Comparison of the two material models 58, 143 in LS Dyna for modelling solid birch wood

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1 Abstract

Sustainability plays an increasingly important role in the automotive industry. In order to reduce the ecological footprint, the suitability of alternative bio-based materials like wood is investigated within the project WoodC.A.R. In order for wood to be used as an engineering material for structural components or even crash relevant structures, it has to fulfill high mechanical demands. The material behavior has to be predictable and describable in a numerical simulation. Therefore, two material models **`*Mat_58 (*Mat_Laminated_Composite_Fabric)`** and **`*Mat_143 (*Mat_Wood)`** were compared and validated against quasi-static tension and compression tests in all its six anatomical directions but also against three-point bending tests with the wood fibers oriented parallel to the beam's axis. So called "clear wood" samples, i.e. specimens without any growing features, were tested covering the different load levels: linear elasticity, strain-hardening, strain-softening and rupture. While **`*Mat_58`** is an orthotropic material model, **`*Mat_143`** is transversally isotropic which means there is no possibility to distinguish between the radial and the tangential direction of the material. Therefore, a trade-off for both directions has to be found. On the other hand, the material law **`*Mat_143`** is able to consider influences like temperature, moisture content or even the quality respectively sorting degree of the wood. Both material models show that some simplifications considering the hardening and softening behavior, especially in compression have to be taken into account in multi-element specimens. While wood shows softening at longitudinal compression, there is a pronounced hardening in perpendicular direction. The strengths and weaknesses of both material models are discussed.

2 Keywords

Clear wood, birch, Mat_58, Mat_143, crash simulation, automotive industry"

3 Introduction

In the early days of automotive engineering wood played an important role as a construction material for vehicle bodies. Mechanical engineers appreciated the advantages of this natural lightweight material because of its high specific strength, stiffness, its advantageous damping behavior as well as for its extensive availability and low commodity price. However, as a consequence of the development of manufacturing relatively cheap, mass produced structural metal components, wood as a structural material was gradually vanished in the automotive industry. Due to its complex mechanical behavior wooden components require more sophisticated materials models compared to its metal peers.

Within the last few decades more and more studies were conducted to understand and describe the material behavior of wood and wood products, especially in the field of timber engineering for applications in civil engineering. Therefore, most of the studies dealt with the linear elastic material behavior under quasi-static loading or long term loading and were almost exclusively conducted on softwoods like spruce. Hardwoods were rarely used in the field of timber engineering, resulting in a data scarcity. Over the last few years the potential of some hardwood species like birch, ash or beech is increasingly recognized by timber engineers. These changes are not only due to their higher strength and stiffness but also because of climate changes and the associated decrease of coniferous forests. Birch for example is a very tough wood species with relatively high strength and stiffness properties paired with medium density. That is why birch is also found in some historical airplane constructions and can be seen as a favorable material for creating light weight and bio based structural components for automotive applications.

In order to deploy wood as a structural or even crashworthy component in the automotive industry it is necessary to not only know the elastic material behaviour but also how wood samples behave under large deformations up to complete failure. Awareness of these wood characteristics in all its six anatomical directions and for all possible load cases e.g. tension, compression, bending, a.s.o. is mandatory for creating a numerical model. The goal is to find a material model which is able to distinguish between the individual wood anatomical directions, like the orthotropic material model `*Mat_58` or at least between the longitudinal and perpendicular direction of the grain like the transversely isotropic material model `*Mat_143`. Furthermore, it has to be applicable to different kinds of loading, most importantly tension, compression, and bending but also shear. Ideally, the material model shall be able to replicate strain rate behaviour. In contrast to other studies like [1] and [2], which only put emphasis on describing the characteristic due to compression loading within an explicit finite element model.

4 Methode

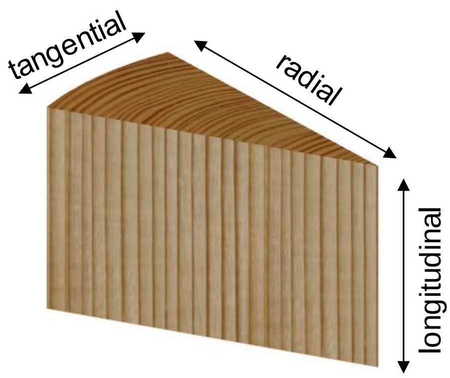
Wood is quasi-brittle, orthotropic, visco-elastic and strain-rate dependent material, sensitive to changes in moisture content and temperature, requiring a multitude of characterization tests. Already to characterise its orthotropic behaviour eighteen test configurations are needed. Being a natural product, solid wood has a wide statistical spread of material parameters. This is why test specimens were picked from up to ten different individuals according to DIN 52180 [3]. This is essential for statistical verification and for calculating mean (or quantile) value curves. The input data and settings of the material models are based on quasi-static tests which are introduced in this chapter.

4.1 Material characterization

Solid wood has three anatomical directions, referred to as longitudinal (L), tangential (T) and radial (R) direction (see Table 1). In LS-Dyna the axes of the material coordinate systems as well as stiffness values are commonly denoted as A, B, C, while strength properties are expressed as X, Y, Z or 1, 2 and 3.

