Pre-Drop Analyses of the Dynamic Behavior of Accelerations and Strains of the POLLUX Cask

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INTRODUCTION

With the POLLUX cask a series of drop tests has been performed by the German Federal Institute for Materials Research and Testing (BAM) in cooperation with GNS/GNB in 1994. The series comprised three drop tests under conditions of loaded cask equipped with impact limiters falling from 9 m height onto an unyielding foundation and two drop tests under conditions of loaded cask falling without impact limiters from 5 m height onto a simulated concrete floor of a storage facility:

9-m horizontal drop, trunnions in drop direction,
9-m vertical drop onto the lid side,
9-m edge drop with center of mass over impact point,
5-m vertical drop onto the bottom side,
5-m horizontal drop, trunnions in drop direction.

In a benchmarking process for design assessment these drop tests have been analyzed prior to the experiments using different approaches. This article briefly describes the methods used and presents some results in comparison to measurements performed by BAM.

TEST CASK

The POLLUX cask is depicted in Figure 1a. It consists of an outer *s*hielding *c*ask (**SC**) made of ductile cast iron with screwed lid and an inner *f*inal *d*isposal *c*ask (**FDC**) made of stainless steel with bolted primary lid and welded secondary lid. During the experiments the cask content was simulated by a dummy load inside the cavity of the FDC. At the top and bottom end, impact limiters were attached to the cask body during the 9-m drop tests. The test cask was equipped with a large number (> 60) of accelerometers and strain gauges to get detailed information about the loading at the relevant locations. These data are also intended to serve for benchmarking the analysis tools.

CALCULATIONAL APPROACHES

The calculations of the different drop tests were performed using three different methods currently in use at GNS/GNB. They comprise two finite element approaches as well as one analytical approach. These methods will be described below.

ANSYS APPROACH

The well known ANSYS finite element computer program (Swanson 1992) was used to model all drop conditions. A detailed model of the POLLUX was generated (Figure 1b). ANSYS currently utilizes an implicit solver for nonlinear transient dynamic analyses. Therefore a special solution technique, already applied and described in (Diersch 1994 a and b), was used to reduce solution time. Firstly the highly nonlinear response of the wood shock absorbers was calculated separately using appropriate models. Figure 1c shows the FEM model used for the 9-m horizontal drop. In the nonlinear transient dynamic analysis of the cask itself the ANSYS SPRING39 element was used to represent the load deflection curves derived in the first step. Secondly, the substructuring technique was used to reduce solution time.

ANALYTICAL APPROACH

Though finite element analyses are widely used nowadays, analytical approaches are also still in use, for example in Russia. To test their capabilities the POLLUX drop tests were also investigated analytically.

Taking the impact limiter as a crushable member and the cask itself as a rigid body, the cinematic and dynamic components of the drop event (i.e., velocity, deceleration, reaction force, etc.) were calculated in a first step. The calculations of the POLLUX cask strains are based on the theory of one-dimensional wave propagation described in scientific textbooks, for example in (Goldsmith 1957). The so called *method of characteristics* has been used to solve the one-dimensional wave propagation equation. The calculation of the lids of POLLUX was done using the so called *reduction method* reducing the lids to a mass-spring-system acted on by a reduced loading due to inertia (limiter loading) and due to elastic vibration of the cask. The reduction method was also used for the calculation of the 9-m horizontal drop. The cask body was treated as a beam loaded on its ends. The mass and the stiffness of the cask are replaced by a reduced mass and a reduced stiffness, the load being replaced by a reduced load.

DYNA3D APPROACH

DYNA3D (Hallquist 1989) is a three-dimensional finite element program which works explicitly and was developed especially for the solution of dynamic problems. The code takes into account geometric and physical non-linearities, as well as contact problems. It was used to calculate the complex 5-m vertical drop of the POLLUX onto the concrete foundation. Figure 1d shows the FEM model used. It comprises all cask components as well as the foundation. Contact surfaces were defined between the cask components as well as between outer cask and concrete foundation. This foundation was modeled with the concrete/geological material type (Material Type 16, Mode II) of the DYNA3D material library.

