MECHANICAL IMPACT ASSESSMENT OF CUBIC WASTE CONTAINERS DEPENDING ON TARGET CONSTRUCTION

U. Zencker, Th. Quercetti, G. Wieser, H. Völzke, B. Droste

Bundesanstalt für Materialforschung und -prüfung (BAM), D-12200 Berlin, Germany

SUMMARY

BAM as the German competent authority for design testing of transport and storage packages for radioactive materials performed design tests (representing a handling accident inside a repository) with a cubic container made of ferritic ductile cast iron (DCI) with outer dimensions of 2.0 m x 1.7 m x 1.6 m, a wall thickness of 150 mm and a maximum gross weight of 20 Mg.

Current results of very extensive experimental and numerical stress analyses for a drop from 5 m height flat onto a real target without additional impact limiters are presented. The investigated real target consists of a concrete slab put onto the 1000 Mg IAEA target with a layer of wet sand in between. Several drop tests with a fully instrumented prototype container have shown a highly dynamic behaviour of the container structure with maximum stresses up to the yield stress (Droste et al. 1992). The detailed strain measurement data are compared with numerical finite element stress calculations. The experimental and numerical analyses show a contact duration of approximately 5 ms. The deformation of the container is mainly characterized by bending respectively bending vibrations of the container walls. Highest demands on the cubic container structure were found in the vicinity of inner corners and edges, in the middle of the walls and especially of the container bottom plate.

INTRODUCTION

The cubic container design for transport, interim storage and final disposal of non-heat-generating nuclear waste may be advantageous because of the maximum utilisation of the available space in the storage and disposal facilities. Depending on the level of radioactivity of the waste products different requirements are defined for the packages, which have to be fulfilled under normal and accident conditions. The requirements from the three fields of operation are defined by the IAEA regulations for transport, by the technical acceptance criteria for the German interim storage facilities and by the preliminary requirements for the German Konrad repository, a former iron ore mine which is currently in the licensing process.

Recently BAM performed design tests and safety analysis for a cubic ferritic ductile cast iron (DCI) container with outer dimensions of 2.0 m x 1.7 m x 1.6 m, 150 mm wall thickness, a structural net mass of approximately 18.3 Mg and a maximum gross weight of 20 Mg (Figure 1). This container of the Konrad Type VI has to withstand a drop from the highest stacking position in the repository. Tests with different drop heights and positions were done.

For more detailed and precise drop test analyses BAM has developed special finite element modelling (FEM). The numerical procedure gives the dynamic stresses and strains in the container structure as a result of the violent impact and accounts for the complex behaviour of the real target. The calculation results are compared with representative strain measurement data from drop tests with an original prototype container. The development of improved analysis techniques is carried out in a research programme where the use of ductile cast iron melted with contaminated scrap metal from the decommissioning of nuclear installations as container material is investigated. The more detailed stress analysis is required because the scrap metal additions influence negatively the mechanical properties of such containers what requires a more stringent safety assessment.

DROP TESTS

Extensive investigations by BAM have demonstrated that a 5 m drop flat onto the real ground of the Konrad repository represents the most critical accident scenario concerning integrity and tightness of such Type VI containers, if they have to fulfil the stronger Konrad Class II requirements for containers with higher activity limits (Brennecke 1995, Martens 1995). Because no shock absorbers are provided inside the Konrad repository, the 5 m drop normally leads to higher decelerations and impact stresses of the container structure compared with the IAEA test scenario for shipping casks equipped with well designed impact limiters.

BAM performed two extensive drop test series in the years 1991 and 1993, a final low temperature test in 1995 (Droste et al. 1992, Droste et al. 1994, Völzke et al. 1995). First of all, the results of the measurements in 1991 showed relatively high tractional strain at some measuring points nearby the edges and in the middle of the walls. Further the signals gave rise to the suspicion that during and after impact the global deformation of the container is bending of its walls so that still higher values could be expected in the middle of the walls and in the concave moulds between the container walls, which were not instrumented in the first test series. A corresponding instrumentation of the container in the second test series confirmed this suspicion: the main deformation is bending and the critical loaded locations on the container are the concave moulds between the side walls and in the centre of the bottom plate. In the first location positive (tractional) strain reached up to 2600 μm/m. In the centre of the bottom plate it reached up to 1500 μm/m.