Table 1: Definition of wood anatomical terms and labeling options.

longitudinal (L)	1	A	X
tangential (T)	2	B	Y
radial (R)	3	C	Z



In the case of tensile loading there are six possible test configurations, which are shown in Fig. 1. This is due to the fact that not only the direction of loading is important, but also the orientations of the sample perpendicular to loading, especially when measuring the poisson-ratio [4]. Therefore, each test orientation consists of two digits. The first one defines the loading direction whereas the second digit is the direction in which the poission-ratio is measured. The examination of the tensile tests as well as the sample geometry are based on DIN 52188 [5]. The samples for longitudinal tension are 470 mm long, while the samples in perpendicular direction are only 120 mm long. This is due to production issues.

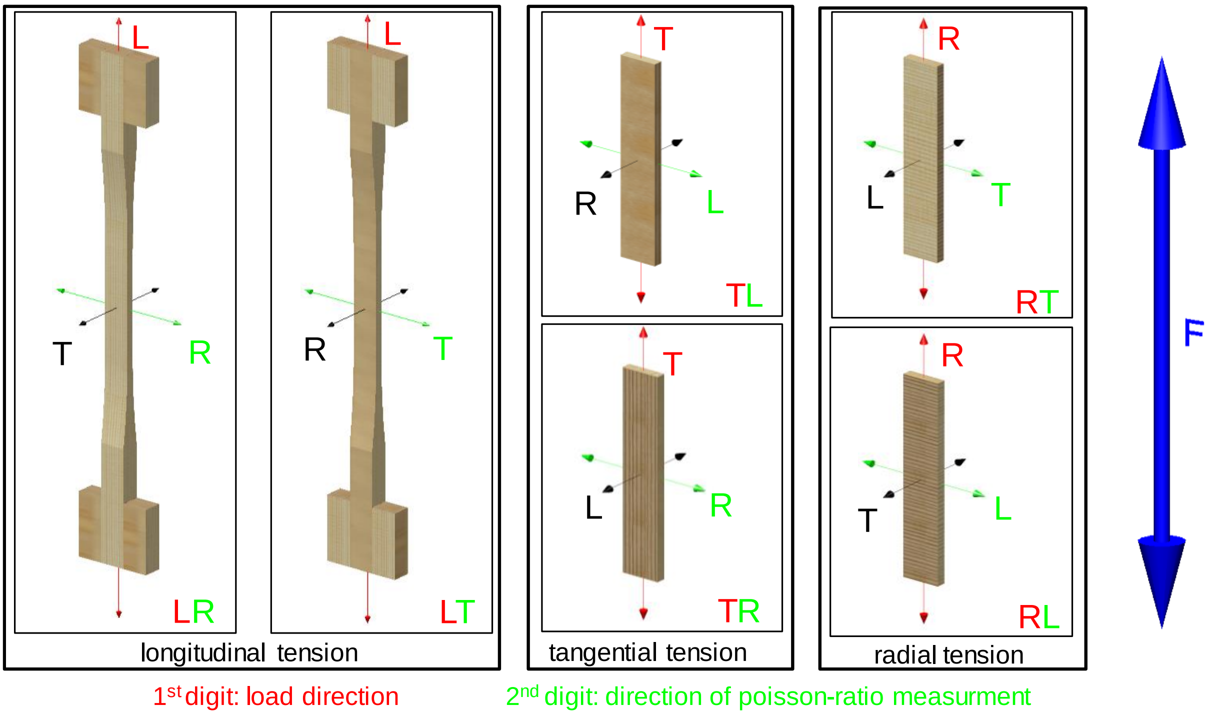


Fig.1: Samples for tension tests in all its six anatomical directions.

The same nomenclature is used for the compression tests (see Fig. 2). In contrast to the tensile tests the geometry of the compression tests is the same for each individual loading direction. Material geometry and test execution are based on DIN 52185 [6], but tested up to complete failure, in order to determine the behavior beyond elasticity.

