Development of a Wood Material Model for Impact Limiters of Transport Packages – 14111

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ABSTRACT

Packages for the transport of SNF and HLW are usually equipped with impact limiters to reduce the loads that result from the regulatory 9 m drop test. A common impact limiter design in Germany is a welded steel sheet structure filled with wood. The material wood is the main energy absorber, while the steel sheet provides the integrity of the impact limiter. The IAEA allows mechanical safety cases of transport packages to be carried out computationally, as long as the models used are reliable. In this context, a Finite Element (FE) modeling approach for wood and its application to impact limiters in the calculation of a 9 m drop test is presented.

A user material model for wood was developed for the dynamic FE-Code LS-DYNA. Its features are based on a series of crush tests with spruce wood specimens. The model considers wood as a material with transversely isotropic properties, i. e. in the directions parallel and perpendicular to the fiber. The plastic material behavior depends on the state of stress. This has shown to be important to account for the lateral constraint of wood in impact limiters resulting from steel sheet encapsulation. Lateral constraint or respectively, a multiaxial stress state, increases the compression strength level of wood, limits the softening effect and increases the hardening effect. Lateral constraint also increases volumetric and reduces deviatoric deformation. The wood material model considers various hardening and softening characteristics via input flow curves. It considers effects of temperature and strain rate on strength as well. The development of a multi-surface yield criterion and a plastic potential that enables the user input of plastic Poisson's ratios were the challenges during the development of the material model.

A dynamic FE calculation of a horizontal drop test with an 18,000 kg test package was performed. The wood material model was used to model the wooden impact limiter inlays. The impact limiter deformation and the package deceleration were compared to the experimental drop test results to rate the performance of the wood material model.

INTRODUCTION

Type B packages for the transport of RAM have to endure a 9 m drop test onto an unyielding target according to the IAEA regulations SSR-6 [1]. The packages are often equipped with impact limiters to absorb the impact energy and reduce the loads on the package components. A common impact limiter design is a welded steel sheet structure filled with wood. The wood shall ensure dissipating most of the impact energy, while the steel sheet structure shall provide the impact limiter’s integrity. Safety cases of Type B packages often include numerical modeling using Finite Element (FE) Analysis. A reliable material database and an extensive understanding of materials involved in the FE models are necessary thereby. One particular challenge is to model the material wood appropriately for application in FE drop test calculations, see e. g. Neumann [2] and Qiao et al. [3]. The development of a new wood material model is necessary, regarding the effect of multiaxial stress (or respectively, lateral constraint) in particular. The following strategy was developed to approach this challenge, see also Figure 1:

1. Determination of the the typical loading and boundary conditions of wood in impact limiters. Experimental characterization of wood with regard to these factors.
2. Development of an FE material model for wood that is based on the experimental findings. Evaluation and rating of the material model.
3. Application of the material model to wood filled impact limiters in an FE package model.
4. Comparison of numerical and experimental drop test results. Determination of tentative modifications of the wood material model as well as of the package model.

We will show in the following chapters how the strategy was realized.