Fig. 1a: POLLUX cask

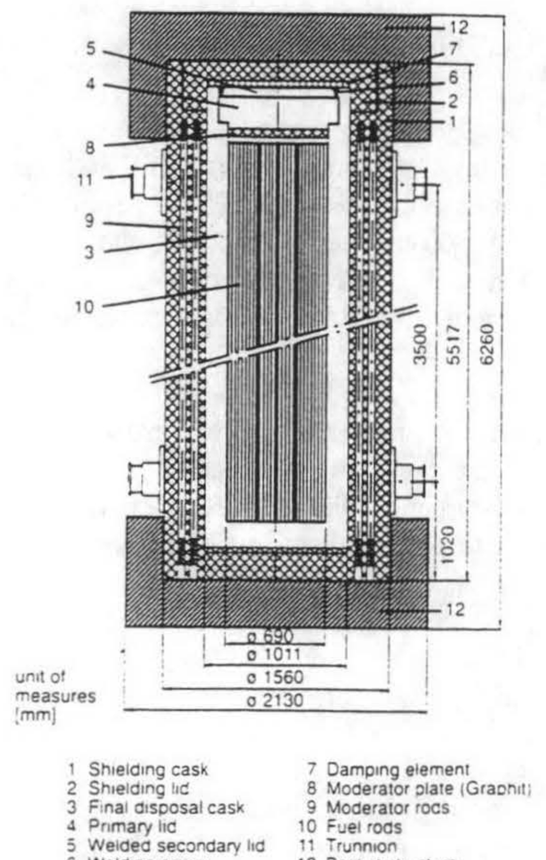


Fig. 1b: ANSYS cask model

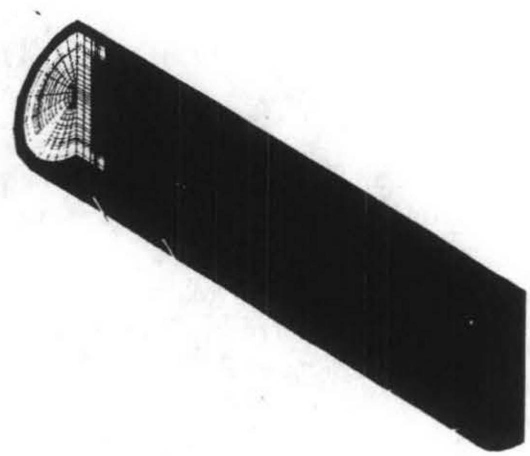


Fig. 1c: ANSYS limiter model

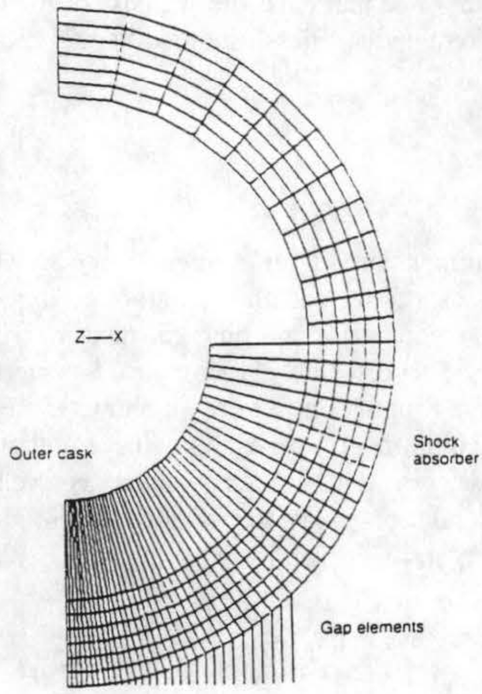
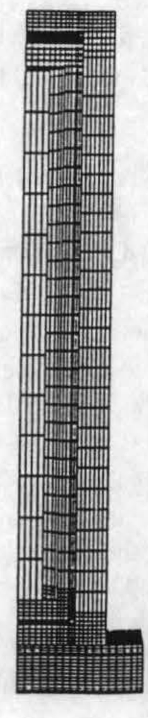


Fig. 1d: DYNA3D model



RESULTS OF LIMITER CALCULATIONS FOR THE 9-M DROP TESTS

Both approaches used for the analysis of the 9-m drop tests (ANSYS and analytical) performed limiter calculations in a separate step. These results are summarized below and compared to post-drop measurements of the limiter deformations as well as to deceleration values averaged from time history curves measured by BAM (the experimental results of BAM are presented in other sessions at PATRAM '95).

