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CRUSHING CHARACTERISTICS OF SPRUCE WOOD USED IN IMPACT LIMITERS OF TYPE B PACKAGES

Germar Eisenacher **Robert Scheidemann**

Martin Neumann **Frank Wille** **Bernhard Droste**

BAM Federal Institute for Materials Research and Testing, Berlin, Germany

ABSTRACT

The material spruce wood is frequently used in impact limiters of Type B transport packages. In order to develop and parametrize an appropriate finite element material model, the crushing characteristics of spruce wood have been determined. A large number of crush tests was performed at BAM test facilities to generate a comprehensive data base. The parameter range in the crush test series results amongst others from the IAEA Regulations for the Safe Transport of Radioactive Material: e. g., the minimum temperature considered was -40 °C and the maximum strain rate applied was derived from the 9 m drop test. Cubical spruce wood specimens were tested using a servo hydraulic impact testing machine for initial strain rates of up to 30 1/s. A machine for guided drop tests was used for initial strain rates of up to 133 1/s. Drop masses of up to 1,200 kg were therefore used from drop heights of up to 9 m.

The results presented in the paper include force-displacement characteristics and deformation behavior of spruce wood. Thereby the effects of strain rate, temperature, fiber-load orientation and lateral constraint are considered. Higher strain rates led to increasing crush forces, especially for loading perpendicular to the fiber. Higher temperature resulted in decreasing crush forces. The crush force level was significantly lower for load perpendicular to the fiber and the crushing characteristics differed compared to load parallel to the fiber. Without lateral constraint, the specimens expanded laterally, i. e. the plastic Poisson's ratio (if wood is considered a continuum) was not zero. Crush forces were comparably low and for load parallel to the fiber there was a significant softening effect. Lateral constraint of the specimens increased the crush force level and limited the softening effect.

The results of the crush tests are used to derive modeling requirements and some assumptions for the development of a finite element material model for spruce wood. Possible future research work is pointed out.

1 INTRODUCTION

Packages for the transport of radioactive material (RAM) like burned fuel rods or high active waste have – amongst others – to endure a 9-m drop test onto an unyielding target, see the International Atomic Energy Agency (IAEA) regulations SSR-6 [1]. Most packages are protected by impact limiters to absorb the impact energy and thus reduce loads on the package. In Germany, a common impact limiter design is a welded steel sheet structure that is filled with wood. Wood is thereby the main energy absorber, while the steel sheets provide integrity. They also limit the lateral dilation of the wood.

Safety cases of RAM transport packages often include numerical modeling. A reliable database and an extensive understanding of the material's characteristics are necessary to model the material wood appropriately for application in safety cases.

1.1 The material wood

Wood consists mainly of lignin and cellulose, which are the materials of the cell walls. The cell walls build the tracheid cells (fibers), which are in the case of softwood about 2.5 mm to 7.0 mm in longitudinal and 0.017 mm to 0.080 mm in lateral dimension. The tracheids are arranged circular to the trunk, with their orientation in the direction of growth. Latewood cells, which grow in the cold season and are rather small in lateral dimension, and earlywood cells, which grow in the warm season, alternate in radial direction and build the year ring structure. Thus, wood is an inhomogeneous, anisotropic and cellular material. Its mechanical characteristics are affected by its structural characteristics. Wood is often considered an orthotropic material with the parallel, radial and tangential directions for calculation purposes. More simplified, wood can be considered transverse isotropic with the parallel and perpendicular directions. For a more detailed description of the structure of wood, see [2, 3].

The mechanical characteristics of wood are broadly discussed in literature. The elastomechanical and strength properties are described in e. g. [2, 4-6]. For this paper, the crushing characteristics at large deformations are of interest. Amongst others, the following investigations exist. The microstructural compressive mechanisms of wood were extensively discussed in [7]. Uniaxial compression characteristics with the focus on kinking mechanisms were discussed in [8]. Redwood specimens with lateral constraint were tested in [9], where also lateral forces were discussed. The actual effect of lateral restraint compared to uniaxial testing was described in [10], where steel sheet capsule spruce wood specimens were crushed. However, an extensive database for spruce wood, that includes data regarding the effects of temperature, strain rate, lateral constraint and fiber orientation, does not exist.