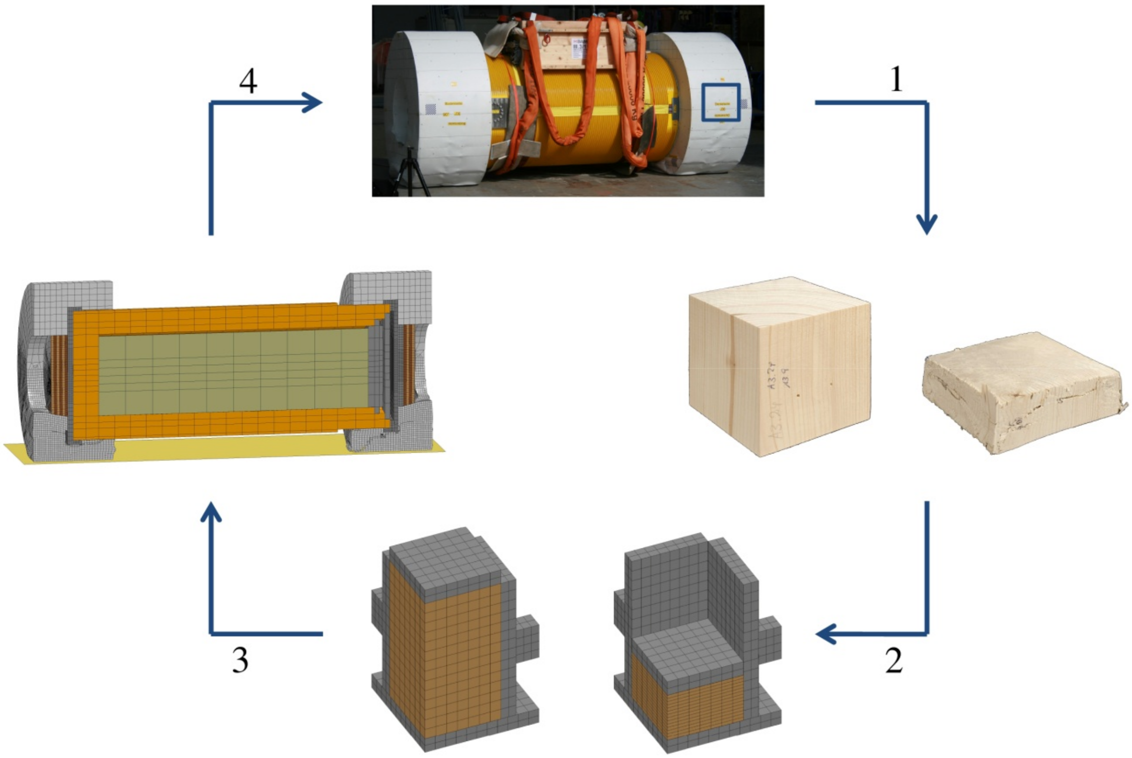

Figure 1. Strategy for the development and evaluation of the wood material model for impact limiters.

CRUSH CHARACTERISTICS OF SPRUCE WOOD

The mechanical loading of wood inside impact limiters consists mainly of dynamic compression loads. The resulting wood compression can be up to 65 %. The fiber-load orientation can vary due to different orientations of wood layers inside the impact limiter. The lateral dilation of the wood during compression deformation is limited due to the adjacent steel sheets. The residual thermal power of the package's content as well as ambient conditions can lead to wood temperatures of -40 °C up to about 90 °C.

A test program was derived to characterize the material spruce wood considering those parameters. Over 600 crush tests with cubical spruce wood specimens (specimen edge length 100 mm) were performed. Effects of fiber-load orientation, lateral constraint, strain rate and temperature were investigated. An executive summary of the test series is given in the following. Details regarding the crush test series were published in [4, 5].

A servo hydraulic impact testing machine [6, 7] and a machine for guided drop tests [8] were used to perform the crush tests. A crush tool transferred the test load to the specimen. The specimen was positioned onto a steel base plate (free lateral dilation) or put into a constraining device (lateral dilation totally constrained).

The deformation of the spruce wood specimens is shown in Figure 2, exemplary for load parallel to the fiber. With lateral constraint, the cross section of the specimen did not change and the deformation was predominantly volumetric. Without lateral constraint, a kink band developed and fiber strands buckled outwards. The deformation was predominantly deviatoric. Loaded perpendicular to the fiber with lateral constraint, again the cross section of the specimen did not change and the deformation was predominantly volumetric. Without lateral constraint, the dilation increased with continuing deformation and was predominantly deviatoric.

Figure 2. Spruce wood specimen before the crush test (lhs). Specimen loaded parallel to the fiber crushed with (middle) and without lateral constraint (rhs).