For the 9-m horizontal drop the analysis of the limiters force-deformation curve revealed that the limiter deformations were exceeding the clearance over the trunnions. The trunnions oriented in drop direction would therefore participate in the deformation process and contribute to the reaction force which was taken into account in the analyses. The basic results for this orientation are listed in Table 1a. The results of both analysis approaches agree well. Measurements of the deformed limiter yield slightly lower deformations. Correspondingly the deceleration range derived from measured time histories exceeds the calculated values.

The limiter analysis for the 9-m vertical drop is rather simple compared to the other drop orientations. Basically the part of the limiter backed up by the top surface of the cask body deforms by vertical compression. The results of calculations and measurements are listed in Table 1b. As for the 9-m horizontal drop the calculations slightly overestimate the final deformations and slightly underestimate the deceleration levels averaged from time history plots.

From the 9-m drops the edge drop probably is the most complicated one since two-dimensional models are not applicable. As depicted in Table 1c this drop leads to the highest limiter deformations whereas deceleration values are rather low compared to the horizontal drop.

The results presented indicate that principal good agreement exists between the calculated and real limiter behavior. Maximum deviations between the calculation and experiment of 18 % for the 9-m horizontal drop are due to the fact that this drop includes additional trunnion impact which makes the analysis a challenge.

Table 1 a, b, c. Limiter Behavior for the 9-m Drop Tests

a) 9 m horizontal drop	ANSYS calc.	analytical calc.	experimental value
max. limiter crush, mm	142	139	121
max. static deceleration, g	153	147	160-180
b) 9 m vertical drop	ANSYS calc.	analytical calc.	experimental value
max. limiter crush, mm	198	189	160
max. static deceleration, g	92	80	100
c) 9 m edge drop	ANSYS calc.	analytical calc.	experimental value
max. limiter crush, mm	383	368	380
max. static deceleration, g	98	112	108

DYNAMIC RESULTS FOR THE 9-M HORIZONTAL DROP

From the 9-m drop tests the horizontal drop leads to the highest deceleration values. Calculated as well as measured time history curves of deceleration for the final disposal cask (FDC) center section are shown in Figure 2a. An impact duration of about 20 ms can be extracted from the curves belonging to the fundamental mode shape describing the rigid body downwards motion of POLLUX. Regarding this mode shape which is assumed to control basically stresses and strains at this location the different curves are in agreement. Some deviations in high-frequency terms are due to the different analysis techniques used and expected to be of little relevance for the cask strains.

Due to the specific length to diameter ratio, high bending strains in the center section of POLLUX are expected. The magnitude of these bending strains being an important design parameter. The time history of axial strains at the center section of shielding cask (SC) is shown in Figure 2b. In the loading period

(≈20 ms) two distinct characteristics can be observed, one belonging to the wood crushing (until $t \approx 8$ ms) and the other to the wood plus trunnion crushing ($8 \text{ ms} < t < 20$ ms, high frequency oscillations). In the rebound phase ($t>20$ ms) the analytical approach clearly overestimates the bending vibrations. In this phase the motion is dependent on the mechanical state (velocity, deformation) just at the end of the loading phase. Measured average strains about 500 1E-6 correspond to stresses about 93 N/mm^2 which are in the allowable region. Similar results hold for the FDC cask.