Literature provides also Finite Element (FE) modeling approaches for wood, see [11]. Most of the models cannot account for large crush deformations as needed for this paper. Some material models do on the other hand, see e. g. [12-16].

1.2 Work scope

The scope of this paper is to provide details of the crushing characteristics of spruce wood. The effects of strain rate, temperature, lateral constraint and fiber orientation shall be investigated. Therefore, the main results of an extensive test series shall be shown. Force-deflection curves as well as the deformation behavior shall be discussed. Conclusions shall be drawn regarding modeling techniques.

2 EXPERIMENTAL INVESTIGATIONS

A comprehensive database to understand and quantify the crush behavior of spruce would was conducted. In course of a research project, about 600 crush tests with spruce wood specimens were performed. In the following, details regarding the specimens, the test facilities, test conduction and evaluation of the results will be discussed.

2.1 Specimens

The specimens were of cubical shape with an edge length of 100 mm. The moisture content, density and size and number of knots underlay tight limits to minimize statistical variations in the experiments. To reduce a change of the moisture content, the specimens were packed in plastic sheets. The specifications are shown in Table 1.

Table 1. Specifications of the spruce wood specimens

attribute	value
bulk density	$0.45^{+.03}_{-.03} \frac{g}{cm^3}$
moisture content	12^{+3}_{-2} %
number and size of knotholes	based upon DIN 4074-1 [17] sorting category S13
dimension (edge length)	$100^{+.8}_{-.8}$ *mm*

2.2 Test setup

Two test facilities were used to perform the crush tests. Figure 1, lhs, shows the servo hydraulic impact testing machine which was used for displacement-controlled crush tests with constant loading speed (maximum 4,500 mm/s). The test force (maximum 1,000 kN) is applied via hydraulic pressure. Figure 1, rhs, shows the machine for guided drop tests. It was used for energy controlled crush tests with variable loading speed and also higher initial loading speed compared to the hydraulic impact facility. The test force is applied via a mass (maximum 1,200 kg) that is dropped of a defined height (maximum 12 m).

Figure 1. Servo hydraulic impact testing machine for constant loading speed (displacement controlled) of up to 4,500 mm/s and test forces of up to 1,000 kN (lhs). Machine for guided drop tests for variable loading speed (energy controlled); maximum drop height 12 m, maximum drop mass 1,200 kg

The test setup was approximately the same for both test facilities, see Figure 2. The test load was applied to a steel crush tool which was positioned onto the specimen. The specimen itself was either positioned onto a steel base plate (crush test without lateral constraint) or was put inside a massive constraining device (crush test with total lateral constraint). A load cell was positioned below the base plate and respectively, the constraining device. A laser triangulation system measured the displacement of the crush tool. Strain gauges were applied to the crush tool as well as the constraining device. Thus force measurement was possible in loading direction (via both load cell and crush tool) and in lateral direction (via the constraining device).

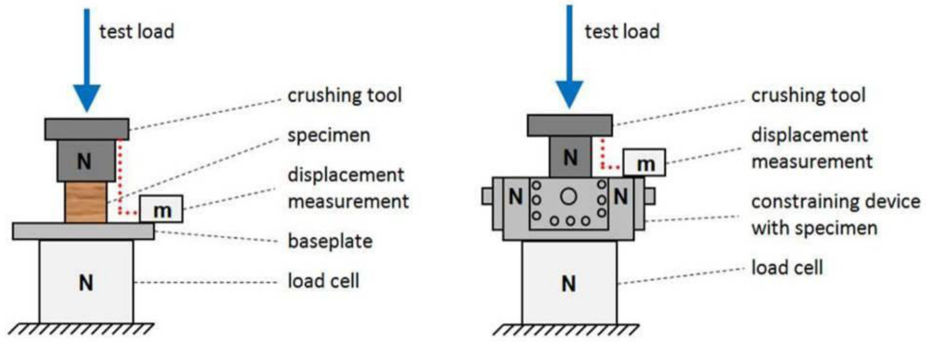

Figure 2. Setup of the crush tests without lateral constraint (lhs) and with lateral constraint (rhs). Force measurement denoted as “N”, displacement measurement denoted as “m”