Figure 3 (lhs) shows the force-displacement curve for load parallel to the fiber. When laterally constrained, it starts linear elastic until the compression strength is reached. Thereafter softening occurs, which is limited due to the lateral constraint. The force remains approximately constant with continuing deformation (plateau region). Hardening takes place when the cells are all fully collapsed. Considerable lateral forces occurred. Thus, lateral constraint results in a multiaxial stress state in the specimen. Without lateral constraint, the elastic behavior and the crush strength are of similar behavior. The buckling of fiber strands leads to distinctive softening. The force level in the plateau region remains on a low level and hardening was not observed. The force-displacement curve for load perpendicular to the fiber is shown in Figure 3 (rhs). For laterally constrained specimens, the beginning is linear-elastic and the transition to the plastic region is smooth. The plateau region with constant force level follows. The force level is much lower than for load parallel to the fiber. Hardening takes place eventually. Again, the lateral constraint results in a multiaxial stress state in the specimen. Without lateral constraint, the force is generally lower and the hardening effect is less significant.

Strain rate and temperature raise and respectively lower the force level. Those effects were published in [4, 5] and shall not be discussed in detail here.

In summary, the crush characteristics of wood are complex. Without lateral constraint, the force level is comparably low and the material expands laterally (predominantly deviatoric deformation). Lateral constraint results in significantly higher forces, more distinct hardening/ less distinct softening and multiaxial stress states. The deformation is predominantly volumetric.

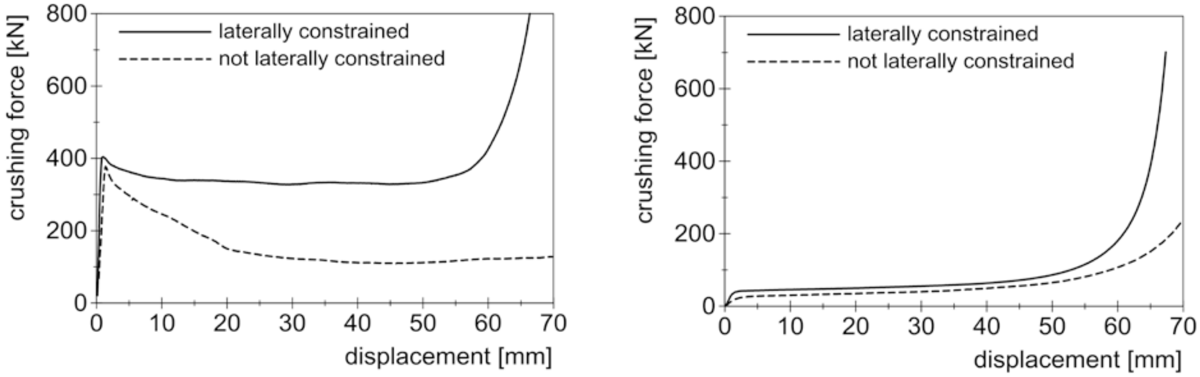

Figure 3. Force versus displacement of spruce wood loaded parallel (lhs) and perpendicular (rhs) to the fiber at ambient temperature and quasi-static strain rate.

TRANSVERSELY ISOTROPIC MATERIAL MODEL FOR WOOD CRUSH (tiM)

Research in technical literature revealed that the development of a new wood material model is necessary, since none of the investigated models is able to consider the effect of multiaxial stress (or respectively, lateral constraint) on the crush characteristics as seen in the experiments. The literature research also indicated that a continuum mechanical approach would be appropriate to model the crush of wood, although macroscopic damage effects occur.

The following assumptions were made to reduce the complexity of the problem:

- Wood is considered as a transversely isotropic continuum material.
- The material model focuses on the representation of the crushing behavior.
- The stress state in specimens crushed without lateral constraint is assumed to be uniaxial.

An elastoplastic and transversely isotropic material model for the crush of wood (tiM) was developed and implemented as a user material model in the explicit FE-Code LS-DYNA [9, 10]. The model contains a multi-surface yield criterion and a non-associated flow rule. A linear interpolation between uniaxial and multiaxial stress states in the compression region was done. For tension and shear, the stresses are assumed to be independent. Figure 4 shows the yield surfaces in the compression and tension region. The evolution of the yield surfaces depends on the deviatoric as well as volumetric strain. This was shown prior to enable a good representation of the different material characteristics when loaded with uniaxial and multiaxial compression. The non-associated flow rule permits plastic straining of the material as experienced in the crush tests. Plastic Poisson's ratios can be specified by the user. Input parameters for the material model were derived using the results of the crush tests.

