CARBON FIBER REINFORCEMENT OF WOODEN PARTS WITH SMALL CROSS SECTIONS – PROCESSING, MECHANICAL PROPERTIES AND SIMULATION

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Abstract

To improve the mechanical properties of wooden parts with small cross sections by inserting only small amounts of composite reinforcments several one-step infiltration processes have been investigated. Even with a carbon fibre based composite reinforcement of only 3 % relative to the overall cross section a significant increase of stiffness up to 40 % can be achieved. With help of extensive experimental testing further effects on homogenising of material properties, extension of service life as well as increase of stiffness and strength were analysed. For the design and verification of real wooden parts with composite reinforcement a finite element simulation model was developed and successfully applied.

1 Introduction

Wooden parts with small cross sections as used for several applications like music instruments, sporting goods, ladders and other working equipment can be exposed to static and high dynamic loads. Next to the demand of a failsafe usage of those wooden parts a low part mass, as well as a request of ergonomic comfortable manageability, has to be considered. But wood as a natural grown material shows an anisotropic and inhomogeneous behaviour with a density-dependent strength and with local imperfections caused by branches or by angular fiber orientations. However, a common way to satisfy the high mechanical demands on previous described parts is a substitution of wood material by metal or, recently, by fibre reinforced plastic (FRP) composites. Thereby, several positive properties of wooden materials like a pleasant haptic, good thermal and electric insulation, an effective damping characteristics and considerable low material costs get lost. An alternative solution can be found in the combination of wood with fiber reinforced plastics (FRP). Hereby, only a small amount of FRP with high tensile properties is applied in order to retain the look-and-feel of wooden applications. However, even with a small cross section ratio of reinforcement material, like carbon fiber reinforced plastics (CFRP), of about 3 % - 6 % of the wooden part, the brittle failure sensitivity compared of natural wood can reduced significantly [1]. Also the elastic anisotropic properties of native wood can be considerably homogenised. Within a public funded joint research project between a German wood research institute and a polymer research institute several topics like (I) manufacturing and processing, (II) material properties and their optimization and (III) numerical simulation and modeling of wood-FRP-composites were investigated.

2 Evaluation of basic materials properties

Different material properties have been investigated in order to evaluate suitable matrix materials as well as getting required material parameters of the FRP and the wood component of the wood-FRP composite for finite element analysis (FEA).

For reinforcement mainly carbon fibres with high tenacity properties (HTS or HTA) made by Toho Tenax have been applied with refinements from 800 tex up to 3200 tex. Additionally, ultra high modulus (UMS) carbon fibres and basalt fibres have been used as reference. The linear elastic properties of the applied fibres have been taken from the specifications provided by the manufactures, as shown in Table 1. For indication of the transversal-isotropic material behavior the fibre direction is indicated with 1 and the perpendicular directions are marked with 2.

Fibre material	**Carbon (HT)**	**Carbon (UMS)**	**Basalt**
E-Modulus, E_1 [GPa]	210	395	89
E-Modulus, E_2 [GPa]	16	15200	89
Shear-Modulus, $G_{2,1}$ [GPa]	50	28,6	36,5
Poisson ratio, $\nu_{2,1}$ [-]	0,27	0,2	0,3
Poisson ratio, $\nu_{2,2}$ [-]	(0,3)	(0,3)	(0,3)

Table 1: Mechanical properties of the considered fibre materials

In order to avoid thermal wood modification due to high curing temperature only cold curing two component epoxy resins, with curing temperatures up to 60 °C, have been considered. Next to a standard tensile test, according to DIN ISO 527-2 (Type 5A), also DMA testing has been applied to evaluate thermal conditions of the resins. Mainly standard and easy to supply epoxy resins as offered by Hexion have been considered. Additionally, an alternative epoxy resin, called Greenpoxy made by Sicomin Composites, which has 55 % of its molecular structure originating from plants, has been considered as well. Mechanical and thermal properties are summarized together with the specific reaction times in Table 2.

