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USING SCALE MODEL IMPACT LIMITER IN THE TYPE ASSESSMENT OF TRANSPORT CASKS FOR RADIOACTIVE MATERIAL

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ABSTRACT

In Germany, the Federal Institute for Materials Research and Testing (BAM) is the competent authority for the mechanical and thermal design safety assessment of transport casks for radioactive material according to IAEA regulations. The combination of experimental and numerical safety proof forms the basis for a state of the art evaluation concept.

Reduced-scale models are often used in experimental investigation for design assessment of transport packages corresponding to IAEA regulations. This approach is limited by the fact that a reduced-scale model cask can show different behaviour from a full-scale cask. The paper focuses on the peculiarities of wood filled impact limiter of reduced-scale models. General comments on drop testing with reduced-scale models are given, and the relevant paragraphs of the IAEA regulations and Advisory Material are analysed. Possible factors likely to influence the energy absorbing capacity of wood-filled impact limiting devices are identified on the basis of similarity mechanics. Among possible significant influence factors on the applicability of small scale models are strain rate and size effects, failure mechanisms, underground compliance, gravitational and friction effects. While it was possible to derive quantitative estimations for the influence of strain rate, size effects and target compliance, it was not possible to evaluate the influence of compression mechanisms and gravitation. In general, if reduced-scale models are used in proof of safety, uncertainties increase in comparison with full-scale models. Additional safety factors to exclusively cover the uncertainties of reduced-scale model testing have to be demanded. The possible application of reduced-scale models in regard to crucial aspects for proof of safety have to be analysed critically.

INTRODUCTION

In Germany, the Federal Institute for Materials Research and Testing (BAM) is the competent authority for the mechanical and thermal design safety assessment of transport casks for radioactive material according to the IAEA Regulations [1]. Experimental and computational (analytical, numerical) methods are, combined with additional material and/or component tests, the basis for the safety evaluation and assessment concept at BAM according to the state of the art.

Experimental tests according to the IAEA Regulations [1] are frequently carried out with reduced-scale models. However, it must be considered that a reduced-scale model can exhibit different behaviour during testing in comparison to a full-scale cask. Correct use of similarity laws regarding the test aims has to be demonstrated appropriately in the safety assessment procedure. The IAEA Regulations [1] and the Advisory Material [2] must be interpreted accordingly and applied correctly.

Paragraph §701(c) of the IAEA Regulations [1], which is necessary for the execution of a drop test, only provides general recommendations:

[1], §701(c): “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. When a scale model is used, the need for adjusting certain test parameters, such as penetrator diameter or compressive load, shall be taken into account.“

Further advice and explanation concerning reduced-scale model tests is given in the IAEA Advisory Material [2], which deals with particularities of tests with reduced-scale models, especially in mechanical tests according to the IAEA Regulations [1]. The IAEA Advisory Material [2] states that usage of scale models in type assessment can be problematic, especially with materials like wood and honeycomb incorporated in impact limiter [4].

Impact limiting devices are applied to limit the load on cask components in different scenarios. Typical constructions consist of thin steel plates filled with wood, which are in general attached to casks at their lower and upper ends [17]. The impact limiter absorbs the major part of the kinetic energy as it is relatively soft compared to the cask. Impact intensity on the cask body, lid and lid bolts is lowered significantly. Wood, as the essential part of the impact limiter, thereby has the task of absorbing the main part of the kinetic energy by converting it into deformation energy.

Deployment of scaled models in type assessment demands a detailed examination (e.g. numerical calculations) from the applicant to ensure reasonable and appropriate application of scale models ([2], §701.14). Resulting transferability considerations, which are often conducted by Finite Element (FE) calculations and component tests, are all too often more expensive than anticipated. Experience of BAM shows that full-scale model tests with prototypes should always be considered in the type assessment [3, 4, 5].

APPLICATION OF SIMILARITY THEORY

In practical terms, it is impossible to achieve precise similarity between reduced- and full-scale models in all aspects. The response pattern is comparable, if the full- and reduced-scale models are similar in geometry, kinematics, dynamics, gravitation and materials. This leads to a reasonable interpretation of impact behaviour, which can be assessed adequately. Further and more detailed explanations can be found in [3].

However, it is complicated, or even impossible to implement all mentioned aspects of similarity in one model. The similarity of geometry, dynamics and materials is in contradiction to impact time and strain rate effects at the comparison of reduced- and full-scaled drop tests. Difficulties arise in the interpretation of measurement signals and the transferability of loads from the reduced to full-scale model cask.