Fig. 2a: Deceleration at the FDC center section

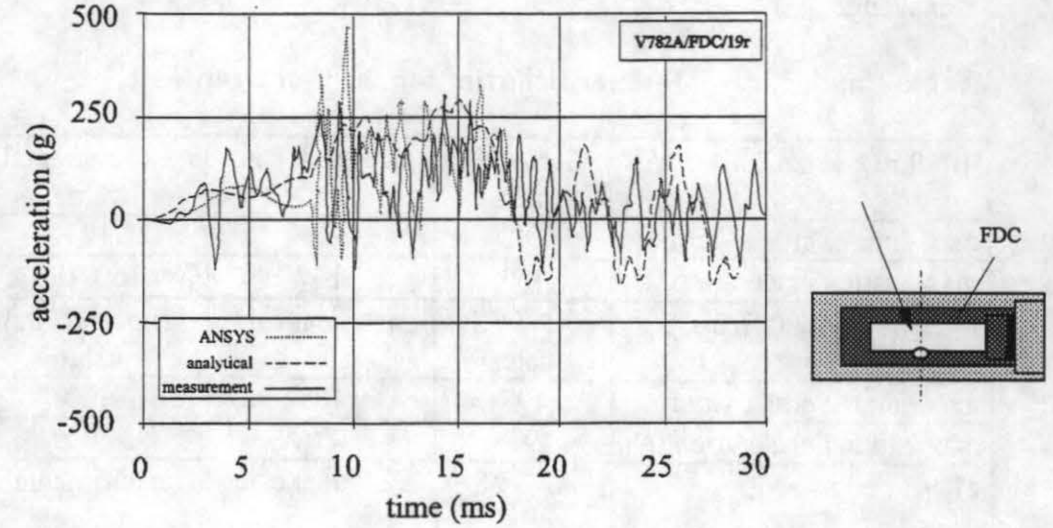
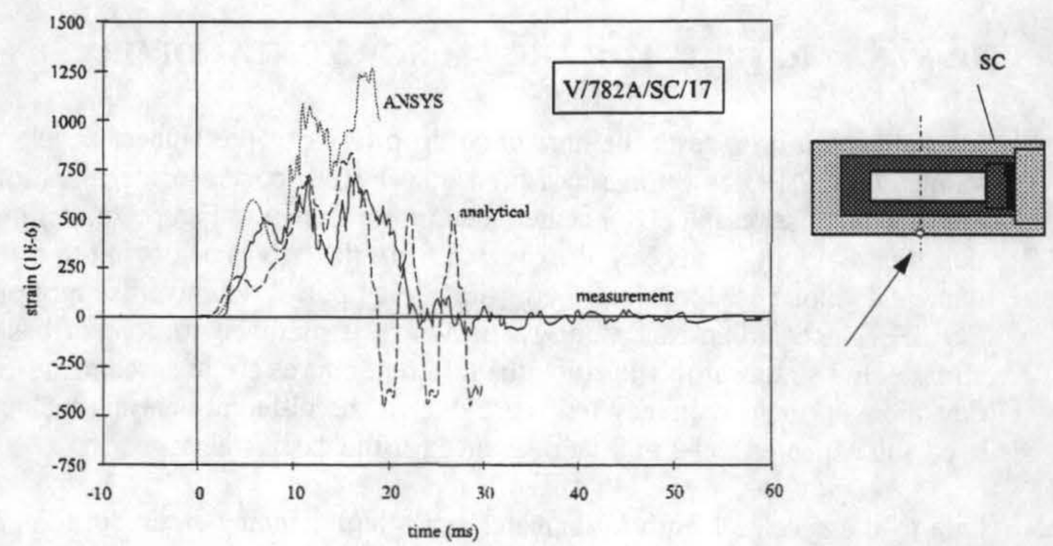


Fig. 2b: Axial strains at the SC center section



DYNAMIC RESULTS FOR THE 5-M BOTTOM DROP ONTO CONCRETE FOUNDATION

The analysis of the 5-m bottom drop without impact limiters onto this concrete foundation appeared to be a difficult task. The transient ANSYS analyses were run with a loading curve derived from an analytical model of the foundation behavior postulating cracking of the concrete slab. This turned out not to be the case in the experiment. Therefore, these results are not included in the following figures. The results using DYNA3D predicted that the concrete would not be destroyed, which turned out to be true. Due to the impact, a 28-mm vertical imprint of POLLUX into the concrete was calculated. This value is to be seen as bounding value since no energy absorption of the sand layer was taken into account. A worst case assumption was made in the analytic analyses treating the concrete foundation as an unyielding IAEA foundation.

The time history of axial accelerations in the center section of the FDC is shown in Figure 3a. The DYNA3D results correspond to the experimental ones regarding the duration of the loading process of about 10 ms and in the amplitude of the corresponding frequency of about 250 g.

This impact load and the wave propagation in the cask is a cause for heavy lid oscillation which is shown in Figure 3b for the center of the secondary lid in the FDC. The amplitude of the calculated oscillations corresponds to the measured one. The measured signal is showing some resonance effect with signals beyond the measuring range from t > 9 ms.