Epoxy resin	**EP L20 + EPH 161**	**EP L + EPH L**	**EP L + EPH 500**	**EP L1100 + EPH 294**	**Greenpoxy 55 + GP 505**
Reaction time, t_R [min]	90	40	60	15	45
E-Modulus, E [GPa]	3158	2829	2108	2975	2495
Tensile strength, R_m [MPa]	77	58	37	67	54
Ultimate strain, ε_m [%]	4,3	3,6	3,1	4,0	3,7
Glass transition Temperature, T_g [°C]	93,2	79,8	65,5	83,7	74,2

Table 2: Mechanical and thermal properties of the considered epoxy resins

Considering different aspects like material costs, curing time and mechanical properties, two epoxy resins with their specific hardening components, EP L + EPH L as well as Greenpoxy 55 + GP 505, were chosen for further utilisation. The influence of curing respectively hardening conditions for these two resin types have been investigated systematically. It was found, that standard curing conditions at room temperature (RT) for 24 h lead to wide varying mechanical as well as thermal resin properties. In contrast, curing at 60 °C for 10 h results in much more homogenised material properties. Figure 1 shows stress-strain curves for the EP L + EPH L epoxy resin with different curing respectively hardening conditions.

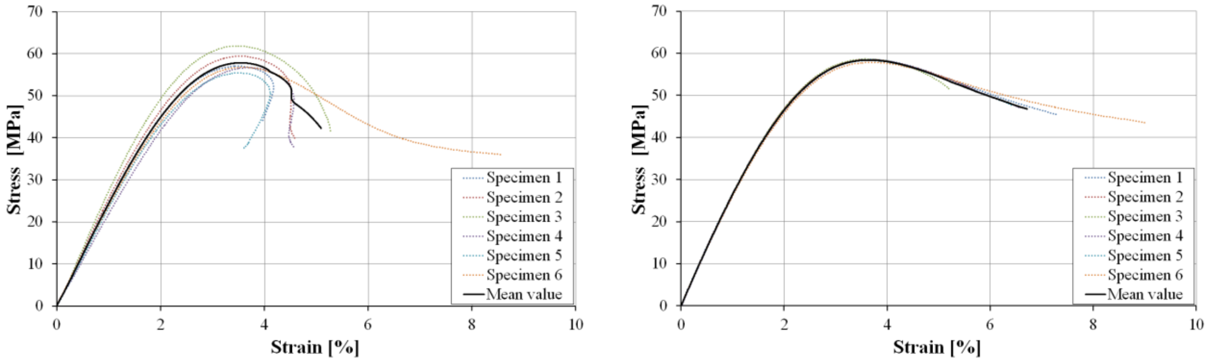

Figure 1: Stress-strain curve of the epoxy resin EP L + EPH L cured at room temperature for 24 h (left) and hardened at 60 °C for 10 h (right)

The preferred used wood species in the project was ash (Fraxinus excelsior L.) since it is in widespread use for statically and dynamically highly stressed small cross-sections of wooden applications. For determination of linear elastic wood material properties an orthotropic material behavior can be applied [2, 3]. Considering that nearly small cut stripes are used for the mentioned application wood fibre properties have been analysed according to the main direction (longitudinal, radial and tangential) as shown in the principle sketch in Figure 2 [4].