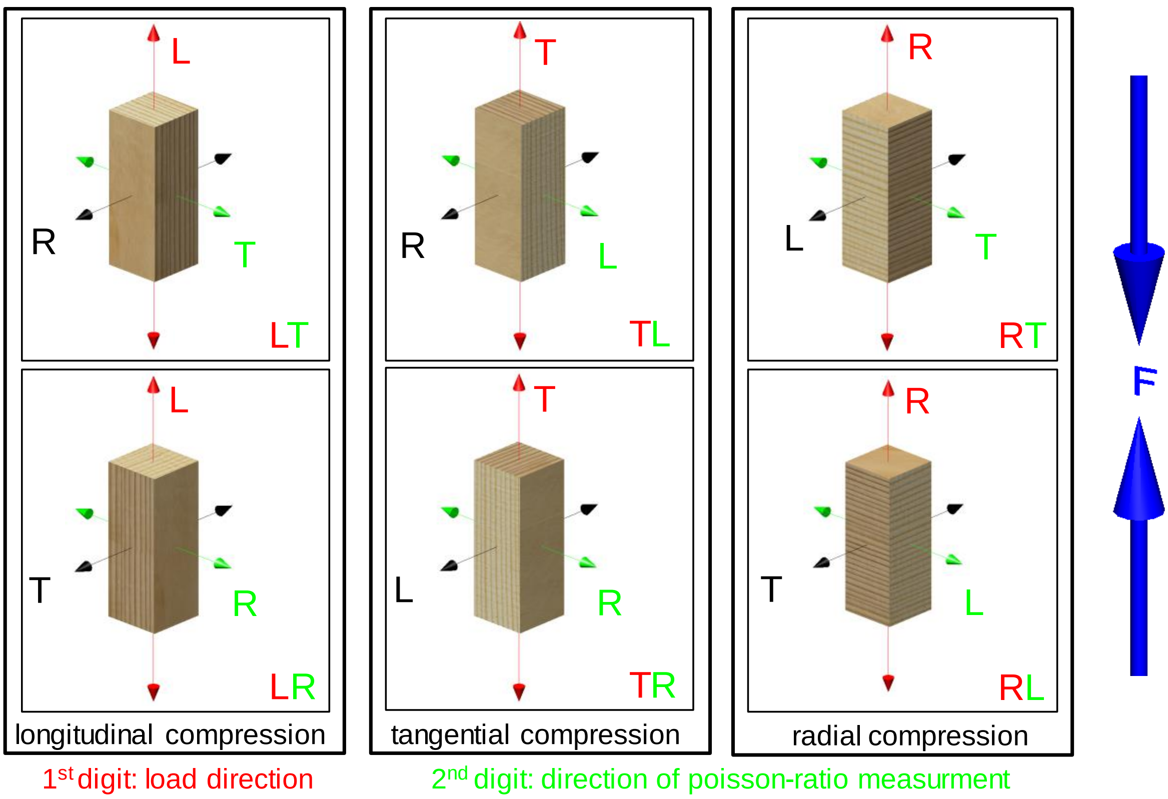
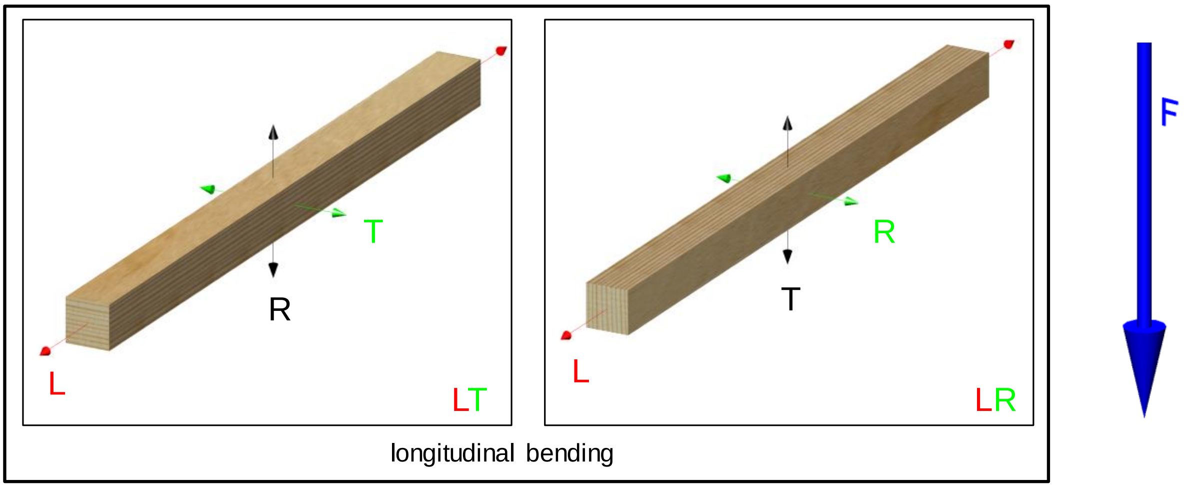


Fig.2: Samples for compression tests in all its six anatomical directions.

Unlike the tension and compression tests there are only two orientations required for the bending case, because bending samples were the beam axis is oriented parallel to the radial or tangential direction are almost impossible to generate. Fig. 3 shows the two load cases where the beam axis of the sample is oriented parallel to the longitudinal direction. The test configurations were carried out according to DIN 52186 [7] in order to determine the modulus of elasticity as well as the bending strength.



1st digit: direction of the beam axis 2nd digit: sample width (perpendicular to load direction)

Fig.3: Samples for bending tests with a beam axis oriented parallel to the longitudinal direction.

4.2 Modelling

The obtained density, strength and stiffness values from the tested clear wood samples provided the necessary input data for the material cards **`*Mat_58`** and **`*Mat_143`.** The material properties for the shear modulus as well as the shear strength values are partially from literature [8] and from conducted shear tests which are not further described.

4.2.1 Material model Mat_58

Material model **`*Mat_58`** is commonly used for modelling composite structures, which can be discretized using shell elements. For the purpose of modelling wood structures in mechanical engineering, though, shell elements are not always applicable. When considering a wooden box beam, the plywood shear webs are ideally discretized using shell elements, while the solid-wood girders are calling for solid elements. For the purpose of this study **`*Mat_58`** was implemented for solid elements in LS-Dyna solver beta release R134893. Wood is quasi-brittle in tension, generally leading to sudden failure at strains between 0.9 - 2%. In compression, though, wood behaves similar to honeycomb structures. Such, eroding settings adjusted to tensile loading are inadequate for compression or shear loading. Hence, for the purpose of this study, **`*Mat_58`** in Dyna R134893 features nine eroding strain values, for each individual loading directions in tension, compression and shear. **`*Mat_58`** is an orthotropic material model, which allows to distinguish between longitudinal, tangential and radial strength and stiffness values (see Table 2). It provides softening and strain-rate settings for tension, compression and shear in each direction.

Table 2: Possible density, strength and stiffness entries in Mat_58.

