Modeling the Energy Absorption Characteristics of Wood Crash Elements

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1 Abstract

Wood is a natural and highly anisotropic material. Therefore, mechanical characteristics of the material depend on the direction and type of the load (e.g. deformation behavior of wood is ductile in compression and brittle in tension). The mechanical behavior of crash elements made of wood material was investigated experimentally and numerically at quasi-static and dynamic strain rates for load-carrying and energy absorption characteristics. For detailed investigations on the mechanical properties of wood, specimens were modeled and **`*MAT_WOOD`** (**`*MAT_143`**) was selected in LS-DYNA. The process of parameter identification for the **`*MAT_143`** was clarified. In the scope of the experimental studies, quasi-static compression, tension and bending tests as well as dynamic drop tower tests were performed to characterize the material at low and medium strain rates, respectively. It was found that the investigated wood material is highly strain rate sensitive what can be captured by enhancing **`*MAT_143`** by strain rate dependent fracture energy parameters. All material model parameters used in numerical studies were validated according to the experimental results for the **`*MAT_143`**. Since wood is a natural composite material, it was modeled with 2D shell element formulation and analyzed with single element simulations by composite material models by referring to material parameters used in **`*MAT_143`**. The investigated material models are **`*MAT_54`**, **`*MAT_58`** and **`*MAT_261`**. The aim is to present a base study to enlighten the damage mechanism of wood for further investigations on the potential of wood-based structural automotive components.

2 Introduction

Lightweight structures, which are intelligently designed by considering the satisfying durability against the subjected load with less weight, have become more comprehensive and attractive in many fields of the scientific world with each passing day. It can be obviously noted that the one of the major driver sectors of the utilization of the lightweight materials is automotive industry. In the industry, there is no doubt that the composite materials in various form take the lead in different applications on the basis of their promising mechanical properties. Nevertheless, the cost of the manufacturing process is one of the big obstacles in spite of excellent material properties. On the other hand, the European Commission works on development of regularization policy for the environmental footprint of products and obliges each product must be properly produced in accord with the rules [1]. Therefore, wood-based materials, which are not merely lightweight structures but also natural fiber reinforced composites, have attracted the industry`s interest [2, 3].

Wood is a hierarchically structured biological material consisting of cellular structure. Due to its complex structure, it has anisotropic material properties at several different length scales [5, 6]. The macroscopic structure of wood can be described approximatively by a cylinder coordinate system with the growth direction. There are three principal directions; longitudinal direction (vertical direction in the growing tree), radial and tangential directions (transverse to growth ring in a horizontal plane) [7, 8]. As wood grows, growth rings occur around the growth axis like cylindrical shells and cause varieties in microstructures. These differences in microstructures result in density distribution in the growth ring. This feature causes wood, which is already anisotropic due to its growth direction, to become even more sophisticated to understand anisotropic behavior of wood deeply [9, 10]. In wood structures, wood fibres are predominant and they are multiphase composite materials. The cell wall layers of wood fibres consist of the primary wall, the outer layer of secondary wall, the middle layer of secondary wall and the inner layer of secondary wall. Moreover, the distribution of wood polymers across the cell wall is not uniform. Hence, orthotropic mechanical properties of wood introduces a strong geometric anisotropy [6, 10]. In addition to geometrical anisotropy, the amount of water in wood cell walls related to the environmental conditions, i.e. moisture content and temperature, has a significant effect on mechanical properties [11–

13]. All features mentioned above are for the in-depth understanding of the behavior mechanism of wood.
The findings on effective natural parameters, which may lead to distinctive mechanical properties, were mentioned above. As known one of the advantages of wood is superior load-carrying performance along with different application directions. Some of the application fields in the literature are roadside safety applications [14, 15], wood-based sandwich composite materials under impact loading [16], and shock absorbers filled with wooden blocks under drop weight loads [17]. It is also known that the sophisticated material failure model for complex cases is important for better estimation of progressive damage [16].
According to Murray's approach, theory behind the damage model of composite is implemented for wood [14], [18],[19]. To clarify, the plywood composite material subjected to different impact velocity by a projectile was investigated and failure model analyzed numerically. The importance of moisture content, damage of matrix cracking, delamination and fiber failure was clarified and the numerical model was successfully verified by wood material model [20]. Moreover, modeling wood by various composite material models is also corroborated and vice versa [4, 21, 22].
Damage modes of wood are mainly matrix deformation, fiber breakage, fiber delamination, fiber pull-out, and matrix cracking [23]. However, existing material model for wood allow using solid element definition only. As seen in Fig.1, deformed wood specimen needs to be investigated micromechanically to predict the deformation mode numerically due to the fronds from splaying of the material, wedge and delamination. Taking into account all of these, the modeling of wood as a composite material with shell elements in automotive structures is a new research area. Therefore, the current study aims to present a base study in accordance with this purpose.

a)

b)