The crush tests were recalculated using the new wood material model tiM. The tiM model is able to reproduce the basic strength characteristics of spruce wood. It can also reproduce the effect of lateral constraint due to consideration of deviatoric and volumetric strain in the yield surface evolution. On the other hand, the model overestimates the material strength for load under acute angles. To improve that, shear stresses would have to be considered in the definition of the compression yield surfaces. The tiM model can generally reproduce the effects of strain rate and temperature. However, the input scaling factors should be optimized since there are still some discrepancies.

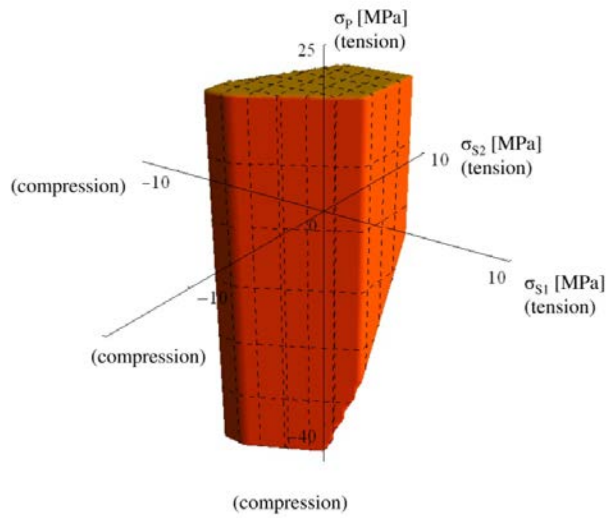

Figure 4. Tension and compression yield surfaces of the transversely isotropic wood material model tiM.

FE DROP TEST CALCULATION (TEST PACKAGE IMPACT LIMITER)

In September 2010, BAM performed a 9.3 m horizontal drop test onto an unyielding target with an 18,000 kg test package of the Gesellschaft für Nuklear-Service mbH (GNS), see Völzer et al. [11]. The impact limiters of the test package consisted of welded steel sheet capsules filled with spruce wood in its compartments. Table I shows the approximate dimensions and masses of the test package. Details regarding the BAM drop test facility can be found in [12, 13].

TABLE I. Approximate dimensions and masses of the GNS test package.

cask length	2,900 mm	total length	3,600 mm
impact limiter length	700 mm		
cask diameter	1,200 mm		
impact limiter diameter	1,700 mm		
cask mass (including lids)	11,400 kg	total mass	18,400 kg
content mass	4,100 kg		
impact limiter mass (both)	2,900 kg		

Description of the FE Model

A dynamic FE model of the test package was created using LS-DYNA [9, 14] to be able to rate the performance of the new wood material model tiM. The FE model is pictured in Figure 5 and has the following attributes:

- The geometry was represented as a half model.
- The meshing was generally done with hexahedron elements with reduced integration. An exception is the steel sheet of the impact limiter which was meshed with four-node

shell elements. The mesh is coarse in general, since no stress analysis of the package components shall be done. The mesh is refined in the regions of the impact limiters where large stress gradients were expected.

- The tiM wood material model was used for the wood inlays of the impact limiter. The von-Mises-plasticity model MAT_024 with a multi-linear flow curve according to Neumann [2] was used for the steel sheet. The remaining steel components were assumed to be linear-elastic (MAT_001). The content, a granulate material, was modeled using MAT_063 with flow curves based on Huang et al. [15]. The target was modeled as a rigidwall.
- Contact surfaces were considered using the contact type "automatic surface to surface". Welding seams and bolted connections were simplified using tied contact. Boundary conditions were applied to the symmetry plane and the rigidwall. The impact velocity of 13.5 m/s was applied to all nodes of the package.