According to [3], different scaling types are possible. Each of these types takes into account certain effects, while other effects are omitted. This paper deals exclusively with the scaling type where material is not scaled and gravitational and rate dependency are omitted (A-4 in [3]).

PARAMETERS AFFECTED BY SCALING

Particular attention when scaling drop test casks has to be drawn to the transferability of time dependent behaviour like the loading rate and therefore, the strain rate dependency of the materials, and the structural mechanisms which are not scaled. The basis of the assumptions arises from the similarity coherences presented in [3] for the scaling of a full-scale prototype cask down to a 1:2.5 scale model cask and vice versa.

Strain Rate

The influence of the strain rate on the strength of five different kinds of wood was analysed in [6] with a "Split Hopkinson Bar" test arrangement For impact speeds of up to 360 m/s it was shown, that a mostly exponential and partly linear correlation between compressive strength and impact velocity exists. In axial compression dynamic-to-static factors of the compression strength of up to 4.5 were derived. It has to be restricted, that the tests were conducted at considerably higher impact speeds and strain rates than appear in drop tests with packagings. The relation between dynamic factor and loading velocity was linear in perpendicular compression.

The compressive strength of balsa in axial compression increases with the loading rate [7], while the compression plateau remains unchanged. Higher strain rates also led to an earlier lock up of the wood. The compressive strength and plateau of the wood in perpendicular compression clearly depend on the strain rate.

According to [3], the strain rate is scaled by a factor to the power of one, which leads – when compared with a 1:2.5 scale model – to a strain rate 2.5 times higher in the reduced-scale model. Corresponding to [8], the rise of the compressive strength can be estimated as 1.03.

Figure 1 presents the statistical interpretation of the results of dynamic compression tests on wood. Cube-shaped wooden samples with an edge length of 100 mm under axial loading were used. The compressive strength increased significantly with the strain rate. Starting with a strain rate of around 25 m/s for a full-scale prototype cask under 9 m drop conditions and extrapolating the slope towards a 1:2.5 scale model (62.5 m/s), leads to an increase in strength (decrease of the general compliance) of the reduced-scale model in comparison to the full-scale model of around 8.4 %.

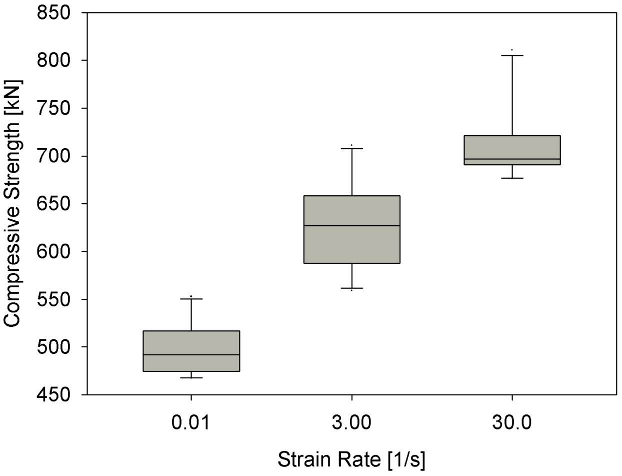

Figure 1. Compressive Strength of Wooden Samples (100 mm x 100 mm) Loaded along the Grain (BAM experiment, M. Neumann, 2007)

Size Effects

Bending tests with small scale wooden samples showed that smaller models had higher strength than bigger ones [9]. Tensile tests with wooden samples with a rectangular cross-section of two different sizes (cross-section area 12.4 mm² and 116.6 mm²) are presented in [10]. Tensile strength in the smaller specimens was statistically 8.2% higher than the tensile strength in bigger samples. This result correlates with the estimation of a general size factor in [11]. The size factor, deduced for the here considered relative volumetric scale between a reduced and full-scale sample of 15.6 (2.5^3) amounts to 0.84 ± 0.08, or an increase in the strength for the smaller sample of around 16%. That implies that reduced-scale impact limiter could have an approximately 16% lower compliance in comparison to the full-scale model.

Compression Mechanisms

The biggest wood-related structural system sizes considered in this context are the annual growth rings. They distinguish zones of different growth and, therefore, different density and cell dimension [12, 13]. Structural sizes have to be negligible compared to the wood dimensions to be able to describe wood as a continuum. Width of wooden layers in a typical impact limiter are approximately 15-50 mm. For european spruce, grown at a fast rate, the dimension of a growth ring is likely to be up to 6 mm, which is not negligible compared to wood dimensions. Therefore, scaling of impact limiters could lead to differences in compression characteristics due to the different failure modes of wood fibres. Figure 2 presents buckled layers of fir wood that have been exposed to compression. Delaminations can be seen on the edges of annual growth rings. The influence of a different ratio of wood dimensions and annual growth ring dimensions is not studied exhaustively and can, therefore, not be assessed yet.