Fig.1: Wood crushing element: a) non-damaged and b) damaged

3 Material and Testing

In this study, specimens made of European Beech were used. Layer by layer peeled material is combined with each other through the adhesive. This is a process with high material and energy efficiency and describes how sustainable raw materials are transformed into a new high-tech material. This creates greater freedom of design and thinner construction with considerable material savings in structural wood. The layered structure, which has a certain thickness, is shaped in the appropriate machine tool considering the desired dimension.
Specimens made of European Beech were produced due to good workability and mechanical properties. In addition, the specimen’s properties such as thickness, orientation and number of the layers were taken into account due to the fact that these properties result in varieties in the determination of strength and failure parameters. The uniaxial tensile test specimens with three different orientation configurations were used in the current study. The fiber direction 0° direction configuration and the direction transverse to the fiber is referred to as 90° direction configuration. In addition, shear tensile experiments were carried out with the specimen having fiber orientation of 45°/-45°. Shear stress, shear deformation and shear modulus are determined.
In order to investigate the compression test properties, the quasi-static crushing tests of the wood were carried out in universal test machine under constant crushing speed. The test specimen was made of two different orientation configurations, i.e. 0° and 90°. In compression experiments, wood specimens

were placed between cross-heads and the top rigid crushing head compressed the specimen along direction at a constant speed while the movement of the bottom rigid head was fully constrained.
Experimental studies continued with the investigations of dynamic properties. For this purpose, drop weight test setup was used with the same compression test specimen. The targets of the drop weight experiments are not only investigate the strain rate sensitivity of the wood and prediction of the approximate load carrying capacity of the wood structures. Drop weight test device was equipped with a tube holder for extra dropping weight, an impactor, a rigid bottom plate to place a specimen and data acquisition system.
In order to validate the material properties considering complex components consisting individual layers, 3-Point Bending test were carried out. The test setup is composed of a punch in the form of a cylinder with a constant speed and rotatable supports. Specimens consist of layers with different configurations were tested, i.e. 0°/0°, 90°/90°, 0°/90° and 45°/-45° configurations.
As consequences of experimental studies, the yield strength, elastic modulus, failure strain, Poisson's ratio and material deformation behavior were determined by means of the experiments carried out at quasi-static strain rates. It is also proven that load-carrying performance of wood material is quite impressive under dynamic loading. Thus, the importance of accurately determining the strain rate sensitivity of the material was observed in order to avoid underestimating the simulation results as the strain rate increases.

4 Modeling

The experiments conducted in the scope of the study were simulated by explicit nonlinear finite element code LS-DYNA.
The simulation studies started with the determination of the tensile properties for **`*MAT_143 (*MAT_WOOD)`**[24]. To simulate the clamping of the tensile specimen, boundary conditions at the element nodes within the boxes were defined. The only difference between 0° direction and 90° direction tensile test simulations is the alignment of the material axes due to the transverse isotropy. In order to determine the initial shear parameters, the tensile test in 45°direction was simulated. The special feature of this simulation in comparison to the previous simulations is that a specimen consists of differently oriented two layers. In this case, each layer was oriented as 45° and -45° with respect to the load axis. In the model, two separate parts were created for each layer with the same material card and the different material axis orientation.
After the determination of tensile properties, the compression test parameters were investigated. The numerical models of the static and dynamic compression tests include three main parts: moving rigid crushing top plate, specimen and fixed rigid bottom plate. In the model, the rigid crushing top plate was allowed to move only in-plane direction and was constrained for all rotations.
The simulation setup of the 3-point-bending consists of a rigid punch moving along the compression direction, specimen and two rigid cylindrical supports. Supports were allowed to rotate, however constrained to displacement. The specimen composed of four identical layers and layer orientations were defined as mentioned in tensile simulation in 45°direction. The contact between the specimen and the rigid parts was defined by surface to surface contact algorithm.
In the drop weight simulations, an initial velocity was defined to the moving top crashing head and drop weight mass in the experiments were applied to the top head. The contact between the specimen and the plates was defined by single surface contact algorithm. The static friction coefficient between the specimen and the plates were taken as 0.2. Viscous damping coefficient was defined as 20. In order to avoid unrealistic increasing the initial peak, the system stiffness was determined by a spring below the fixed support with a spring stiffness of 135 kN/mm. The upper area of the drop weight specimens, where it is crashed, is more finely meshed than the lower area. Constant fine meshing would significantly increase the simulation time. Further information about the visualization of test setups and numerical models can be found in results and discussion section together.
Following the material model verification studies were completed, single element simulations with composite material models were investigated at quasi-static strain rate. **`*MAT_54 (*MAT_ENHANCED_COMPOSITE_DAMAGE)`**, **`*MAT_58 (*MAT_LAMINATED_COMPOSITE_FABRIC)`** and **`*MAT_261 (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO)`** material models are implemented in the simulations [24]. Arrows in Figure 2 below indicate the direction of deformations.