2.3 Test conduction

Prior to a crush test, the specimen was unpacked and its mass, moisture content and dimensions were measured and documented. The specimen was then treated with lubricant to minimize friction effects. It was placed onto the base plate or into the constraining device respectively and the crush tool was put on it. Following the crush process was started while recording the signal data with a frequency of up to 1,000 kHz. After the crush test, the dimensions of the crushed specimen were measured.

2.4 Test program

The test program was designed to account for the boundary conditions in an impact limiter. Thus it was important that the crush tests are comparable to an impact limiter regarding the following criteria:

– *Temperature*: IAEA defines the minimum operating temperature of transport casks as -40 °C. The maximum temperature to be considered in an impact limiter results from the thermal power of the package content. It usually is about 90 °C. According to this, the crush tests should include temperatures of -40 °C and 90 °C.

– *Strain rate*: The maximum strain rate in an impact limiter usually results from the 9-m drop test. In common impact limiter constructions, this drop height results in (global) maximum strain rates in the wood of about 50 1/s. This maximum strain rate should be covered in the crush test series.

– *Maximum strain*: The 9-m drop test results in local compression strains of up to 70 % (engineering strain). This maximum compression strain should be considered in the crush test series.

- *Fiber-load orientation*: Depending on the construction and the drop position, different fiber-load orientations occur in an impact limiter. Often, so-called layered wood is used in an impact limiter, which consists of layers of alternating fiber orientations (50 % parallel to the fiber, 50 %perpendicular to the fiber). The crush tests series should consider the fiber-load orientation, concentrating on load parallel and perpendicular to the fiber (wood as a transverse isotropic material). For validation purposes, layered wood should be investigated as well.
- *Lateral constraint*: In an impact limiter, the lateral dilation of the wood is restrained by steel sheets. Since the steel sheets buckle during the impact process and the lateral restraint varies. The crush test series should consider the effects of such a lateral restraint. The crush test series should consider the two cases of "no lateral constraint" and "total lateral constraint".

The parameter sets of the resulting crush test program are shown in Table 2. A number of ten specimens for each configuration was tested. Thus a total of 595 valid crush tests was conducted. The target crush displacement was 70 mm, so the specimen's height reduces from 100 mm to 30 mm.

Table 2. Test program

test facility	load orientation to the fiber	temperature [°C]	loading speed/ drop height [mm/s]/ [mm]	lateral constraint
hydraulic impact facility	parallel	-40, 20, 90	0.02, 0.5, 10, 200, 3000	no constraint, full constraint
	perpendicular	-40, 20, 90	0.02, 0.5, 10, 200, 3000	no constraint, full constraint
	layered wood	-40, 20, 90	0.02, 0.5, 10, 200, 3000	no constraint, full constraint
	15 ° to 75 °	20	0.02	full constraint
facility for guided drop tests	parallel	-40, 20, 90	3000, 9000	full constraint
	perpendicular	-40, 20, 90	3000, 9000	full constraint
	layered wood	-40, 20, 90	3000, 9000	full constraint

3 TEST RESULTS AND DISCUSSION

The results of the crush tests will be shown using mainly force-displacement diagrams. The data recorded at the crush tests were therefore evaluated as follows:

1. Offset of force and displacement signals
2. Noise smoothing of the force and displacement signals
3. Mapping of the force-displacement relation onto a virtual displacement signal
4. Statistical evaluation of the each ten single force signals per configuration (mapped signals)

This procedure enables to compare the single force-displacement curves within each test configuration and also the mean force-displacement curves within the entire test program.

The deformation behavior will be discussed based on the observations made during the crush tests, since there was no measurement system for detailed data recording.

3.1 Deformation behavior

The deformation behavior of spruce experienced in the crush tests is pictured in Figure 3.