Finally a drop test was performed at a material temperature of -20°C with a prototype container prepared with artificial flaw-like defects in the above mentioned highest stressed areas. Also under such extreme conditions preservation of integrity and tightness was generally demonstrated (Völzke et al. 1995) but additional visual inspection after the drop test showed, in some cases, limited crack extension at the tips of the artificial flaw-like defects; this has to be evaluated carefully giving consideration to local material properties.

The first test series was performed with a complete, maximum-loaded container. The second test series was performed with an empty container without a protection lid. For compensation of the lower impact energy in this case, the drop height was increased to 5.59 m. The duration of the primary impact was always about 5 ms, and the decelerations reached up to 1300 g (1 g = 9.81 ms^{-2}). The target was damaged very little with a penetration of only a few millimetres into the concrete slab and some small cracks within the impact area. The maximum stresses of the container structure caused slight deformation, but greater deformation or damage never occurred. The maximum dynamic strain rates reached 7 s^{-1}.

NUMERICAL ANALYSIS

While strain gauge measurements are only possible at discrete positions, a numerical simulation shows all stress and strain components including their rate of change all over the cask structure. The precise modelling of the target is as important as an adequate modelling of the container structure: both are of great influence on the calculation results. For verification of the results from such numerical calculations a comparison to representative test data is essential. Finally, the results from both the experimental and the numerical investigations can lead to a complete understanding of the very complex mechanical container behaviour.

The numerically investigated accident scenario is the 5.59 m drop flat onto a real target representing the ground of the repository. The drop test configuration is shown in Figure 2. The target consists of a reinforced and steel-framed concrete slab put onto the 1000 Mg IAEA target. Both are coupled by a wet sand layer in between. Figure 3 shows a finite element model of a quarter segment of this test configuration. The drop height is prescribed by the initial velocity of the container. Solid 8-node elements with reduced integration and hour-glass control are used. For the container material an elastic material model (Young's modulus E = 162 500 MPa, Poisson's ratio $\nu = 0.29$, mass density $\rho = 7000$ kg/m^3) is used (Frenz 1993). The container body, the lid, the concrete slab, the sand layer and the IAEA target are connected with each other by contact elements without friction. The bolts were modelled as springs attached to the lid and the container body. All dynamic calculations were done using ABAQUS/Explicit.

At first, the accuracy and convergence of the container model was analysed by varying the number of elements over the wall thickness. For this purpose, contrary to Figure 3, an unyielding target was modelled with only two-dimensional rigid surface elements. The analysis of strains in the centre of the bottom plate (inside surface) shows that the period of oscillations in the calculated strain history curves is influenced by the finite element mesh. Therefore, the superposition of propagating stress waves in the container structure due to the impact event is slightly model dependent. It was found that at least three elements over the wall thickness should be used to describe the plate bending vibrations.

TARGET MODEL

The target model determines the accuracy of the calculation results. The energy transfer to the foundation is essential for the remaining energy in the container. An oversimplified description of the real target as a rigid one leads to strain amplitudes twice as high because the full impact energy remains in the container. Additionally, the bending of the bottom plate would be supported by a real foundation. A better model is an elastic-plastic half space which enables the propagation of stress waves in connection with energy transfer to the foundation. Because this simplest real target model is different from the given impact situation the amplitudes of the calculated strains are still higher than the measured ones. The measured impact duration of approximately 5 ms is also not reproduced by the calculation results. It is thus obvious that modelling of the drop test target has to consider more realistic structural and material data.

In the test configuration of BAM, according to Figure 2, the container hits on a concrete slab which is modelled as a linear Drucker-Prager material with a uniaxial compression yield stress of 45 MPa and a friction angle of 66°. The elasticity in conjunction with this model is defined by the parameters $E = 37000$ MPa and $\nu = 0.21$ and the mass density is 2340 kg/m^3 (Bonzel 1988). The steel plate of the IAEA target is considered as an elastic half space meshed with solid elements surrounded by infinite elements ($E = 210000$ MPa, $\nu = 0.3$, $\rho = 8000$ kg/m^3). Between concrete slab and IAEA target there is a layer of wet sand ($\rho = 2000$ kg/m^3). In separate compression experiments ('Odometer' experiments) its stiffness modulus E_S of 106 MPa was measured, which can be expressed by a modulus of elasticity of 79 MPa for an assumed Poisson's ratio of 0.3. More details of the calculations are described elsewhere by Völzke et al. 1997.