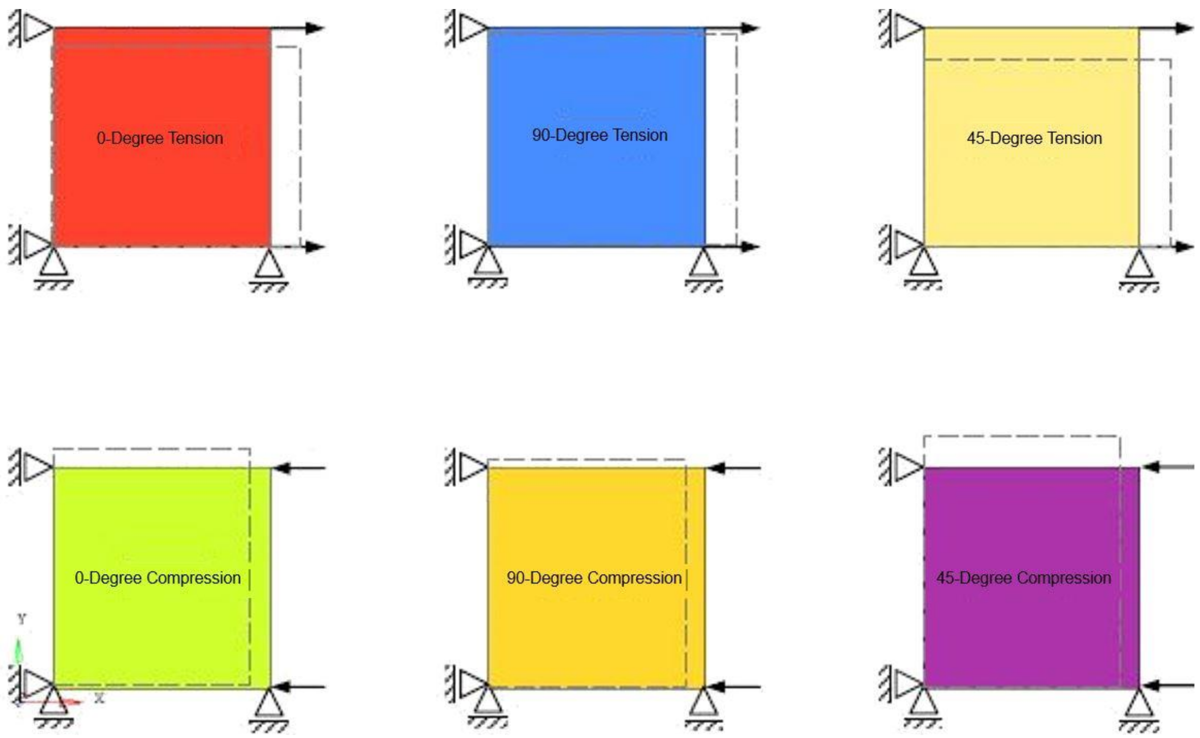
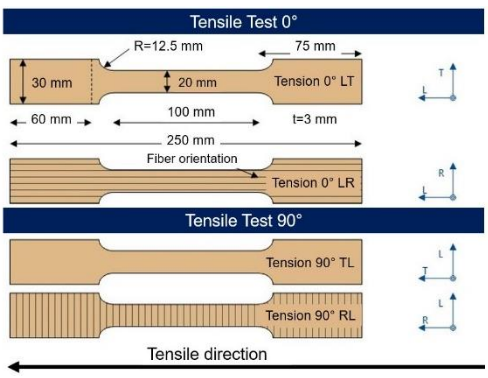


Fig.2: Single element simulations

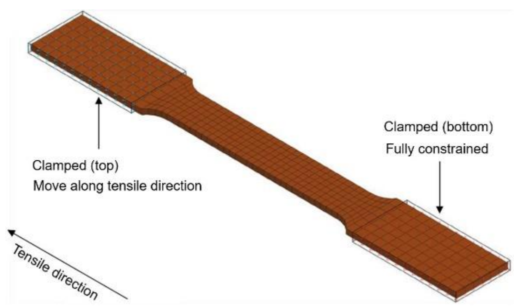
5 Results and Discussion

The study on material modeling of the wood initiates with the understanding of tensile properties of the specimens under quasi-static loadings. The uniaxial tensile test specimens used in this study can be seen in Figure 3a. As seen in the figure, the same direction with the fiber orientation is called 0° direction configuration, however; transverse direction to the fiber orientation is called as 90° direction configuration. In order to count orthotropic material behavior of the wood, experiments were performed on various cutting planes, i.e. LT and LR or TL and RL.
In simulation, the boxes were defined at element nodes for the definition of boundary conditions of the specimen, Figure 3b. In 90° direction tensile simulation, the same specimen is used, however material axes were aligned considering the transverse isotropy. The results of both experimental and numerical tensile tests in 0° and 90° directions can be seen in Figure 3c and Figure 3d, respectively. The grey curves represents experiments while the red one show simulation result.

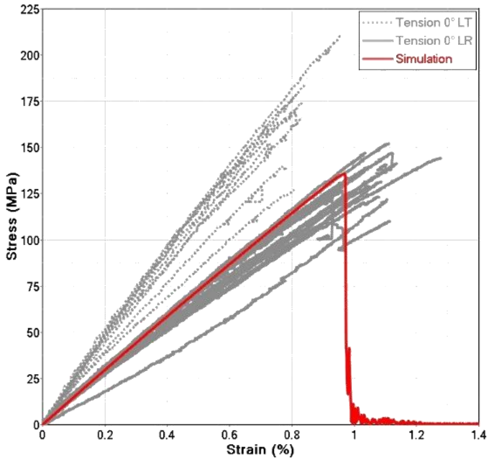
(a)



(b)



(c)



(d)