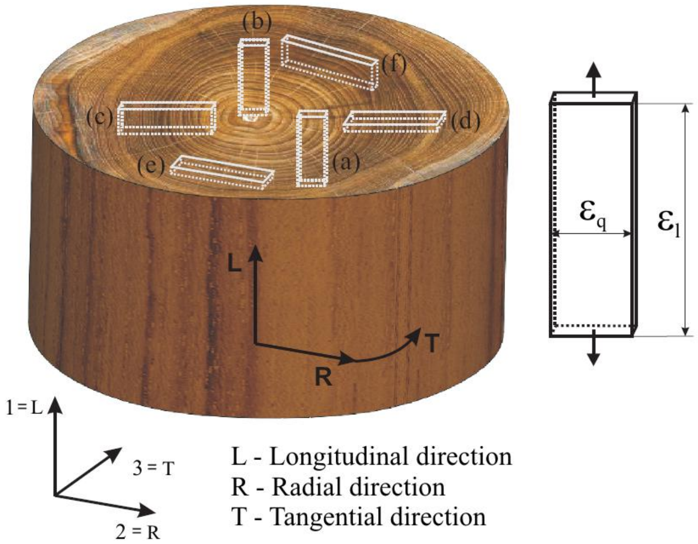

Figure 2: Definition of wood specimen orientation within a bole

In total 9 independent engineering constants E_1, E_2, E_3, G_{21}, G_{23}, G_{31}, ν_{12}, ν_{23}, ν_{13} are needed to describe the orthotropic wood properties appropriate. Next to a tensile test, which have been adapted from the FRP composite testing norm DIN EN ISO 527 – 4, a compression test, according to DIN EN 2850, and a shear test with use of a newly developed shear frame have been carried out. For all tests two different climate conditions (20 °C / 65 % and 85 % relative humidity) have been taken into account. Predominantly, an optical measuring device, named ARAMIS, was used to diagnose the resulting strain as well in parallel as in perpendicular orientation relative to the loading direction. Herewith the resulting Poisson ratios ν_{12}, ν_{23}, ν_{13} could be determined. Figure 3 displays the tensile testing device, a wooden specimen and an example of the optical strain measurements. The different stiffness between early and late wood can be seen with help of the different colored image on the right side of Figure 3.

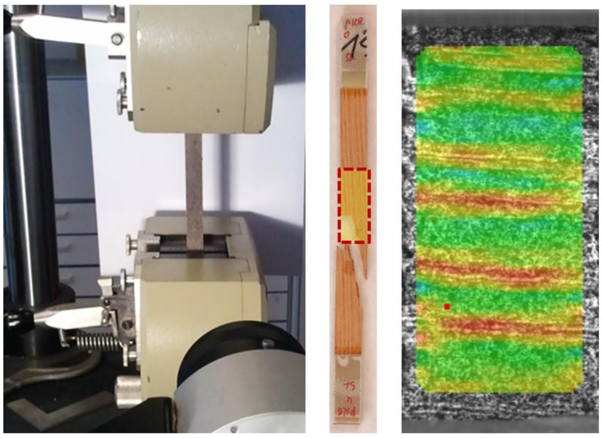

Figure 3: Tensile test with wood specimen (left), specimen with marked area for optical measurement (middle), result of optical strain measurement (right)

The results of the tensile test for an ash specimen of a width of w = 15 mm at 20°C and 65 % relative humidity are shown accordingly to previous defined orientation in Table 3.

Orientation	**Engineering constants**	**E-Modulus, E [MPa]**	**Variation coefficient E-Modulus**	**Poisson's ratio, ν [-]**	**Strength, R [MPa]**	**Variation coefficient Strength**
(a)	E_1, $\nu_{2,1}$, R_1	16337	7 %	0,14	127	2 %
(b)	E_1, $\nu_{3,1}$, R_1	12975	7 %	0,18	132	10 %
(c)	E_2, $\nu_{1,2}$, R_2	1803	18 %	0,35	9	21 %
(d)	E_2, $\nu_{3,2}$, R_2	875	24 %	0,62	10	14 %
(e)	E_3, $\nu_{2,3}$, R_3	811	11 %	0,31	10	6 %
(f)	E_3, $\nu_{1,3}$, R_3	796	29 %	0,15	7	10 %

Table 3: Mechanical tensile properties of considered wood material, ash (Fraxinus excelsior L.), for different main directions at 20 °C / 65 % rel. humidity

It can be seen, that the stiffness of the longitudinal direction is up to 10 times higher than any other of the orthotropic main directions. One reason for the variation of E-Modulus of specimens with the same direction, like (a), (b) and (c), (d) can be explained with the probe preparation. Samples with an ideal aligned wood orientation according to the predefined direction were very difficult to manufacture. However, a drop of mechanical properties of wood samples exposed to a higher humidity level has been proven within all performed material tests.