Figure 2. Buckled Layers of Fir Wood (BAM experiment, M. Neumann, 2007)

Target Compliance

BAM experience in the field of tests with packages for radioactive material shows that a small part of the impact energy is absorbed even by large unyielding targets of more than 2600 Mg such as at the BAM drop test facility in Horstwalde near Berlin [14]. This will be the case especially when packages with hard, integrated impact limiters are used, or in drop tests without impact limiters.

The mass of the reduced-scale cask is smaller by the factor λ^3 (λ=2.5 leads to λ^3=16.625). Therefore, target compliance is overestimated in a reduced-scale model drop test when compared to a full-scale prototype drop test. It has to be stated clearly, that no credit can be taken from this overestimation in regard to the package assessment [1,2].

A suitable estimation of target energy absorption is presented in [16]. In this case, the kinetic energy of the cask before the impact equals the sum of the kinetic energies of cask and target after the collision $E_{kin,c} + E_{kin,t}$, the deformation energies of cask and impact limiter $E_{def,c} + E_{def,il}$, and the deformation energy of the ground $E_{def,gr}$:

$$E_{kin,total} = E_{kin,c} + E_{kin,t} + E_{def,c} + E_{def,il} + E_{def,gr} \qquad (1)$$

All the following considerations assume the point in time when the cask velocity has reached zero, and therefore the kinetic energy of the cask is zero, too.
The kinetic energy of the target can be estimated by taking the measured acceleration-time-dependencies of the acceleration sensors in the target and integrating them by time. Target velocity amounts to 0.34 m/s² for the full-scale model of the MSF69BG® [16]. Target velocity after the drop with the 1:2.5-scale model was 0.01 m/s² [16]. The velocities can be transferred into kinetic energies by the following equation:

$$E_{kin} = \frac{1}{2} m\, v^2 \tag{2}$$

The deformation energy of the ground can be estimated by simulating the ground as nonlinear spring. The integral of the force-deflection curve of the substitute spring over the deflection of the ground describes the appropriate energy estimate:

$$E_{def,gr} = \int_{x=0}^{x=\delta} F(x)\, dx \tag{3}$$

The force-deflection curve $F(x)$ was estimated from measured force-time curves of the foundation, which came from force transducers in the base of the target, $F(t)$, and the double integrated acceleration versus time curves $a(t)$ obtained from acceleration sensors in the target. By adding up the energy of the target and setting it in relation to the total impact energy, the energy absorbed by the target can be estimated:

$$\frac{E_t}{E_{kin,total}} = \left(\frac{E_{kin,t} + E_{def,gr}}{E_{kin,total}} \right) \cdot 100\% \tag{4}$$

Results are presented in Table 1.

Table 1. By Target Absorbed Energy, Relative to Impact Energy

Absorbed Energy, Relative to Impact Energy	
1:1 Model	2.20%
1:2.5 Model	0.15%
Proportion	14.7

Relative to the kinetic energy of the models prior to impact, the target absorbs around around 2 % more energy at the impact of the full-scale prototype than of the reduced 1:2.5 scale model. In [16], a more detailed analysis of the impact foundation in Horstwalde is published.

Gravitation

Regarding similarity theory , the gravitational acceleration of approximately 9.81 m/s² would have to be scaled at a factor of λ=2.5 for the example of a 1:2.5 scale model. This would lead to a gravitational acceleration for the reduced-scale model of 3.94 m/s², but gravitation cannot be scaled. Nevertheless, for a vertical drop with an average deceleration level of 600 m/s², the error amounts to below 1%. This result is, compared to the average deceleration level, negligible.

However, the interaction between inventory and cask is highly influenced by gravity, and can lead to qualitatively different characteristics, as analysed in [4].

Another influence of gravity can be seen at the slap down impact position. Here, the time between primary and secondary impact could allow gravitation to alter the impact kinematics of the cask. The effect has to be reanalysed and reassessed for each separate package [4].

Friction

According to [12], a finer annual ring structure, surface finish, size and distribution of pores and early / latewood relation affect the friction coefficient of wood. Therefore, different failure and compression mechanisms in reduced-scale models can lead to different friction behaviour.

The influence of friction on the energy absorption capacity of impact limiter was analysed with a FE calculation. The model can be seen in Figure 4. The influence of friction coefficients for the contact between wood and steel casing is analysed. The wood has to stay in position under the cask and not move to the sides of the cask, if it is to absorb the impact energy. Figure 5 presents the influence of different friction coefficients on the local deceleration. Smaller friction coefficients lead to a significant change of the shape in the curve towards a lower deceleration at the beginning and a harder impact at the end. This would lead to higher maximum deceleration through excessive compression in the impact limiter.

