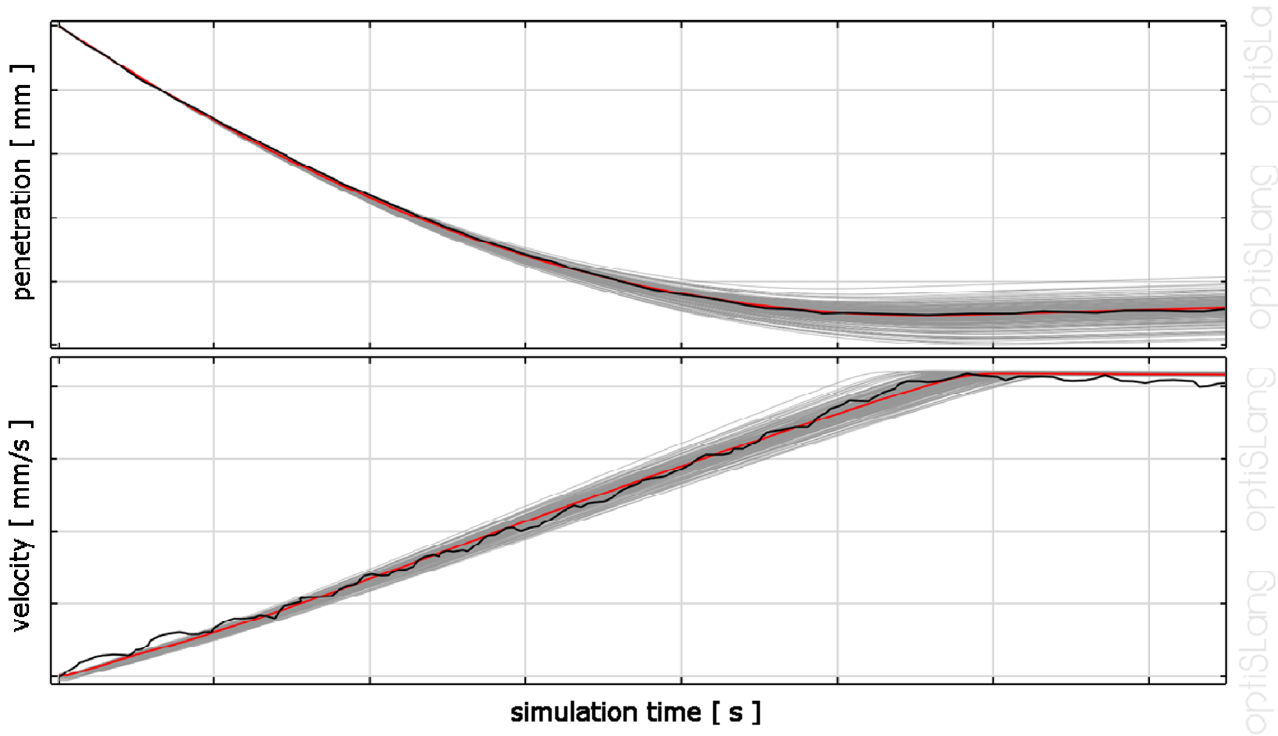

Figure 2. Signals of penetration depth and velocity: test result (black), signals of all calculated designs (gray), best design (red)

SENSITIVITY ANALYSIS FOR IDENTIFYING THE WORST IMPACT SCENARIO

Input parameters: In the event sequence**,** the movement of the cask can be influenced by the movement speed of the cask Vx, the position and height of the edge of the structure x_Pos_T and y_Pos_T, the overhang of the centre of mass of the cask over the edge of the structure at impact x0_Pos_B, the falling height above the edge h_fall, the friction value my_B_T and plastic deformation of the edge. The plastic deformation of the edge is considered by a fictitious yield stress Sig_f_T. In the scope of the sensitivity analysis, also the temporary wooden impact limiter has to be dimensioned. Therefore, the wood-height of the temporary impact limiter h_holz is varied between 350 mm and 500 mm. **Response parameters:** As measure for the mechanical exposure of the cask, maximal decelerations in different phases of the event sequence are used as response values.

By reducing the model size, it was possible to simulate 60 variants of the event sequence with manageable effort (per design app. 10h with 2 CPU's for a simulation time of 5 s) within the sensitivity study. Figure 3 is representing exemplarily the time progress of events for one of these designs. The event sequence is divided into 5 phases:

1) The cask impact onto the edge and the tilting in direction of the ground,
2) The cask impact onto the absorber concrete,
3) The girth surface primary impact onto the temporary wooden impact limiter
4) The rebound of the temporary impact limiter and
5) The second impact onto the temporary impact limiter.