CALCULATION RESULTS

The highest stresses of the cubic container structure were found in the vicinity of inner corners and edges, in the middle of the walls and especially of the container bottom plate. Calculated and measured strain history curves from the centre of the bottom plate (inside surface) using the above described structural and material data are shown in Figure 4. These graphs represent bending strains superimposed by high-frequency stress wave effects. The impact energy is partially transferred to the foundation. The calculated strain history curves show good agreement with the measured impact duration of nearly 5 ms (BAM 1996), but the magnitude of the oscillations is still too high. The beginning of the experimental graph depends on an initial angle (< 1°) between container bottom plate and target because the drop test attitude was not ideally flat. The calculated irreversible penetration of about 0.3 mm into the concrete slab and the maximum vertical elastic displacement of the container bottom plate of about 10 mm are confirmed by deceleration measurements and visual inspection from the drop tests. Inelastic effects were found only in the vicinity of contact surfaces (far away from infinite elements).

Until now the material damping of the ductile cast iron was neglected, which can be included by an additional 'damping stress' proportional to the strain rate and the material's current elastic stiffness. The damping factor $\beta_R = 2 \cdot \xi_i / \omega_i$ can be expressed in terms of a fraction ξ_i of critical damping for a particular frequency ω_i of vibration (HKS 1995). Because the same damping factor is effectively applied to all the modes in an element, a chosen value of $\beta_R = 10^{-5}$s/π reduces frequencies of 1 kHz by 1 % and frequencies of 10 kHz by 10 %. Considering such realistic material damping, the calculated strain histories are in general good agreement with the experimental results (Figure 5). The maximum stresses are 300 MPa.

Our investigations into the numerical simulation of such strong and highly dynamic impact scenarios demonstrated that only realistic modelling of the real structural and material characteristics will lead to sufficient agreement with results from real drop tests.

CONCLUSIONS

The complex mechanical behaviour under the most critical accident scenarios of cubic ferritic ductile cast iron containers for transport, storage and disposal of non-heat-generating radioactive waste has been investigated by BAM.

The development of detailed and precise numerical drop test analyses needs special finite element modelling of container and target for accurate numerical calculation of container stresses as a result of the violent impact of containers without impact limiters. The container model must include plate bending effects and the damping behaviour of the structure. For the investigated test configuration different simplified target models (rigid surface, elastic-plastic half space) were tested, but only a realistic modelling of the real structural and material characteristics leads to sufficient agreement with results from real drop tests.

ACKNOWLEDGEMENTS

The numerical calculations of the DCI container drops are supported by the German Federal Ministry of Education, Science, Research and Technology under research contract No. 02 S 7584 (Stillegung und Rückbau kerntechnischer Einrichtungen).

REFERENCES

BAM *Instrumentierte Fallversuche (Fallhöhen 0,9 m, 3 m und 5 m) mit einem Abfall-Endlagerbehälter der Bauart Gußcontainer Typ VI zur Endlagerung radioaktiver Abfälle*, Confidential test report: BAM-Versuchsbericht Nr. 20328 (Berlin: BAM (1996)).

Bonzel, J. *Beton*, In: Betonkalender Teil 1 (Berlin: Verlag Ernst & Sohn) pp. 1-104 (1988).

Brennecke, P. *Anforderungen an endzulagernde radioaktive Abfälle (Endlagerungsbedingungen, Stand: Dezember 1995) - Schachtanlage Konrad*, BfS-ET-IB-79 (Salzgitter: Bundesamt für Strahlenschutz (1995)).

Droste, B., Gogolin, B., Quercetti, Th. and Rittscher, D. *Drop Test of a Cubic DCI Container for Radioactive Wastes*. In: Proc. PATRAM '92, 13-18 Sept. 1992, Yokohama City, Japan, Vol. 3, pp. 1435-1442 (1992).

Droste, B., Zeisler, P., Völzke, H. and Rödel, R. *Development and Evaluation of Containers for Radioactive Waste Disposal*. Int. J. Radioact. Mater. Transp. 5(1), pp. 27-32 (1994).

Frenz, H. *Mechanical Properties of Ferritic-Perlitic Ductile Iron*. Sandia National Laboratories Report No. SAND92-0421 (Albuquerque, New Mexiko: Sandia National Laboratories (1993)).