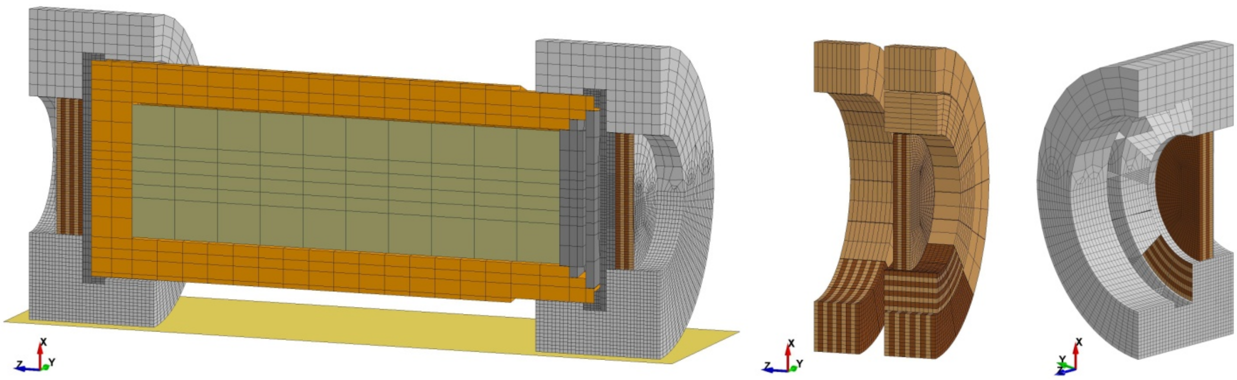

Figure 5. FE model of the GNS test package with wood filled impact limiters.

FE Simulation Results

Figure 6 (lhs) shows the deformed package model at the time of maximum impact limiter deformation. The stress component in the vertical direction is also displayed. The steel sheets are not displayed to be able to see the wood inlays. The stress distribution of the wood in the impact zone has a strap-like pattern because the wood layers are oriented parallel and perpendicular to the drop direction in turn. The maximum wood stress occurs in layers that are oriented with the fiber parallel to the drop direction. The stress is comparably lower in the layers with the fiber perpendicular to the drop direction due to the lower strength level. Some energy dissipation occurs also in the outer wood regions that are not overlapped by the cask body. The stress distribution in the wood is generally plausible.

The impact limiter's deformation is also plausible: high compression takes place in the regions overlapped by the cask body. Because of the buckling of outer steel sheet, the wood can strain laterally. Figure 6 (rhs) compares the impact limiter's deformation of experiment and simulation. Apart from different local buckling effects of the steel sheet, the deformation is similar. The maximum impact limiter deformation in the FE model is underrated by 13.1 % (lid side) and overrated by 4.1 % (bottom side).

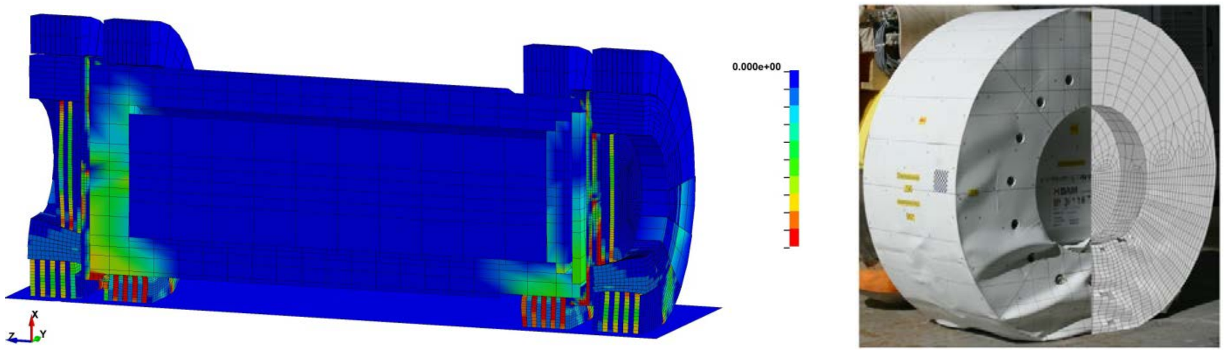

Figure 6. Stress component in the x-direction (lhs) at maximum impact limiter deformation and impact limiter deformation after the drop test (rhs). The axes are not labeled due to confidentiality issues.