With the help of this model, decelerations occurring in phases 2 up to phase 5 have to be examined. The analysis is carried out until the cask is rested on the temporary wooden impact limiter.

In phase 2, horizontal and vertical cask decelerations are always smaller than 3 g. The sensitivity analysis shows that the variation of maximal values is almost only influenced by the input parameter x0_Pos_B.

Important in phase 3 is the cask deceleration in lateral direction. In the anthill plot in Figure 4, left, the calculated maximal lateral deceleration of all designs is shown. A quadratic regression function through these points is drawn in red. The maximum value of almost 30 g occurs at the upper bound of x0_Pos_B. In case of overhang of approximately 300 ≤ x0_Pos_B ≤ 500 mm, the smallest vertical deceleration can be expected. The sensitivity analysis shows that again x0_Pos_B (coefficient of determination CoD = r^2 = 85 %) is the most important parameter.

Also in phase 5, the deceleration in lateral direction of the cask is the most important. The anthill plot in Figure 4, right, shows that the maximal vertical deceleration about 25 g can be expected in case of overhang of approximately 400 ≤ x0_Pos_B ≤ 800 mm. With a coefficient of determination CoD = r^2 = 71 % the input x0_Pos_B is most important once again.

In optiSLang not only a simple pair wise correlation analysis (global variance based sensitivity analysis) can be done, but also further statistical methods are available to identify cross correlations (multivariate statistics) for example by using a metamodel of optimal prognosis (MoP). As an example, Figure 5 visualizes the MoP responsible for the maximal cask deceleration a_aq_Z3 in vertical direction in phase 5. On the basis of such a metamodel, coefficients of prognosis (CoP) are calculated which show the sensitivity of the response parameter. In this case, a_aq_Z3 shows a strong sensitivity regarding x0_Pos_B (CoP =71 %) and a weak dependency onto x_Pos_T (CoP = 19 %) and h_holz (CoP = 18 %). The MoP reveals a tendency that deceleration is increasing with flatter design of the temporary impact limiter. However, the increase of the deceleration is so small that a temporary impact limiter with a height of 350 mm is enough to damp the impact of the cask acceptably.