Crushed parallel to the fiber and with lateral constraint, the cross section of the specimen did not change. Kink bands (see [8]) developed with orientation perpendicular to the load, where deformation localized. Without lateral constraint, at first one kink band developed and the cross section did only change little. Eventually, fiber strands constantly buckled outwards (starting at the kink band) and re-orientated with continuing deformation. The cross section grew, though now containing gaps. Since the location of the kink band differed in each specimen, the deformation pattern differed as well. Unloading the specimens resulted in an elastic recovery of approximately 10 mm (specimen's height before crush test 100 mm, after crush test 30 mm, after unloading 40 mm).

For load perpendicular to the fiber and with lateral constraint, the cross section was constant. There were no visible damages of the structure. Without lateral constraint, there was only little lateral dilation at first. Dilation grew with continuing deformation, though in only one lateral direction. At high deformation, the lateral dilation was higher and also cracks developed. Unloading the specimens resulted in an elastic recovery of approximately 20 mm (specimen's height before crush test 100 mm, after crush test 30 mm, after unloading 50 mm).

Figure 3. Top: specimens before crush test with load parallel to the fiber (lhs), crushed with lateral constraint (middle), crushed without lateral constraint (rhs). Bottom: crush test with load perpendicular to the fiber, accordingly

3.2 Crushing characteristics

Figure 4 shows the crushing characteristics for load parallel to the fiber. The force-displacement curve starts linear elastic up to the compression strength. Thereafter the kink band development results in a softening. The softening is limited and the force remains approximately constant with continuing deformation (plateau region) due to the lateral support via the constraining device. Eventually hardening takes place for the cells are all fully collapsed and cell wall material is compressed only. An increasing loading velocity results in higher crush strength and also a higher plateau. Figure 7 shows that the plateau is raised by approximately the factor 1.3 to 1.4 if loading speed increases to 3000 mm/s. Crush via a 9-m mass drop raises the plateau by approximately 1.5 to 1.8. Without lateral constraint, elastic behavior and crush strength is similar. The unrestricted buckling of fiber strands results in a distinctive softening and the remaining force level remains on a comparably low level. Apart from the crush strength, a higher loading speed has apparently no major effect.

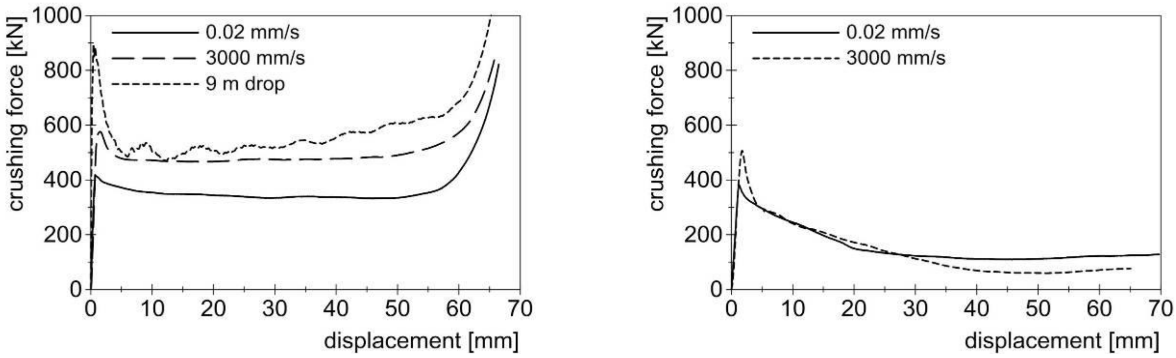

Figure 4. Crushing characteristics for load parallel to the fiber and different strain rates. Crush test with lateral constraint (lhs) and without lateral constraint (rhs), 20 °C

The crushing characteristics for load perpendicular to the fiber are shown in Figure 5. It starts linear-elastic with a continuous transition to the plastic region. Following is a constant force level (plateau region), that is much lower compared to load parallel to the fiber. Hardening takes place when all cells are closed. Naturally the hardening forces are comparable to load parallel to the fiber. As before, higher loading velocities result in higher plateau forces (3000 mm/s: about factor 1.6 to 1.7; 9-m drop: about factor 2.5). Without lateral constraint, the force plateau is lower and a higher loading velocity doesn't raise it considerably.