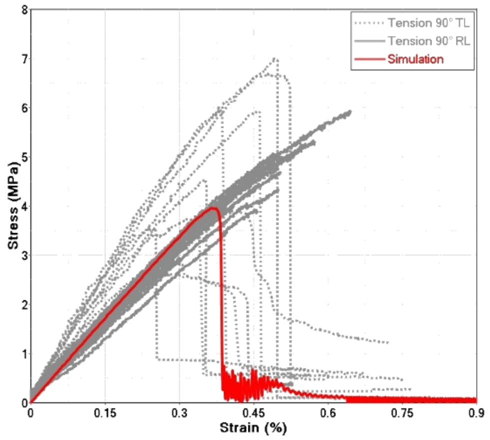
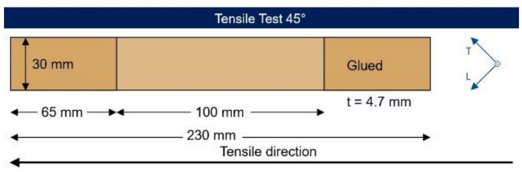


Fig.3: Tensile test specimens: a) experimental and b) numerical; Quasi-static tensile results: c) 0° and d) 90°

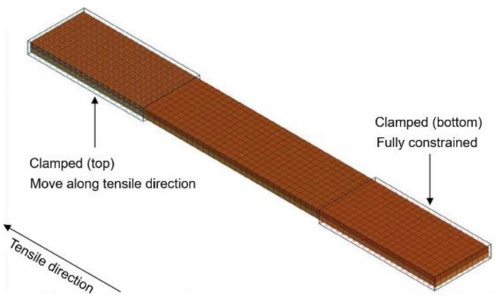
In addition to the determination of uniaxial tensile test properties, shear tensile experiments were carried out with the specimen having fiber orientation of 45°/-45°. Shear tensile test specimen is shown in Figure 4a and numerical model is in Figure 4b. The peculiarity of this simulation in comparison to the previous simulations is that here a specimen of differently oriented layers is modeled. In this case, the each layer was oriented as 45° and -45° with respect to the load axis. The comparison of the simulation result with respect to the experiments can be found in Figure 4c.

After the uniaxial tensile and shear properties were determined, the quasi-static compression properties of wood were investigated. The illustration of the experimental and numerical compression specimens are presented in Figure 5a and Figure 5b, respectively. Figure 5c and Figure 5d show the compressive stress-displacement curves of wood specimens in 0° and 90° directions at quasi-static strain rate by the grey curves, the red curves are simulation results. The numerical models of the static compression test includes three main parts. These are a moving crushing top plate, a specimen and a fixed bottom plate. Furthermore, the crushing top plate was allowed to move only in-plane direction and constrained for all rotations whereas the fixed bottom plate was constrained to move all directions. The displacement is the path of the crushing top part. As seen from the figures, strength values change in the range of approximately 65 MPa to 90 MPa in the 0° direction whereas this interval stays between about 30 MPa and 40 MPa in the 90° direction. The variety in the deformation behavior in the plastic range due to the direction dependency are also obvious in the related figures below.

(a)



(b)



(c)

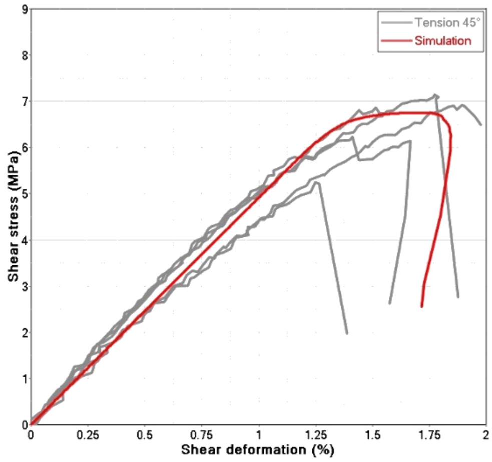


Fig.4: Shear tensile test specimen: a) experimental and c) numerical; c) quasi-static results