The deceleration versus time is shown in Figure 7 (lhs) for an accelerometer which was placed at the lid side. The experimental curve starts with a high slope when the cask body hits the impact limiter. The stiffness of the impact limiter and the deceleration decrease when the wood undergoes plastic deformation and buckling of steel sheet takes place. The contact surface of impact limiter and target increases with continuing deformation, as does the deceleration. When the potential energy is dissipated, the deceleration decreases eventually. The simulation overestimates the initial slope of deceleration. However, it overestimates the following deceleration peak (maximum deceleration) only slightly by 1.6 %. The simulation does not reproduce the subsequent decrease of deceleration and overestimates the deceleration during the remaining time. The total impact time of the simulation is underestimated therefore.

The calculated kinetic, internal, hourglass and total energies are shown in Figure 7 (rhs). The kinetic energy decreases nearly linearly with time. That conforms to the approximately constant progress of deceleration. The internal energy increases nearly linearly with time, according to the conversion of kinetic energy. However, the internal energy does not reach the amount of initial kinetic energy, mainly due to friction losses. The total energy is slightly increasing due to hourglass stabilization.

The underestimated deformation and the overestimated deceleration indicate that the impact limiter's stiffness during plastic deformation is overrated. Numerical sensitivity studies have to be carried out in the near future to determine the exact reasons. They should comprehend further investigations regarding steel sheet modeling and friction coefficients. The modeling of the content showed to have a rather large influence too. However, the wood material model tiM produced feasible and numerically stable results.

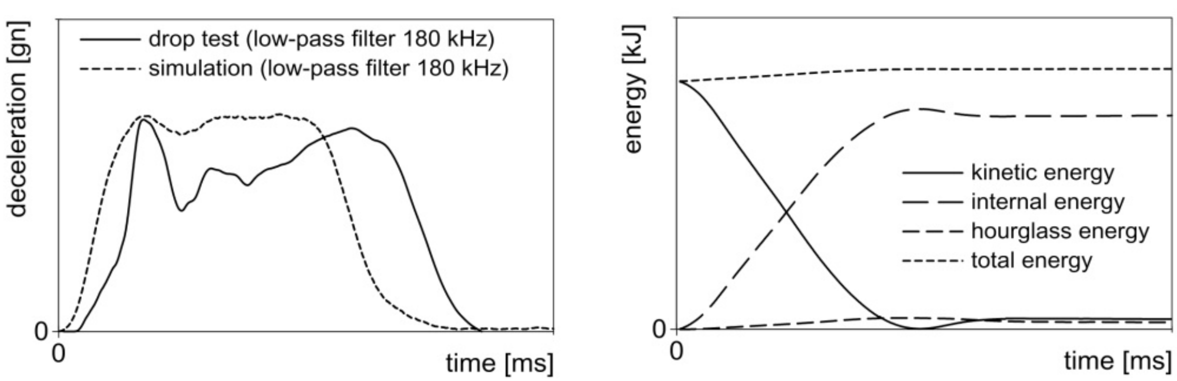

Figure 7. Package deceleration in the drop test and the FE calculation (lhs) and calculated energies (rhs). The axes are not labeled due to confidentiality issues.

CONCLUSIONS AND PROSPECTS

The new material model tiM for the crush of wood for application in RAM package safety cases was developed. A strategy was derived and followed step-by-step.

The tiM material model is based on the findings of a series of crush tests with spruce wood specimens. In particular, the effect of lateral constraint affects the strength characteristics as well as the material's deformation significantly. The tiM material model is transversely isotropic and contains a multi-surface yield criterion whose evolution depends on volumetric and deviatoric strain. The model was able to recalculate the crush tests with spruce wood specimens appropriately except for acute fiber-load angles and dynamic scaling factors that need to be optimized.

The drop test calculation with a test package confirmed that the wood material model tiM can basically be used for the modeling of wood filled impact limiters. The material model showed to be numerically stable and produced plausible results. However, the quantitative drop test results are not yet sufficiently reliable. Further analysis is necessary, considering steel sheet modeling and friction coefficients amongst others.

The numerical and experimental investigations shall be carried out in the future to be able to perform a comprehensive verification of the material model itself as well as component models. The model shall enable a detailed stress analysis of RAM packages and also non-regulatory investigations as e. g. shown by Droste [16].

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