3 Processing

For demonstration of the process technology the FRP stripes were applied to small notches on opposite planes of the wooden specimens. The total fraction of the composite cross section relative to the wooden base material was 3 % respectively 6 %. For the experimental research wood samples of a nominal cross section of 20 mm x 20 mm with a length of 360 mm have been used as shown in Figure 4. Compared to a simple gluing of, e.g. pultrused CFRP beams, a higher flexibility in shaping, material combination as well as an improved adhesive strength was aimed by using a one-step infiltration process [1].

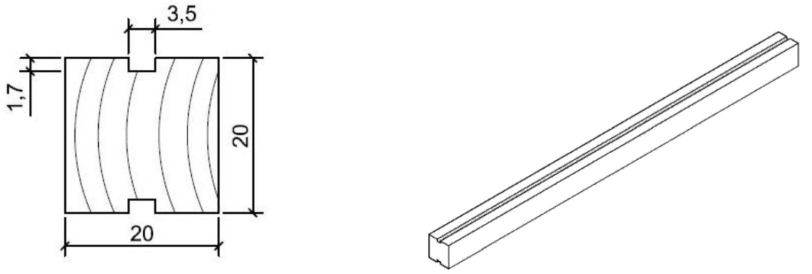

Figure 4: Geometry of the wood samples used for infiltration development and wood-FRP-composite testing

Within the context of the research project we focused on the development of methods for different one-step infiltration processes. In general three different infiltration types have been conducted: resin injection, vacuum infusion and the application of pre-impregnated roving material. We found that the use of pre-impregnated rovings led to enormous difficulties regarding the manufacturing process itself and the final FRP quality. However, good results have been achieved with help of injection or vacuum infusion processes. Both processes have been used on the laboratory scale as technical process variants. Corresponding to the aimed fiber volume content, dry fiber rovings were inserted into a routed-out groove and then the resin was applied with the aid of over- or low-pressure. In case of injection the resin was pushed through holes of a plain PMMA cover with either help of disposable syringe or a peristaltic pump. For not being contaminated with resin the flanks have been sealed with an adhesive tape in a previous step. The injection process is shown in Figure 5. Due to the solid PMMA injection counterpart the final FRP surface is of high quality. On an experimental scale we achieved up to 45 % of fibre volume fraction. However, due to the required precise fitting of the upper tool surface complex shaped wood geometries could be difficult to inject on.

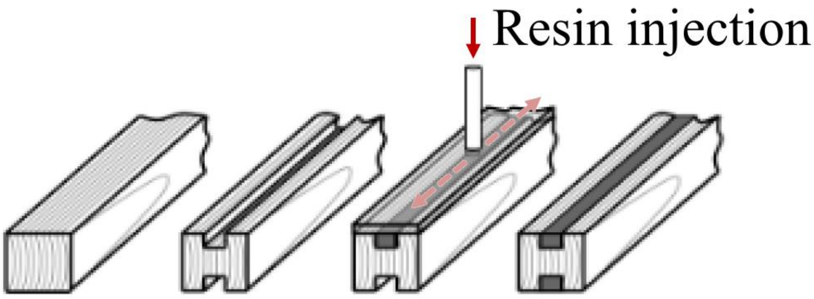

Figure 5: Principle sketch of the injection process, red marks the resin flow direction

An alternative way of infiltration is the vacuum infusion process. This can be done in two possible ways, however it is always necessary to put the specimens with inserted fibre material into a vacuum bag. In case of an infusion along the fibre, respectively the groove direction, less vacuum equipment is needed (e.g., infusion membrane, exhaust meshes). However, in that case the pressure drop can become very high, especially if fibre volume fractions are larger than 30 %. In that case, even on a relatively short specimens length of l = 360 mm, no full matrix infiltration was achieved. By use of an additional vacuum membrane bag the infiltration route of the resin is much shorter, due to a fast resin distribution on the specimen’s surface with help of a mesh like distribution medium. With this method even high fibre volume fraction up 55 % have been generated. Nevertheless, the whole wood surface within the membrane bag needs to be covered with adhesive tapes to avoid a wood-resin contact outside the infiltration area. Additionally, it was found out that a reduced vacuum pressure is required. Otherwise the low viscous epoxy resin is spreading through open wood channels like tracheids or medullary rays and exits on arbitrary locations on the wood surface. Usually a lower pressure of about 150 mbar - 200 mbar relative to the ambient pressure worked quite well for infusion, as well as for the achievable FRP quality. Due to the use of a peel ply fabric as first layer on top of the FRP material a final step of polishing is necessary to achieve a smooth surface.