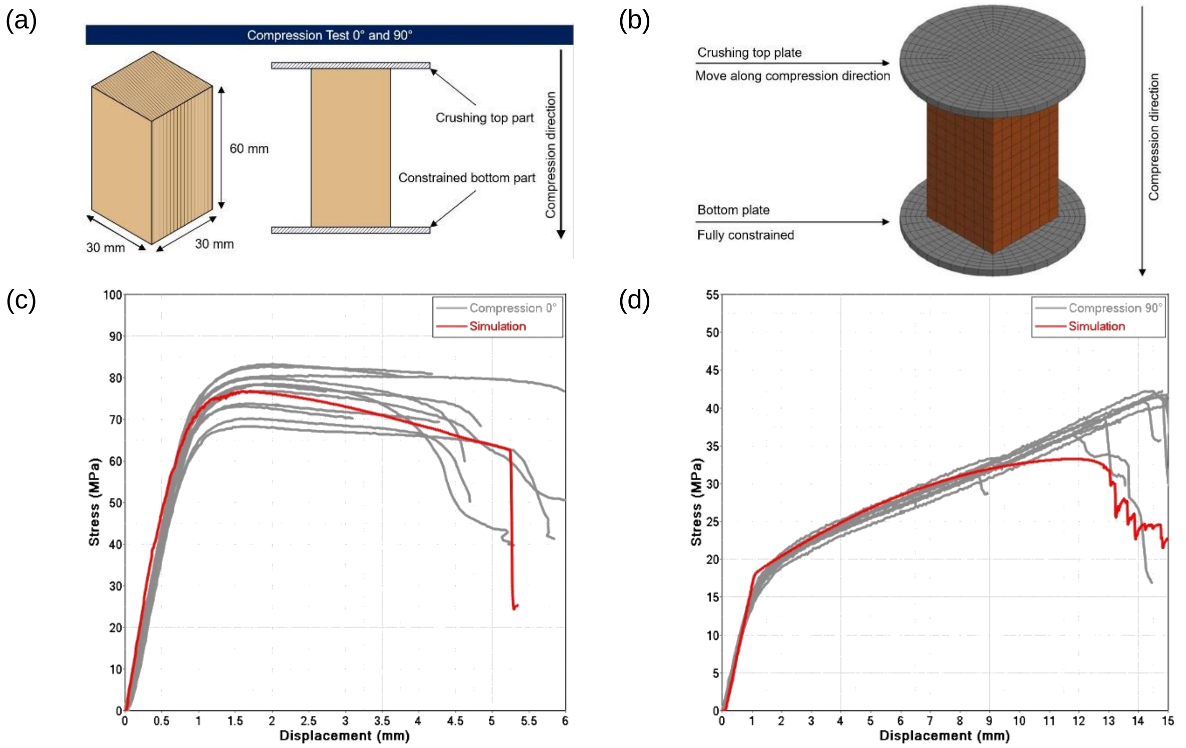
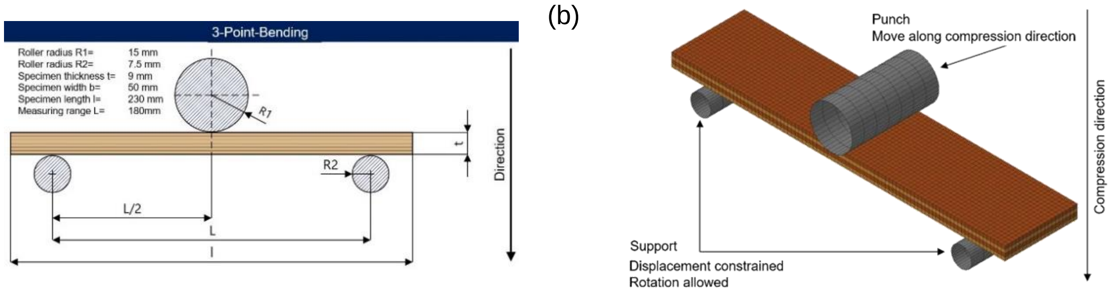


Fig.5: a) Compression test specimens: a) experimental and b) numerical; Quasi-static results: c) 0° and d) 90°

To validate the material properties considering the individual layers, 3-Point Bending tests were carried out. The test setup, the numerical model and specimen properties are given in Figure 6a, Figure 6b and Figure 6c respectively. The comparison of experimental and numerical results are given in Figure 7. Material properties were determined and validated corresponding to the quasi-static experiments. As seen, the 0°/0° configuration has the highest load carrying capacity with the force level of at least 1.5 kN when compared to the others. This value reduces to 1.25 kN for 0°/90° configuration and 0.1 kN for 90°/90° configuration. As seen in the results of 45°/-45° configuration, the material can carry about 0.6 kN force level and failure occurrence is located mostly between 15 mm and 25 mm of the deformation.

(a) (b)



(c)

Specimen	K1	K2	K3	K4
Angle α	10°	4°	7°	7°
Angle β	90°	90°	92°	93°
Diameter d	30 mm	45 mm	36 mm	36 mm
Top face	532,87 mm²	1333,43 mm²	980,33 mm²	980,33 mm²
Bottom face	3711,01 mm²	2827,43 mm²	2870,43 mm²	2568,90 mm²
Number of tests	2	2	1	1

Fig.6: 3-Point-Bending test setup: a) experimental and b)numerical; c) specimen properties

(a) (b) (c) (d)