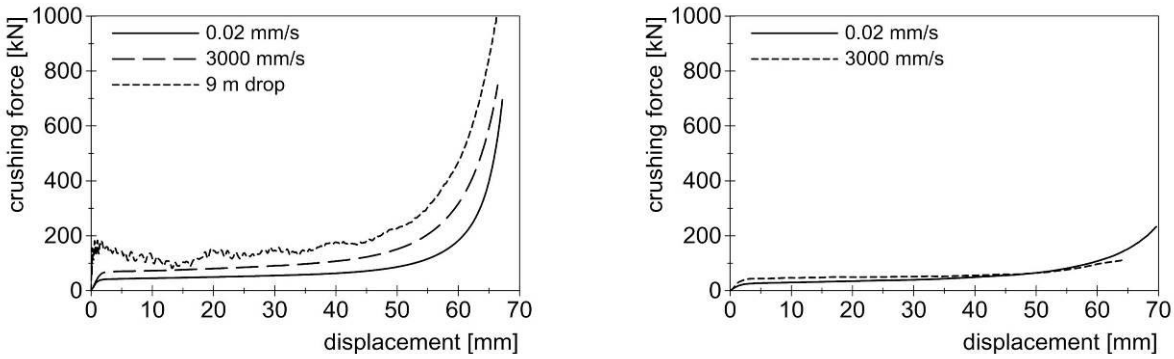

Figure 5. Crushing characteristics for load perpendicular to the fiber and different strain rates. Crush test with lateral constraint (lhs) and without lateral constraint (rhs), 20 °C

Figure 6 demonstrates the effect of the specimen's temperature. Loaded parallel to the fiber at -40 °C, there is no softening effect anymore and the force plateau is raised of about the factor 1.25 to 1.5 (Figure 7). Raising the specimen's temperature to 90 °C results in a lower plateau (factor 0.6 to 0.8). The force level increases with continuing deformation because the specimen cools down during the crush test. Loaded perpendicular to the fiber, the plateau forces increase by the factor 1.25 to 1.75 at a temperature of -40 °C. The factor is about 0.75 at a temperature of 90 °C.

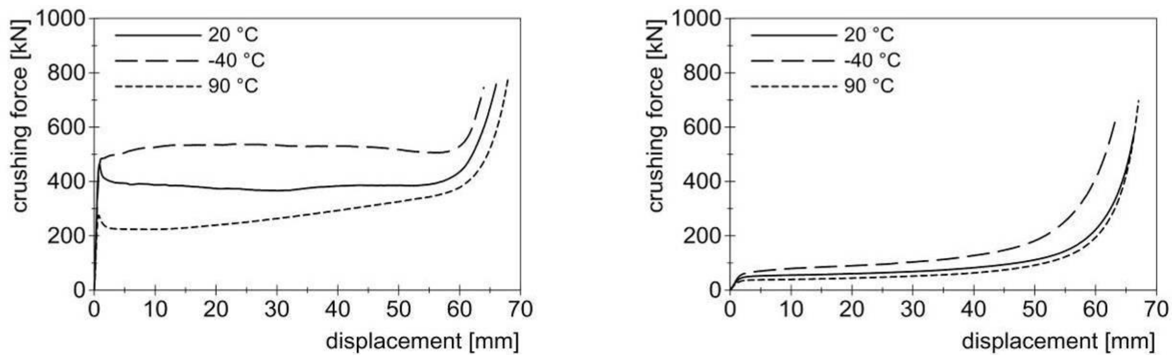

Figure 6. Effect of temperature on the crushing characteristics. Load parallel (lhs) and perpendicular to the fiber (rhs), quasi-static loading velocity, lateral constraint