RO	EA	EB	EC	PRBA	PRCA	PRCB	
GAB	GBC	GCA	XC	XT	YC	YT	SC
ZC	ZT	SC23	SC31	RO… density		E… Young's modulus	
PR… poisson-ratio		C… compressive strength		T… tensile strength		SC… shear strength	

4.2.2 Material model Mat_143

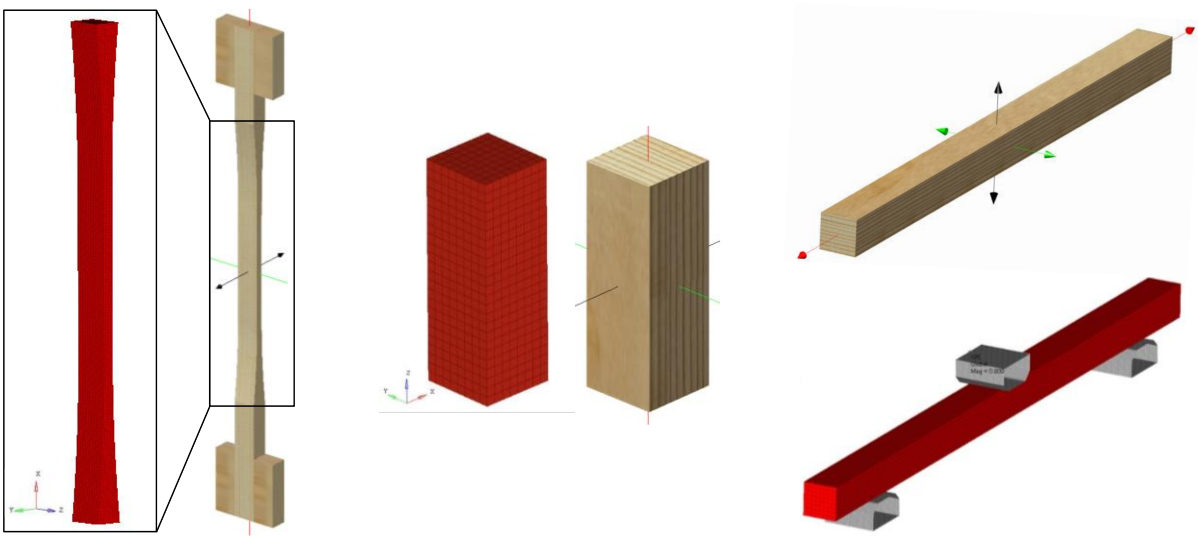
In contrast to the orthotropic material model ***Mat_58** the material model ***Mat_143** is only transversely isotropic, which means that is not possible to distinguish between the radial and tangential material direction. Therefore, a tradeoff between those two anatomical directions has to be found for the strength as well as for the stiffness values. Furthermore, only one poission-ratio can be defined. Softening can only be defined for tension and shear but not for compression loading. It also shows strain-rate dependencies but is only available for solid elements.

Table 3: Possible density, strength and stiffness entries in Mat_143.

RO	EA	EB		PRBA			
GAB	GBC		XC	XT	YC	YT	SC
		SC23		RO… density		E… Young's modulus	
PR… poisson-ratio		C… compressive strength		T… tensile strength		SC… shear strength	

4.2.3 Validation

In order to validate and compare the two presented material models the test setups from the quasi-static material characterization tests were simulated (see Fig.4). All of the samples were modelled using solid elements. The 3-point bending test also includes the impactor as well as the bearing blocks. Contact between specimen, support and impactor is established through ***CONTACT_ERODING_SURFACE_TO_SURFACE.**
The model of the longitudinal tension test consists of the central tapered part of the dog-bone like test sample only. The tension test specimen model, which is quite thin, was discretized with 1mm solid elements, while the bending or compression specimen models have an element size of 2.5 mm. With both material models element type 1 was applied. In all models hourglass model type 4 was consistently applied. For the purpose of compression tests ***CONTACT_INTERIOR** with standard setting was introduced, to prevent negative volume errors and to replicate raise in compression force, once the material is fully compressed.
Quasi-static tests were simulated with the explicit Dyna solver. Strain rate models were disabled in material models and loading rate was 0.00133 /ms. Energy balance was checked for kinetic energy.



tension:
sample geometry:
470 (120) x 20 x 6 mm^3

compression:
sample geometry:
60 x 20 x 20 mm^3

3-point bending:
sample geometry:
360 x 20 x 20 mm^3

Fig.4: Modelling of the samples: tension (left), compression (middle), bending (right).

5 Results

For the purpose of comparing the two material models against each other and also against the quasi-static tests the resulting curves were plotted on a force - deformation diagram. The diagram not only displays the two simulation curves and the individual curves obtained from material characterization tests but also a mean curve calculated from all individual tests. The calculation approach for the mean curve is based on the gradient change of the individual test curves.

5.1 Tension

Birch clear wood samples show a tensile strength which is almost three times higher than the compression strength in longitudinal direction, the fracture behavior is very brittle. The ultimate elongation ranges from averagely 0.9 % in longitudinal direction up to around 2.0 % in tangential direction.

5.1.1 Tension in longitudinal direction

The characteristic of solid birch wood loaded under tension in longitudinal direction is almost perfectly linear elastic until the final failure of the sample (see Fig. 8). Therefore, both material models are able to fit the mean curve quite well. The dispersion concerning the Young's Modulus of the individual curves is low.