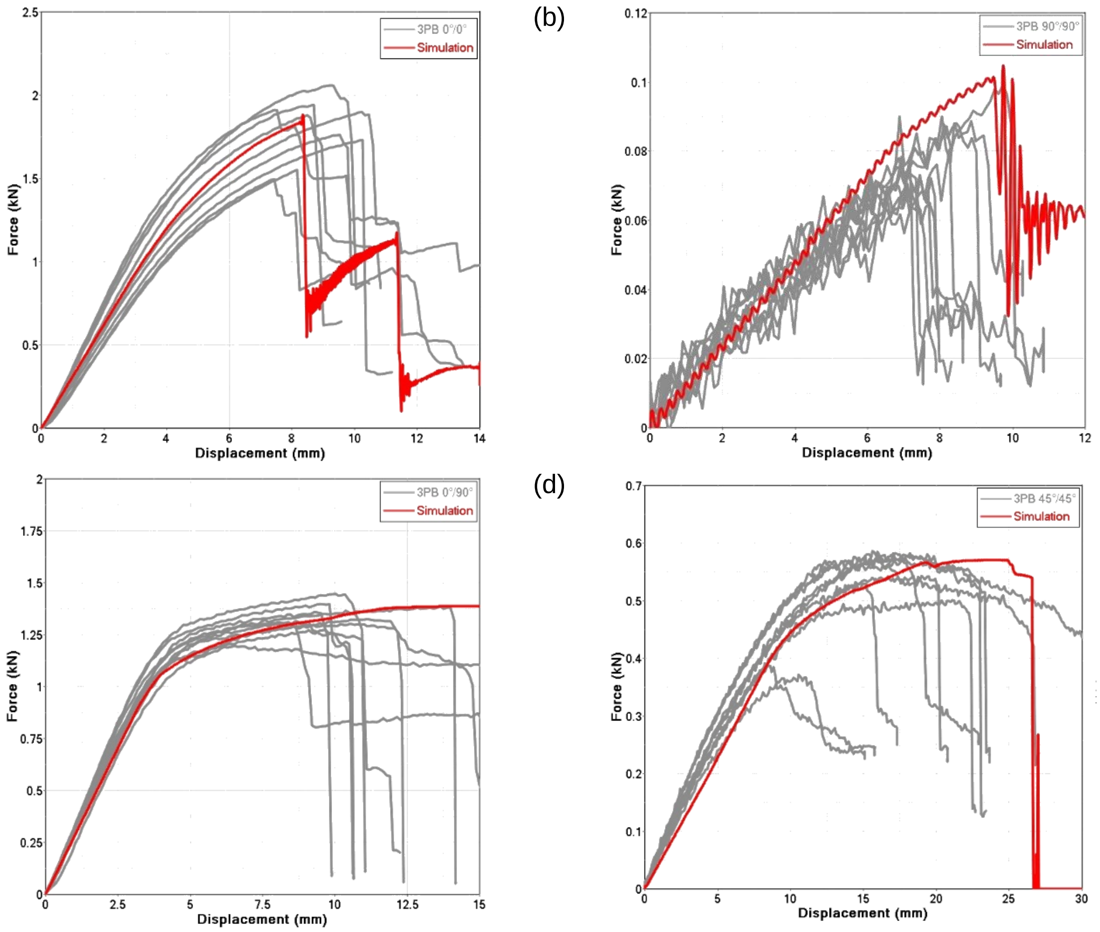


Fig.7: 3-Point-Bending test results: a) 0°/0°, b) 90°/90°, c) 0°/90° and d) 45°/-45°

As previously mentioned, wood is a highly strain rate sensitive material. The targets of the drop weight experiments are to investigate the strain rate sensitivity of wood. Therefore, dynamic behavior under drop weight can be predicted by scaling the fracture energy parameter in `*MAT_143` with respect to the strain rate. Drop weight experiments and simulation results are in the figures below. In the tests, drop weight device was equipped with a dropping mass of 360 kg from a height of 580 mm onto the specimen. The crushing head reaches an impact speed of approximately 3400 mm/s. As seen, K2 achieves the highest initial force level of up to 180 kN. On the other hand, K1 reaches the lowest force level of about 70 kN. The initial force level of K3 and K4 specimens is similar and approximately 120 kN.