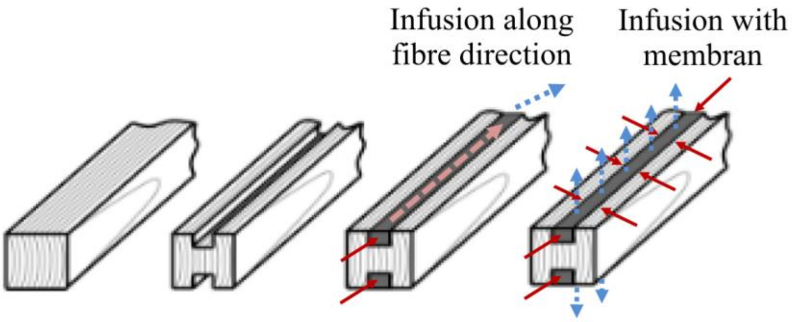

Figure 6: Principle sketch of the possible infusion processes, red marks the resin and blue the air flow direction

In general, both resin injection and infusion methods have their advantages and disadvantages, regarding flexibility, manual efforts, material usage and costs as well as quality issues. The choice of a certain manufacturing process is highly depending on the shape, size, quantity and necessary quality of the FRP reinforced wooden component.

4 Experimental evaluation of wood-FRP-composite structures

A lot of different testing methods have been applied to characterise the wood-FRP composite structure. To analyse the bonding strength various delamination, shear and peel-tests have been carried out. As one result, no significant difference between probes made by injection or infusion, regarding the bonding properties, were found. However a similar tendency according to the strength of the applied matrix resins could be found. With help of microscopic inspections the resin distribution within the wood structure was analyzed. Further dynamical fatigue tests and highly dynamical impact tests as well as static loaded long term tests have been carried out on 3-point respectively 4-point bending loaded specimens. The results from the static 4-point bending tests, according to DIN 52186 and DIN 408 and shown in Figure 7, point out the homogenization effect on wood samples with an inserted FRP segment.

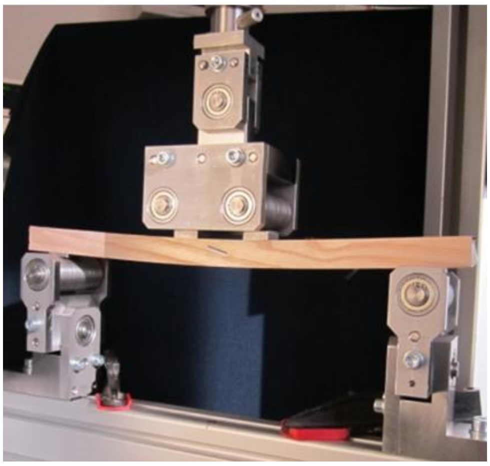

Figure 7: Setup of a 4-point bending test

With help of a calculated bending modulus, according to DIN 52186, a homogenisation effect of the stiffness behavior of wood with CFRP reinforcement (HT fibres material) under different humidity conditions at 20 °C has been proven. Considering two different epoxy resins the results have been compared to native wood samples without CFRP reinforcement as shown in Figure 8. The CFRP reinforcement was only about 3 % of the wooden specimen cross section by an average fibre volume content of about 35 %.