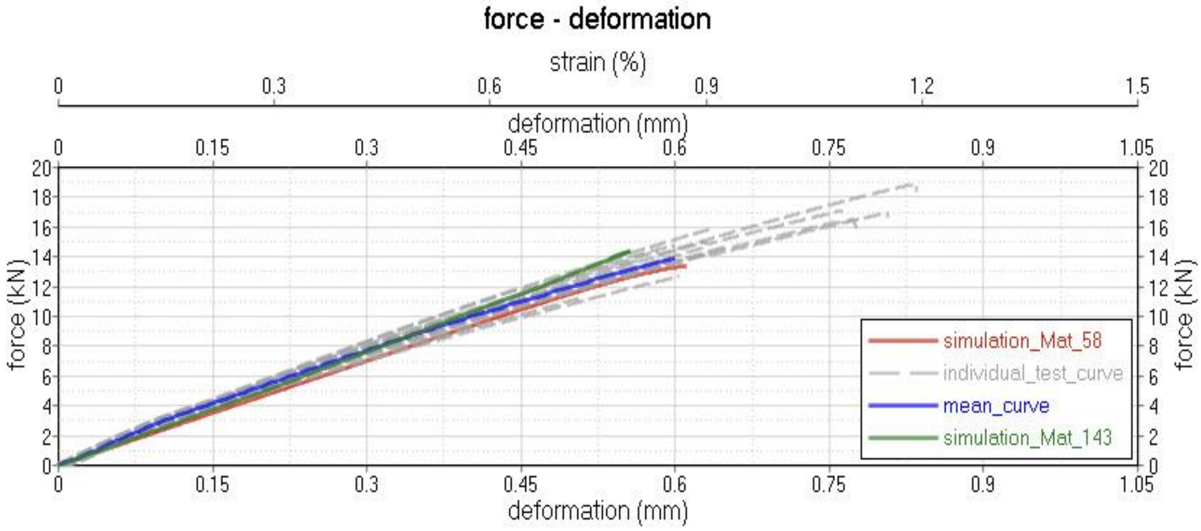


Fig.5: Force - deformation diagram for tension in longitudinal direction (LR and LT).

5.1.2 Tension in tangential direction

In case of the tangential material direction a pronounced flattening of the force deformation is found. The advantage of the material model **`*Mat_58`** is that it can display this flattening characteristic quite well, which is based on its exponential approach. On the other hand, the material model **`*Mat_143`** only enables a linear elastic characteristic under tension, which means that there are increasing deviation at higher strains (see Fig.9).

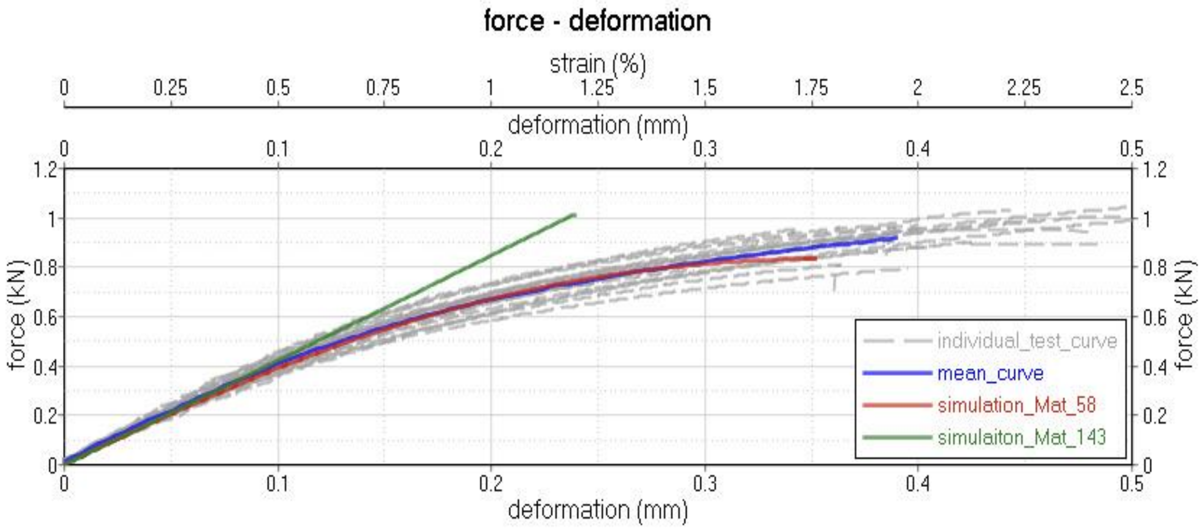


Fig.6: Force - deformation diagram for tension in tangential direction (TR and TL).

5.1.3 Tension in radial direction

The characteristic of wood under tensile load in radial direction concerning the ultimate elongation, maximum strength and the flattening of the force - deformation curve is in between the longitudinal and the tangential direction. The material model **`*Mat_58`** is able to fit the mean curve quite well. In case of the material model **`*Mat_143`** the trade-off which has to be made between the tangential and radial direction is quite significant. That is why the gradient of the simulation curve is about 40 % less steep than the mean curve obtained from the experimental tests. The dispersion of the test curves in radial direction is higher than for the longitudinal and tangential direction shown in Fig.10.