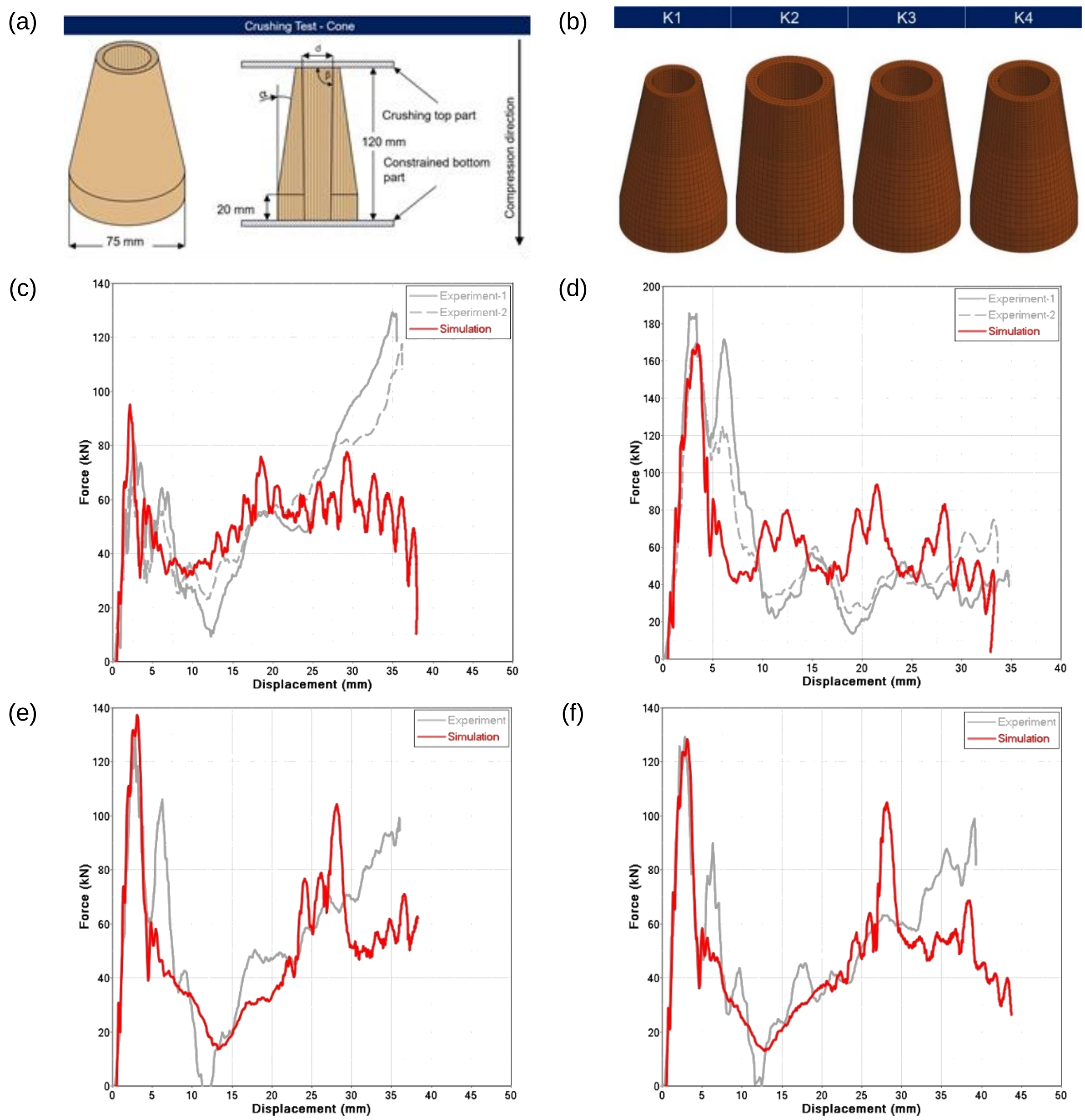


Fig.8: Drop weight specimens: a) experimental and b) numerical; Drop weight results: c) K1, d) K2, e) K3 and f) K4

Once the simulation is verified, the model is able to capture the behavior of even different wood structure under different impact loadings. To illustrate, the experimental and numerical force responses of a wood specimen in different geometry and test conditions are given along with the deformation in Figure 9b. In the experiment, drop weight device was equipped with a dropping mass of 447 kg from a height of 1004 mm onto the specimen. The crushing head reaches an impact speed of approximately 4500 mm/s. As seen in the figure, the numerically predicted local maximum and minimum points corresponding to the deformation are in good agreement with the experimental dynamic deformation history of the wood specimen.

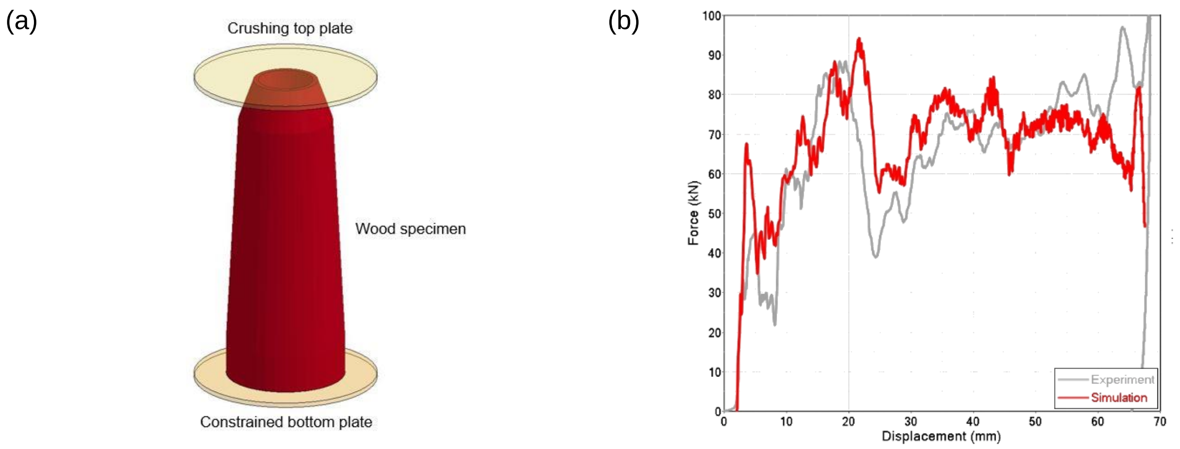


Fig.9: a) numerically modeled drop weight test setup and b) comparison of force-displacement curves

After initial preparation of the theoretical basics of wood and its physically justified failure mechanisms, the calculation of wood properties with some aforementioned orthotropic material models was performed by one-element simulation methods and shell element formulation. The comparison of the orthotropic material models of wood is given in Figure 10.