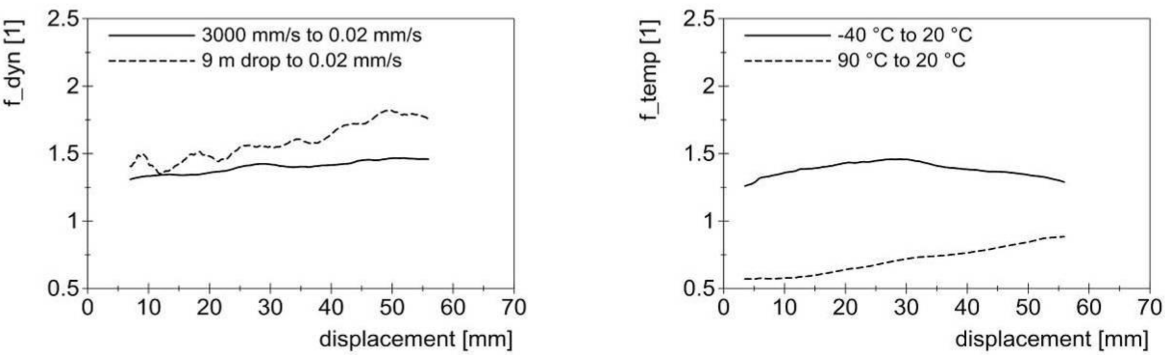

Figure 7. Factors f_dyn and f_temp, demonstrating the increasing or decreasing force plateau compared to the standard configuration (quasi-static loading, room temperature). Load parallel to the fiber, lateral constraint

3.3 Conclusion and prospects

A series of about 600 crush tests with spruce wood specimens was conducted to create an adequate database for FE modeling of wood filled impact limiters. The deformation behavior of the specimens was discussed. The effects of fiber orientation, lateral constraint, loading velocity and temperature were considered to account for the boundary conditions of an impact limiter. The results are summarized and conclusions for FE modeling are drawn in the following.

The deformation behavior of specimens with lateral constraint is rather simple. The cells collapse and eventually cell volumes get closed. In a macroscopic view the crushed wood is still a continuum. The deformation behavior is complex without lateral constraint. When loaded parallel to the fiber, the lateral dilation develops from less to more, gaps develop where fiber strands buckled and in any event, no specimen has the same deformation pattern. Loaded perpendicular to the fiber there is dilation in only one lateral direction which also gets more intense with continuing deformation. One can draw two conclusions for modeling: First, it seems almost impossible to be able to put the complex and not even defined deformation behavior in a mathematical pattern. Thus a continuum approach may be appropriate, neglecting local damage effects like gaps, the local buckling spots or reorientation of fibers. Second, the lateral dilation of a specimen is not constant. Thus it seems appropriate to use plastic Poisson’s ratios that can be defined as a function of e. g. the compressive strain.

The fiber orientation changes the crushing characteristics significantly. The force level as well as the softening due to kink band development differs greatly between load parallel and perpendicular to the fiber. A transverse isotropic modeling approach that considers these two directions is therefore very important.

Lateral constraint has also a great effect on the crushing characteristics. Without lateral constraint, the force level is comparably low and the hardening effect is lacking. The softening effect for load parallel to the fiber is much more distinctive. The effect of lateral constraint is equivalent to the effect of a multiaxial stress state, since lateral constraint induces a multiaxial stress state in the wood. A material model has to consider that multiaxial stress states change the crushing characteristics.

An increase in loading velocity results in increasing force levels of the crushing characteristics. A material model should consider that. Since the effect is neglectable for specimens without lateral constraint (where deviatoric deformation is dominating), a dependency upon the volumetric strain rate seems appropriate.

The effect of temperature shows in increasing or decreasing force levels. This may be considered in a material model via scaling of the yield surface using factors depending on the compressive strain.

Future research work is necessary on both experimental and numerical fields. The experimental data regarding the material behavior may be sufficient for the selection and parametrization of a material model. However, to be able to model a component like an impact limiter, additional tests are necessary. One needs to have information about the interaction of wood layers with the steel casing or adjacent wood layers (e. g., friction coefficients). One also needs to validate component models and therefore needs component tests like drop tests with an impact limiter and a drop mass. A material model needs to be selected and parametrized on the numerical field. It needs to be validated using appropriate experimental data. Eventually, component models have to be built and verified as well.

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