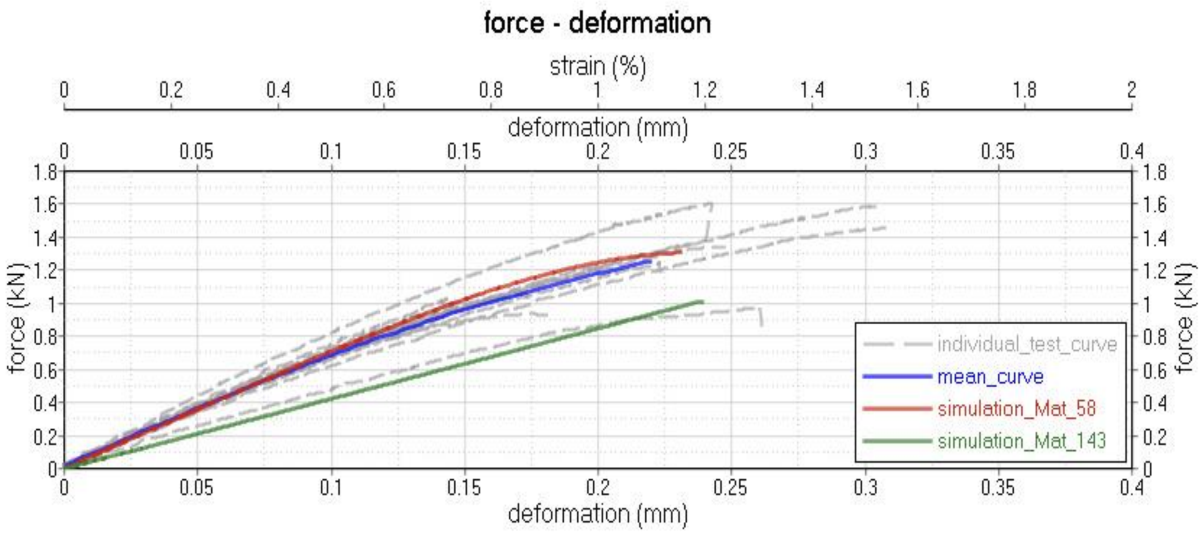


Fig.7: Force - deformation diagram for tension in radial direction (RL and RT).

5.2 Compression

Due to the cellular structure of wood it is a material which can be highly deformed and behaves quite ductile. Therefore, the strain under compressive loading ranges from about 50 % up to 75 % for those solid birch wood samples.

5.2.1 Compression in longitudinal direction

For the case of compression in longitudinal direction, there is a considerable statistical spread when it comes to yield-stress (see Fig.5). After reaching the maximum strength, softening sets on, leading to a gentle force drop with its lowest point between 40 % and 50 % strain. However, on most of the samples the softening phase is followed by a strain-hardening phase where the force is increasing again up to strains of around 70 %. In case of the material model **`*Mat_143`** which has no softening options for compression loading the maximum force is kept constant in yielding. On the other hand, the material model **`*Mat_58`** provides softening settings but the sample is completely eroded at a strain of about 5 % due to kinking.

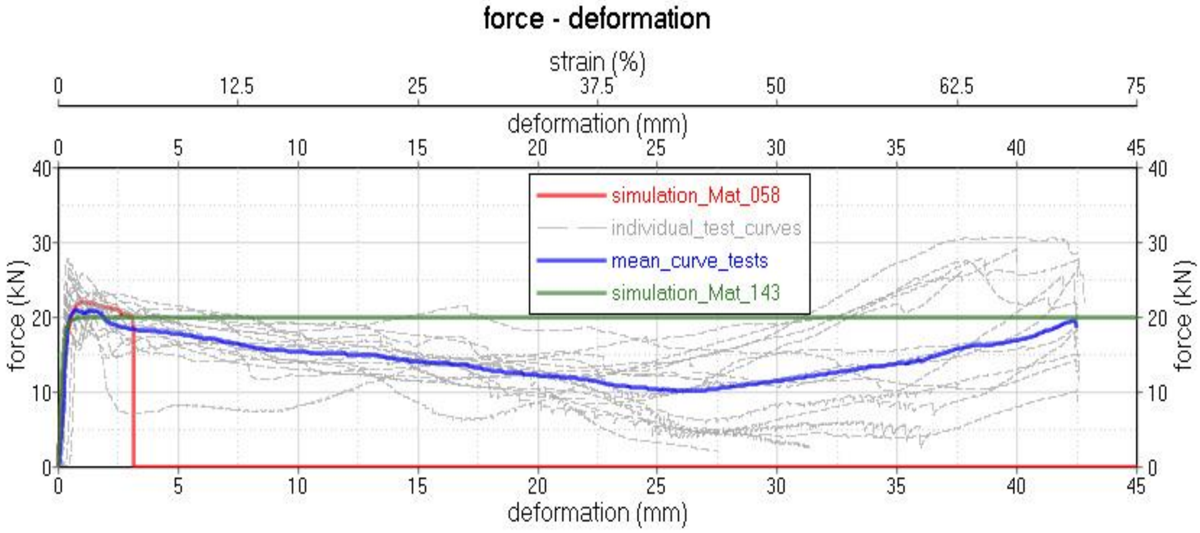


Fig.8: Force - deformation diagram for compression in longitudinal direction (LR and LT).

5.2.2 Compression in tangential direction

In contrast to the longitudinal direction the statistical spread of the samples in tangential direction is very low. Once the material yields, there is a pronounced hardening up to a strain of about 50 % followed by a complete and sudden softening. The material model **`*Mat_58`** provides no capabilities to display hardening, therefore the maximum force is held constant after leaving the linear elastic phase. In case of **`*Mat_143`** there are limited options to describe hardening but the problem is that the model shows implausible high compression stresses with an increasing deformation in perpendicular direction. Therefore, the compression strength had to be set to a lower value (see Fig.6).