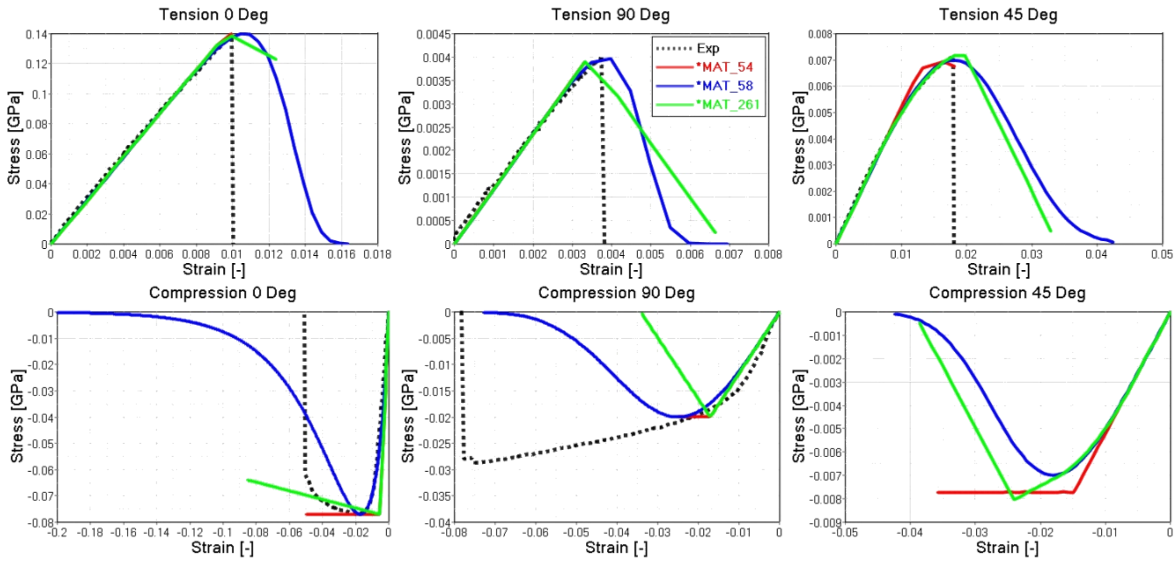


Fig.10: One-element simulations

As seen from the figure above, orthotropic material models can be used for modeling of wood with shell element formulation at quasi static strain rate. The comparison of the results of orthotropic material models for the 2D FE simulation of wood is given in the figure above. In addition to quasi-static condition, the calculation of dynamic problems is in the foreground for future research projects. However, the investigation of strain rate effect in orthotropic material models is a detailed study and questions on damage modes of wood is going to be answered in future. Illustration of wood specimen modeled with multi layered 2D shell elements is given in the figure below, which is a representative visualization of future projects.

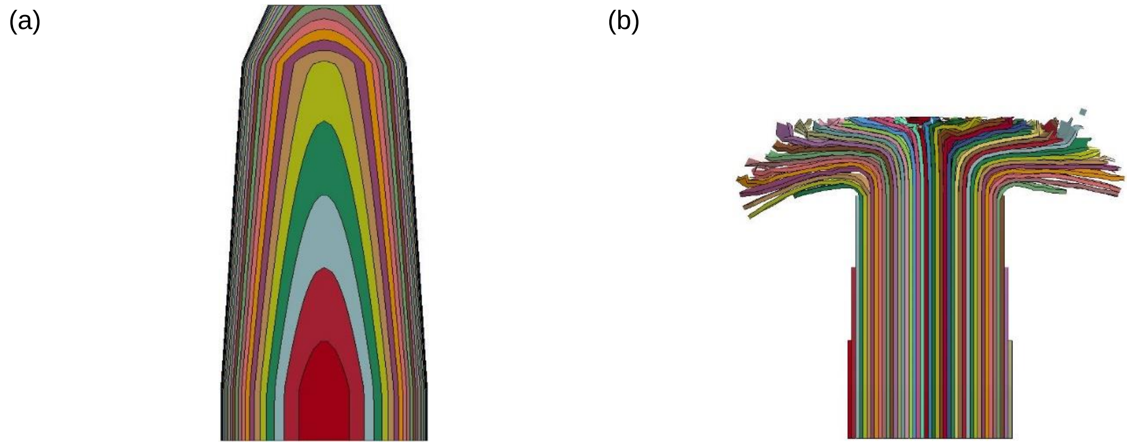


Fig.11: 2D wood crushing element: a) non-damaged and b) damaged

6 Summary

Crashworthiness and load-carrying performance of wood structures made of European Beech were investigated at different strain rates both experimentally and numerically. Numerical studies were carried out in LS-DYNA. An initial material card for ***MAT_143** was created on the basis of the strengths determined by quasi-static tension and compression tests. 3-point-bending simulations were executed for the validation studies of the initial material card. The quasi-static simulation results showed good agreements with the experiments. The material model predicts dynamic behaviour by means of strain-rate-dependent scaling of the strengths, however fails to scale the fracture energies responsible for the subsequent failure. Therefore, another material card for dynamic conditions was created by scaling only the fracture energies in accordance with the strain rate. Drop weight experiments were performed on four different structures. The dynamic material card for ***MAT_143** achieved satisfying agreement for energy absorbing structures, which are loaded in the fiber direction. In order to confirm the validation of the dynamic material card, drop weight experiment in different test condition was carried out with another wood crash element. The result showed that the numerical deformation force closely resembles the experimental deformation at dynamic strain rate. The results proved that further numerical studies on more complex structures under different load conditions can be captured by this numerical model.
In addition, a base study on the modeling of wood with composite material models was conducted for future research projects. For this purpose, single element simulations by using 2D shell element formulation were performed at quasi-static strain rate. The results showed that the composite material models have a potential of predicting the wood material behavior and it is worth to investigate.

7 Literature

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