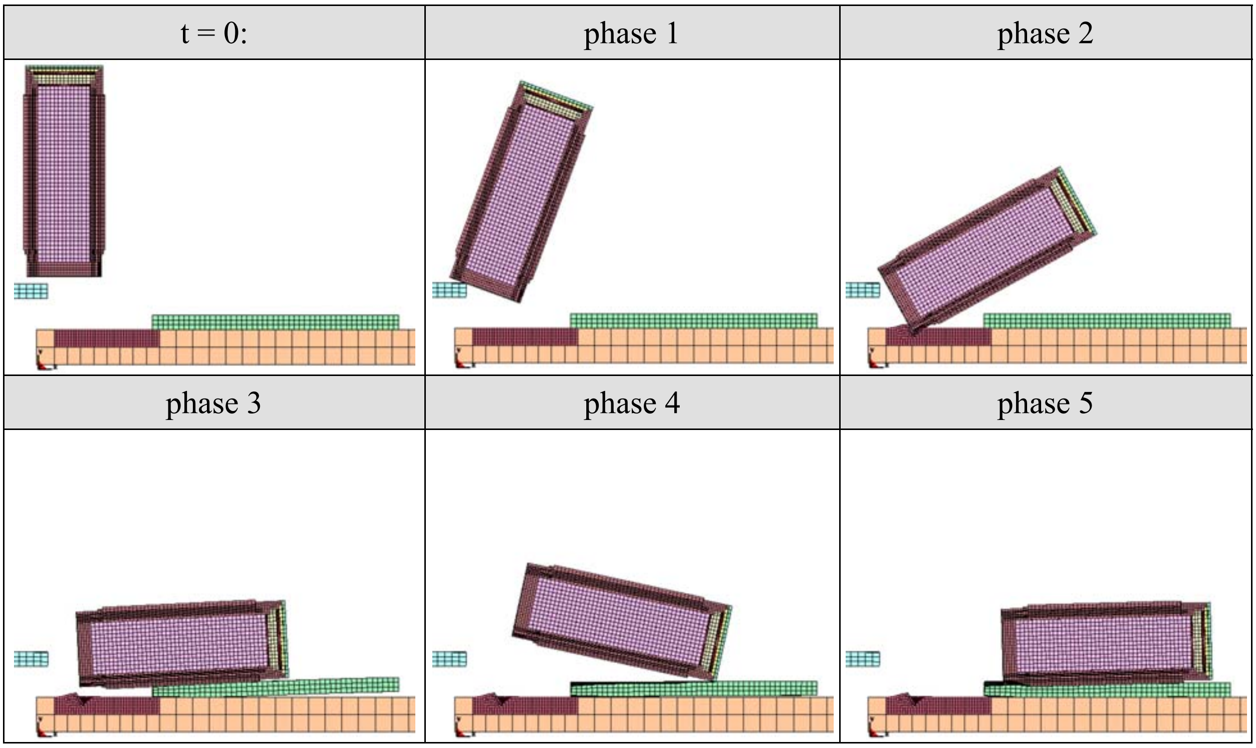

Figure 3. Exemplary points of time of the calculation

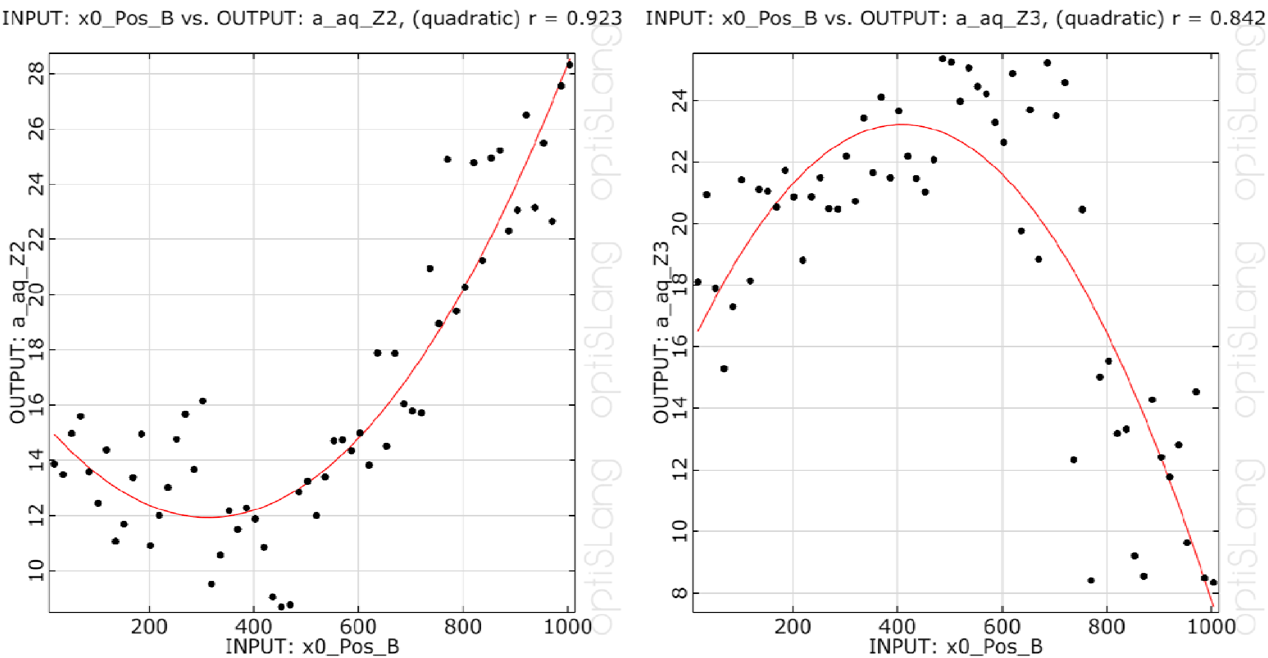

Figure 4. Maximal deceleration of the cask a_aq_Z2 in phase 3 and a_aq_Z3 phase 5