Fig. 3a: Axial decelerations at the FDC center section

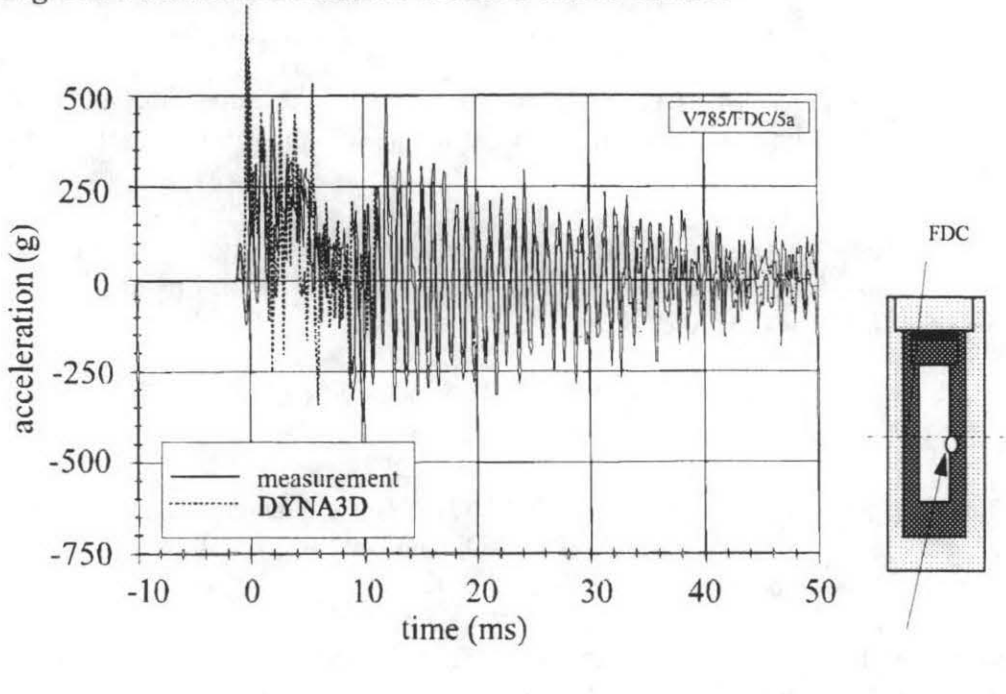
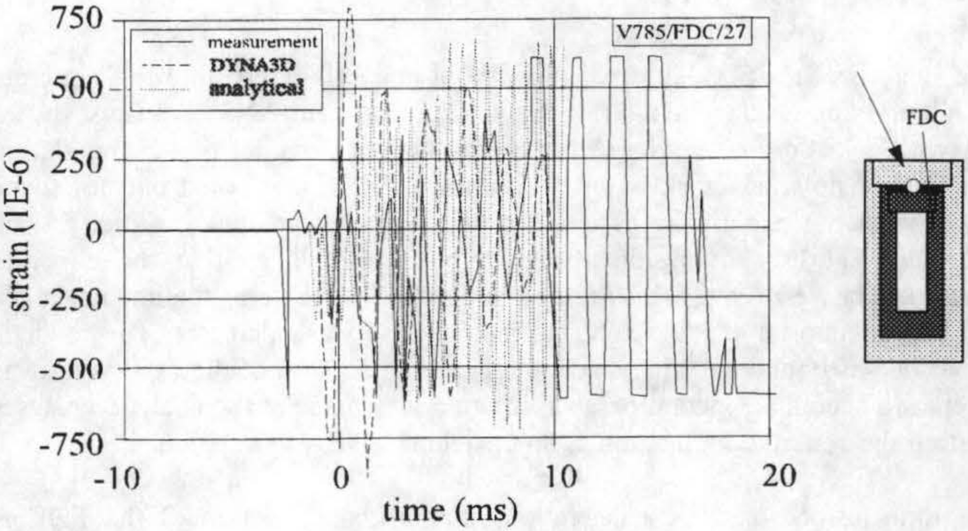


Fig. 3b: Radial strains at the center of FDC secondary lid



CONCLUSIONS

For the 9-m drops with impact limiters all methods used (ANSYS and analytical) seem to be suitable for calculating the dynamic behavior of transport and storage casks in an appropriate manner. Regarding the 5-m concrete drops without impact limiters onto concrete foundation, the explicit DYNA3D code gives the best results. These statements will be further investigated taking into account all of the huge amount of measurement locations.

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