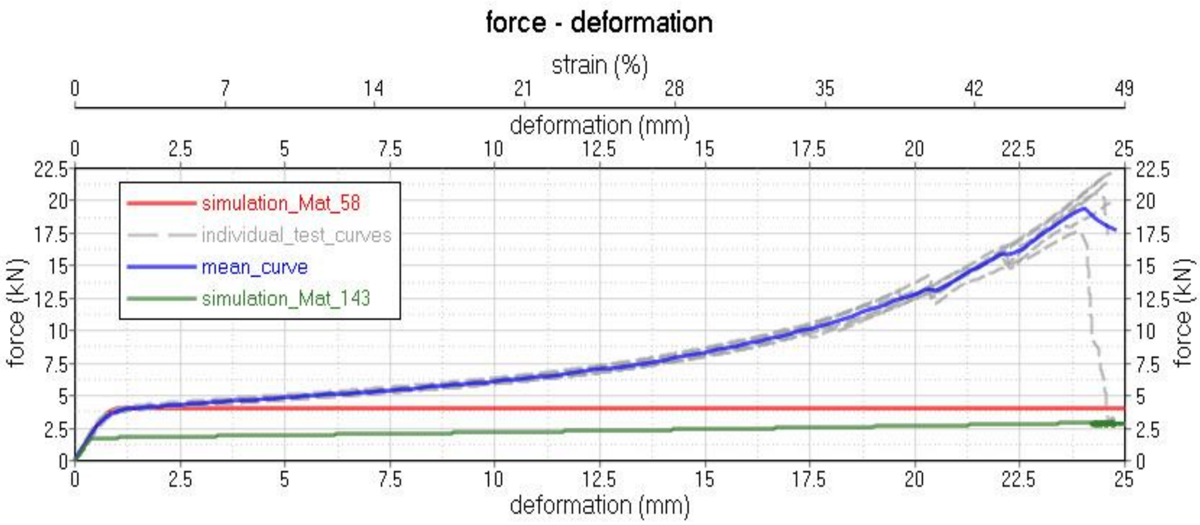


Fig.9: Force - deformation diagram for compression in tangential direction (TR and TL).

5.2.3 Compression in radial direction

For the case of compression in radial direction a considerable statistical spread in experimental tests is found. Some of the samples show a pronounced softening after about 15 % strain while others go into a gentle hardening phase. However, the mean curve shows an almost constant force -

deformation characteristic and this is why the simulation curve obtained from **`*Mat_58`** fits the test results quite well. Due to the transversal isotropic structure of the material model **`*Mat_143`** the force deformation characteristic shown in Fig.7 is the same as in tangential direction (Fig. 6).

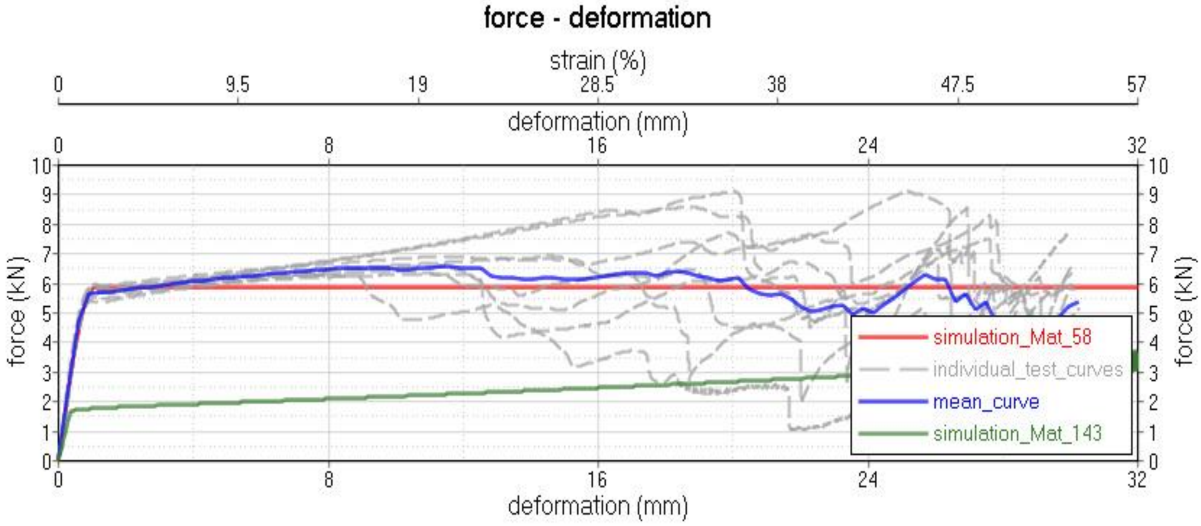


Fig.10: Force - deformation diagram for compression in radial direction (RL and RT).

5.3 Bending

In case of the 3-point bending test both the ductile behavior under compression loading and the brittle behavior under tension are coming together. This leads to a force - deformation characteristic with a pronounced flatting of the test curves until it reaches its maximum strength followed by a sudden often stepwise softening of the sample. Both material models are able to fit the mean curve up to a deformation of about 10 mm quite well. In case of the material model **`*Mat_58`** there is a sudden complete softening at about 10 mm deformation caused by a complete erosion of the entire specimen. Attempts to prevent a sudden erosion of almost the entire specimen through a discharge slope, i.e. through the introduction of a damage-based relaxation, to smooth the energy release, were not successful (as it had negative effects on other load cases). On the other hand, the material model **`*Mat_143`** shows even a slight decrease of the maximum force over an unrealistic wide deformation range until finally softening occurs (see Fig.11).