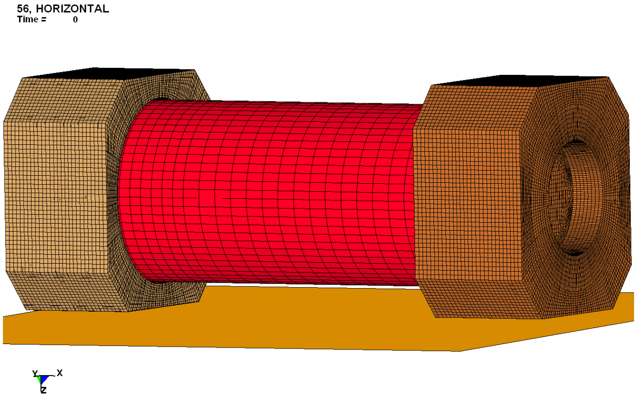

Figure 4. Finite Element Model for the Parameter Analysis (BAM calculation, M. Neumann, 2007)

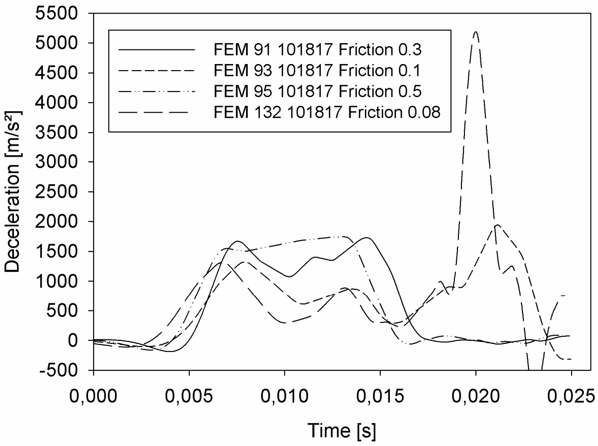

Figure 5. Influence of Different Friction Coefficients on Calculated Deceleration-Time Curves (BAM calculation, M. Neumann, 2007)

It can be stated that friction has a high influence on the energy absorption capacity of impact limiters. Scaling the wood dimensions without scaling the compression and failure mechanisms could lead to different friction behaviour and therewith, to different energy absorption (Compare to Figure 5)

COMPARISON WITH DROP TEST RESULTS

A detailed comparison between drop tests with a 1:1 and a 1:2.5 model is presented in [4]. The comparison does not reveal ambiguous proof for the direction of difference of measured deceleration signals and deformation between 1:1 and 1:2.5 model. For the Slap down impact position (10°), the reduced-scale model had a harder impact with higher deceleration, smaller deformation and a shorter impact duration compared to the full-scale model. For the vertical drop position, the reduced-scale model had, in general, “softer” behaviour, including smaller deceleration, higher deformation and shorter impact duration. The impact of the inventory on the primary lid, which constituted the highest loads for the primary lid and lid bolts und the full-scale model, did not occur at the reduced-scale model. The underlying phenomena have to be analysed extensively.

CONCLUSIONS

Among possible significant influence factors on the applicability of small scale models are strain rate and size effects, failure mechanisms, underground compliance, gravitational and friction effects. While it was possible to derive quantitative estimations for the influence of strain rate, size effects and target compliance, it was not possible to evaluate the influence of compression mechanisms and gravitation.

The higher strain rate leads to an increase in compression strength by a factor of around 1.08 for a scaling factor of 1:2.5 in the experimental results presented here. Size effects result for 1:2.5 scaling in an around 1.16 higher strength compared to the full-scale model. The lower target compliance in relation to the full-scale model test leads to an approximately 2% higher load in the reduced-scale 1:2.5 model.

More detailed examinations for every individual design and drop position are for the other factors (compression mechanisms and gravitation), essential. As an example, there is no simulation of the inventories’ impact on the primary lid in the case of a vertical drop for the reduced-scale model [4]. The impact of the inventory determines the highest load in the lid and lid bolts for the full-scale model.

In general, if reduced-scale models are used in safety analysis concepts, uncertainties increase in comparison to full-scale model tests. Additional safety factors have to be demanded exclusively to cover exclusively uncertainties concerning reduced-scale model testing, and to cover immanent uncertainties of calculations needed to transfer small-scale package results to the original design. Possible application of reduced-scale models in regard to crucial aspects for proof of safety has to be analysed critically.

ACKNOWLEDGMENTS

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