HKS *ABAQUS/Explicit User's Manual Version 5.5* Hibbitt, Karlsson & Sorensen, Inc. (1995)

Martens, B.-R. *Produktkontrolle radioaktiver Abfälle (Stand: Dezember 1995) - Schachtanlage Konrad*, BfS-ET-IB-45-Rev-3 (Salzgitter: Bundesamt für Strahlenschutz (1995)).

Völzke, H., Wieser, G., Droste, B. and Gogolin, B. *Extended Brittle Fracture Safety Demonstrations of Cubic Ductile Cast Iron Containers*. In: Proc. PATRAM '95, Las Vegas, Vol. 3, pp. 1356-1363 (1995).

Völzke, H., Wieser, G., Zencker, U. and Droste, B. *Mechanical and Thermal Safety Analyses and Demonstrations for Cubic DCI-Multi Purpose Containers*, 4th Intern. Conf. on Transportation for the Nuclear Industry, 13-15 May 1997, Bournemouth, U. K.

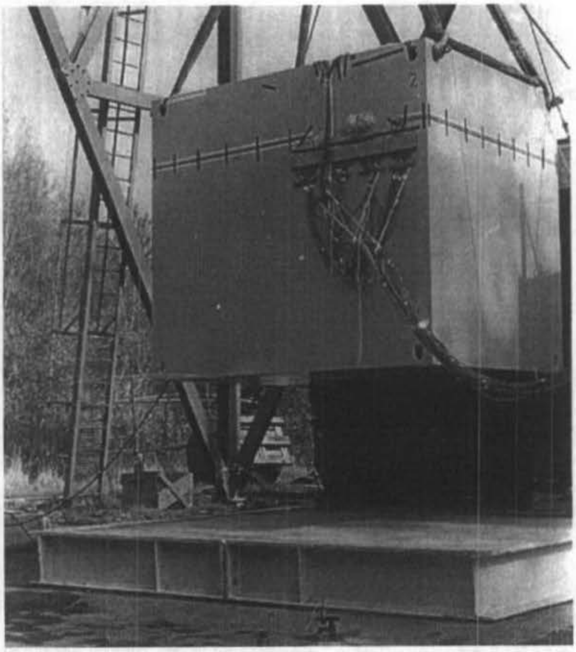

Figure 1. DCI container of the Konrad Type VI and real target

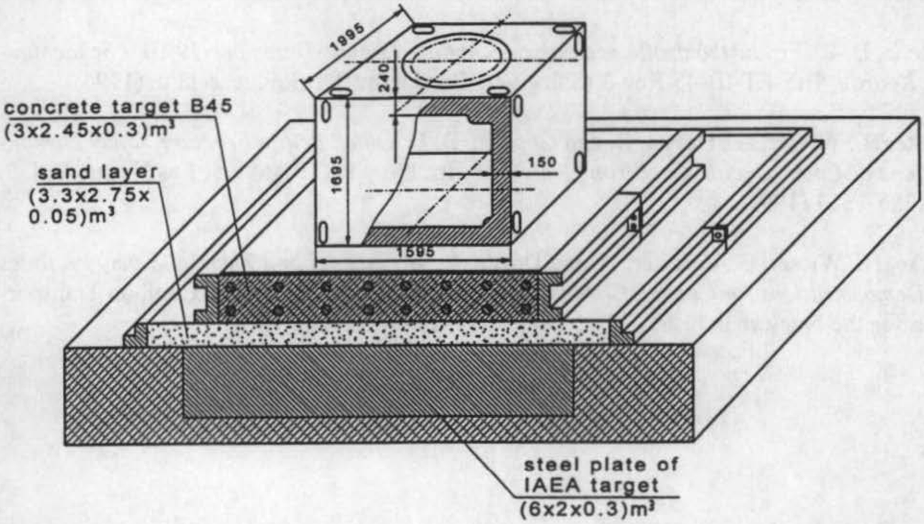

Figure 2. Drop test configuration

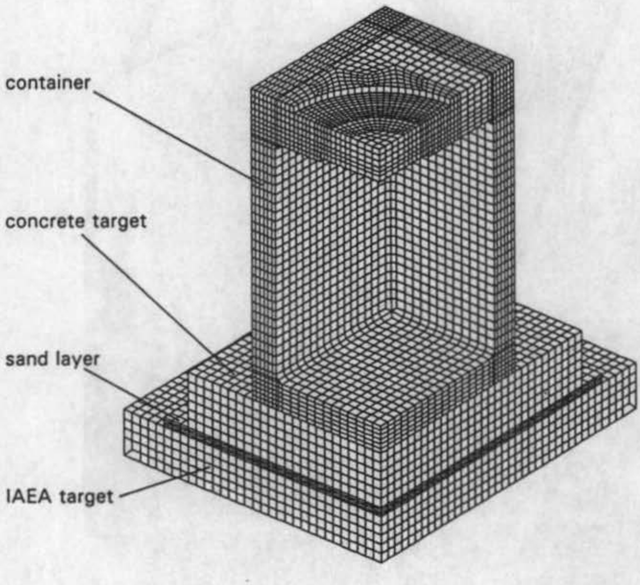

Figure 3. Finite element model of a quarter segment of the test configuration

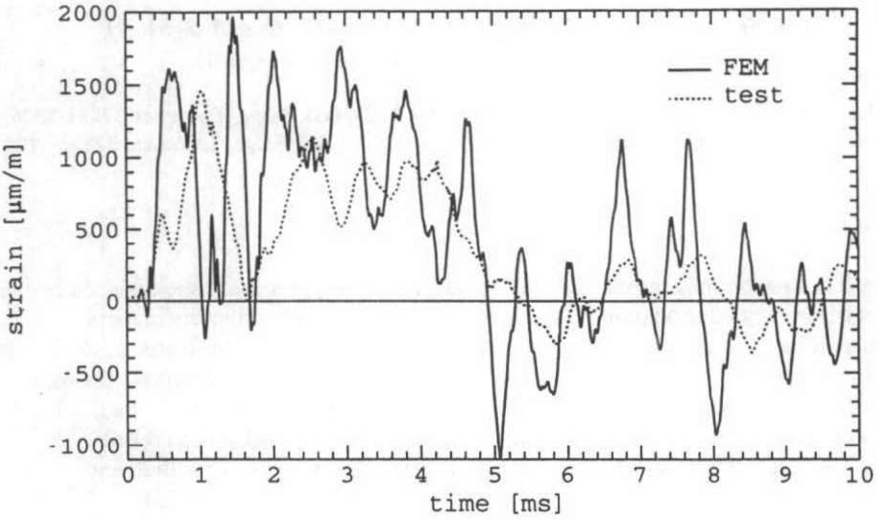

Figure 4. Calculated strain history (without consideration of damping) in the centre of the container bottom plate compared with the test result

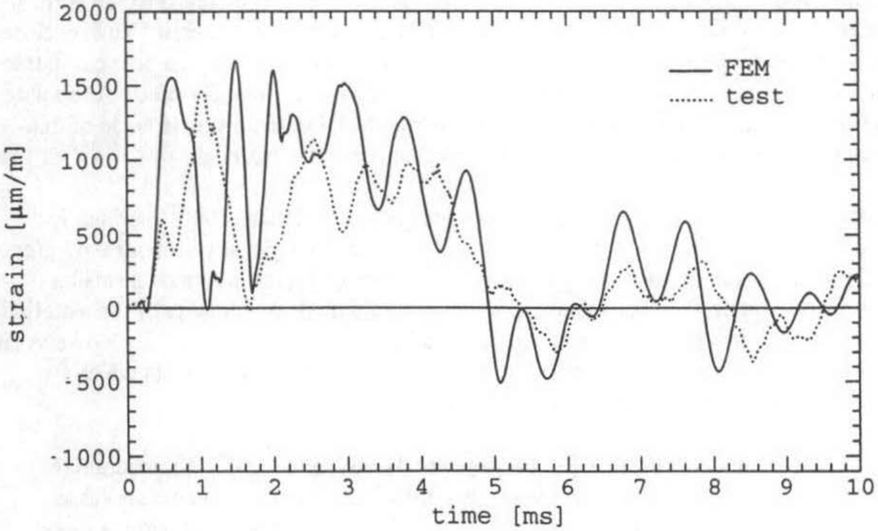

Figure 5. Calculated strain history with damping effects in the centre of the container bottom plate compared with the test result