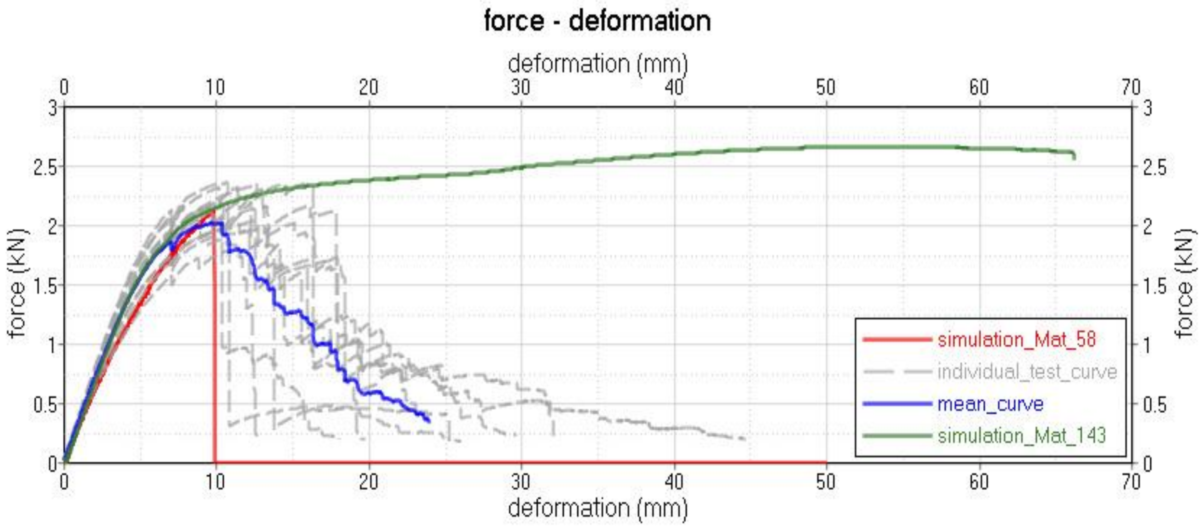


Fig.11: Force - deformation diagram for 3-point bending (LR and LT).

6 Conclusions

It was shown that both material models do have their limitations in displaying the direction-dependent characteristics of wood under compression loading. So there is no softening in combination with hardening like in the longitudinal direction but also no progressive hardening like in the tangential direction depictable. In case of the tensile characteristics of birch wood the material model ***Mat_58** is able to fit this curves up to complete failure very nicely. The material model ***Mat_143** shows good agreement for the longitudinal direction but due to the trade-off between radial and tangential direction the curve fitting is not so well. For the bending case the simulation results from both models are not satisfactory yet. The problem with ***Mat_143** is that the load level for longitudinal compression is held constant whereas in a real test sample softening occurs. This softening leads to a higher compression of the bending sample at the impactor. Therefore, the effective cross-section is reduced which leads to a pseudo flow joint formation. As a result, the tension side of the sample is stretched much more which leads to a step wise tensile failure and a drop in force. On the other hand, the material model ***Mat_58** has the numerical issue that the eroding of one element leads to a chain reaction where the whole part is eroded instantly. It also has to be mentioned that the material models would fit the test curves much better if only one individual load case has to be described. In the present study the focus was putted on describing all load cases with the same material settings as good as possible.

Although the input data for the material models as well as the test curves for the validation process came only from quasi-static tests they already give a good overview which requirements a material model has to fulfill for representing the mechanical characteristics of wood. The next steps are further adaptions on the material models in order to improve their behavior in individual load cases. Furthermore, material characterization test on shear samples have to be done in order to obtain further input data for the material models and for validation purposes. Further on also dynamic tests have to be carried out to obtain the strain-rate effect on different types of loading which are used as parameters in the material model.

Last but not least a material model for the purpose of describing the material characteristics of wood is not completed without considering environmental influences like temperature, humidity but also product dependent influences like sorting grade or the type of wood product. Therefore, the plan is to introduce a “modifier” for scaling the material parameters depending on those influences.
The following Table 4. shows a short summary of the capabilities and limitations of both material models.

Table 4: Capabilities and limitations of Mat_58 and Mat_143.

Loading	Direction	Effects	Required	*Mat_143	Remark	*Mat_58
Comp-ression	Long-itudinal	Pre-Peak Hardening/Non-linearity	Nice to have	Yes		No
		Post-Peak Softening	Must	No		Yes (SLIM)
		Post-Peak Hardening	Must	Yes (GHARD)	GHARD has effect on parallel and perpendicular	No
	Tang-ential	Pre-Peak Hardening/Non-linearity	Nice to have	Yes		Yes (SLIM)
		Post-Peak Softening	No	No		No
		Post-Peak Hardening	Must	Yes (GHARD)		No
	Radial	Pre-Peak Hardening/Non-linearity	No	Yes	Same as Tangential	Yes (SLIM)
		Post-Peak Softening	No	No	Same as Tangential	No
		Post-Peak Hardening	No	Yes (GHARD)	Same as Tangential	No
Tension	Long-itudinal	Pre-Peak Hardening/Non-linearity	No	No		Yes
		Post-Peak Softening	No	Yes		Yes
	Tang-ential	Pre-Peak Hardening/Non-linearity	Yes	No		Yes
		Post-Peak Softening	No	Yes		Yes
	Radial	Pre-Peak Hardening/Non-linearity	No	No	Same as Tangential	Yes
		Post-Peak Softening	No	Yes	Same as Tangential	Yes

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8 Literature

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