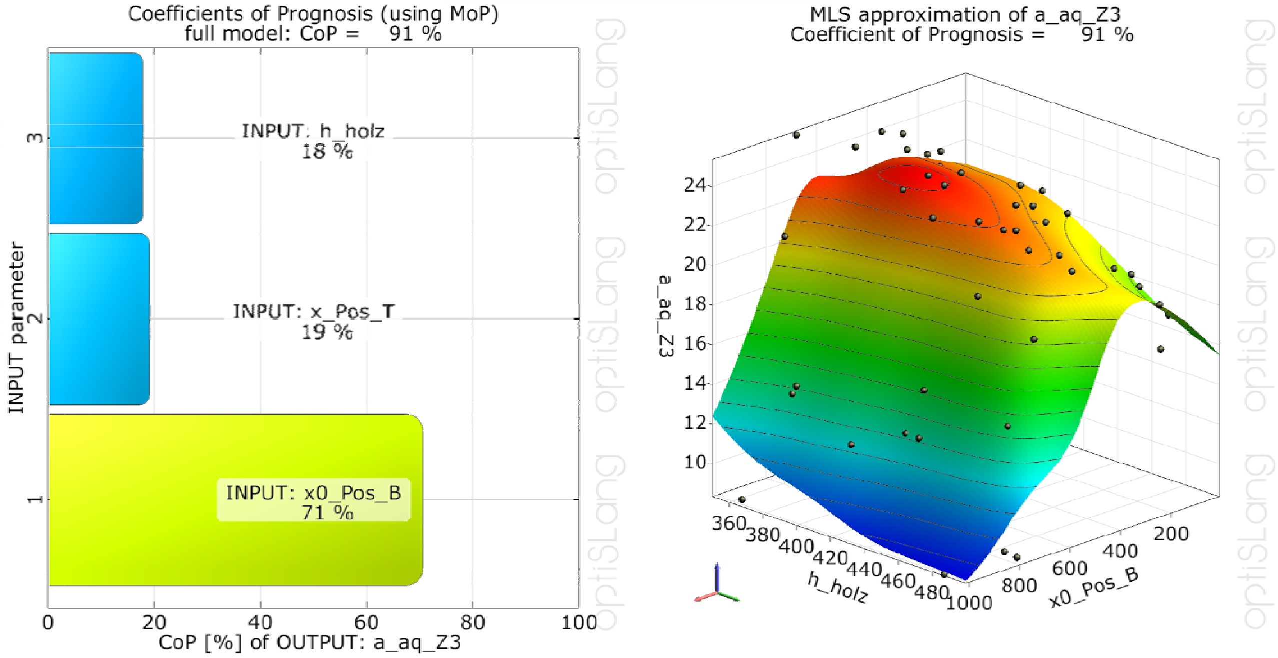

Figure 5. CoP and MoP of the maximal cask deceleration a_aq_Z3 in phase 5

USE OF THE RESULTS FOR ANALYSIS OF A DETAILED FE-MODEL

For the final analysis of a detailed FE-model, the deformable cask is positioned directly before the impact onto the temporary wooden impact limiter. Position and kinematic values are transferred from important designs of the sensitivity analysis. The FE-model used for this purpose is discretised fine enough to detect local stresses and strains. With this complex numerical model, only the small time sequence from phase 2 to 5 has to be calculated. For an analysis of one design with a simulation time of 100 ms, 4 CPU’s and about 40 hours calculation time are necessary. On the basis of the calculated stresses and strains, a stress evaluation for each element is carried out with a special algorithm.

CONCLUSIONS

The examinations of the regarded impact scenario show that for entire complex drop sequence, especially the overhang of the cask over the edge of the structure is important. The cask deceleration is much less during the impact onto the absorber concrete (phase 2) than in the primary or second impact onto the temporary impact limiter. For high overhangs starting from 700 mm, the vertical deceleration in phase 3 is important. For small overhangs, phase 5 is essential. In case of a high overhang, the cask is hitting the porous concrete steeply. That is why it hits the temporary impact limiter at a flat angle in phase 3 with a high area of its girthed surface. Subsequently after short impact duration, high vertical decelerations are appearing. Whereas in case of a small overhang, the cask is hitting the absorber concrete shallowly and is rolling into the temporary impact limiter. In doing so, the contact area is increasing continuously during longer impact duration. Thus, the cask is slowly decelerated in phase 3 and a higher kinetic energy has to be dissipated in phase 5 of the second impact.

The variation of the height of the temporary wooden impact limiter shows only a weak influence, so that a height of 350 mm is sufficient for the damping of the impact.

This example confirms the relevance of the applied method regarding the interpretability and reliability of the analysis.

REFERENCES

[1] LS-DYNA® 971, Rev. 3.2.1 (Double Precision), Livermore Software Technology Corp. (http://www.lstc.com)

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[3] "Dämpferbeton" Colloquium on 12th April 2005, Technology Centre Walldorf, HOCHTIEF Construction AG, Frankfurt / Main