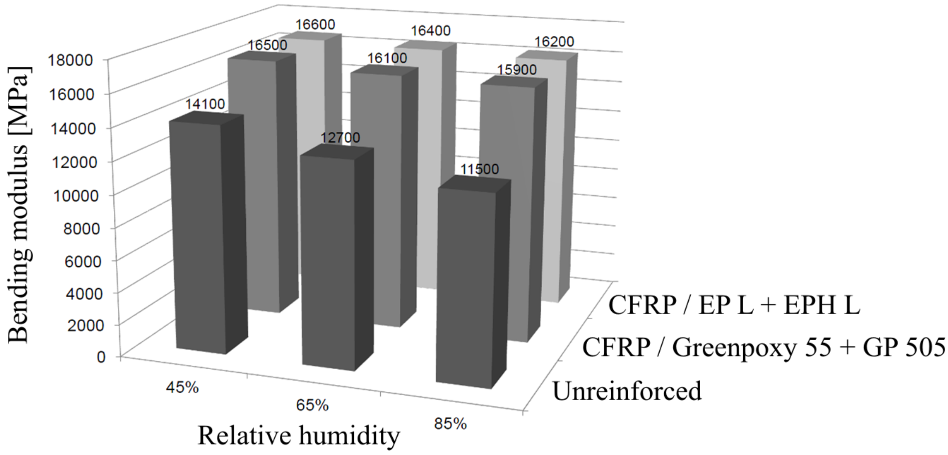

Figure 8: Bending modulus of CFRP reinforced wood specimens under different humidity conditions and with two different epoxy resin type applied

In contrast to unreinforced wood specimen, where an increase of humidity from 45 % up to 85 % causes a degradation of stiffness of about 18,5 %, the reinforced samples show merely a loss of stiffness of about 2,4 % in case of using the EP L + EPH L resin, respectively of 3,6 % when the Greenpoxy 55 + GP 505 resin was applied. However, in terms of strength the achieved improvement was not as high, but still significant. From 45 % up to 85 % humidity the CFRP reinforced specimens showed only a 15 % drop of strength instead of 33 % as found on unreinforced wood. Hereby the estimated strength data are independent of the applied matrix resin. However, a significant influence on both stiffness and strength has been detected by hardening the matrix material after the infiltration at 60 °C for 10 h compared to specimens with a resin curing only at room temperature for more than 24 h.

5 Numerical simulations of wood-FRP composite structures

In order to avoid excessive experimental testing to evaluate the improvement of stiffness of wooden components with FRP reinforcements a finite element analysis (FEA) model was created. Based on given respectively experimental found material properties of the fibre materials, the epoxy resins and the wood properties of ash a quasi-isotropic material model for the FRP component [5] and accordingly orthotropic material properties for the wooden component were implemented. A simulation model was built accordingly the previous mentioned static 4-point bending test as shown in Figure 9, considering various parameter settings, like different materials, wood fiber orientation, groove length and cross section geometry. For three different fibre materials (HT-, UMS-carbon fibres and a basalt fibre type) a variation of the fibre volume fraction was simulated considering only 3 % FRP reinforcement relative to the wood cross section. The results are shown in Figure 10. Additionally, single experimental results have been added to the chart, which do correspond to the simulation results quite well. It can be seen that even at high fibre volume fraction the basalt fibre reinforced plastic (BFRP) reinforcement does not cause an adequate stiffness improvement, as possible with a CFRP reinforcement leaving all other parameters constant.

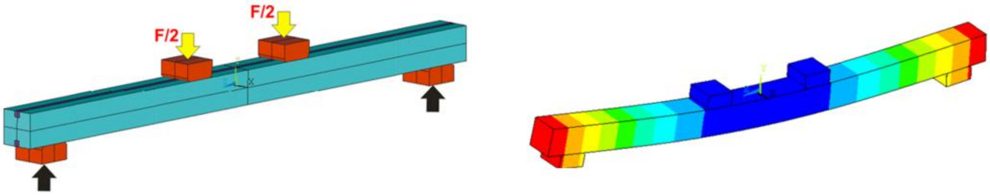

Figure 9: FEA model of a 4-point bending test with boundary condition (left), displacement in load direction (right)

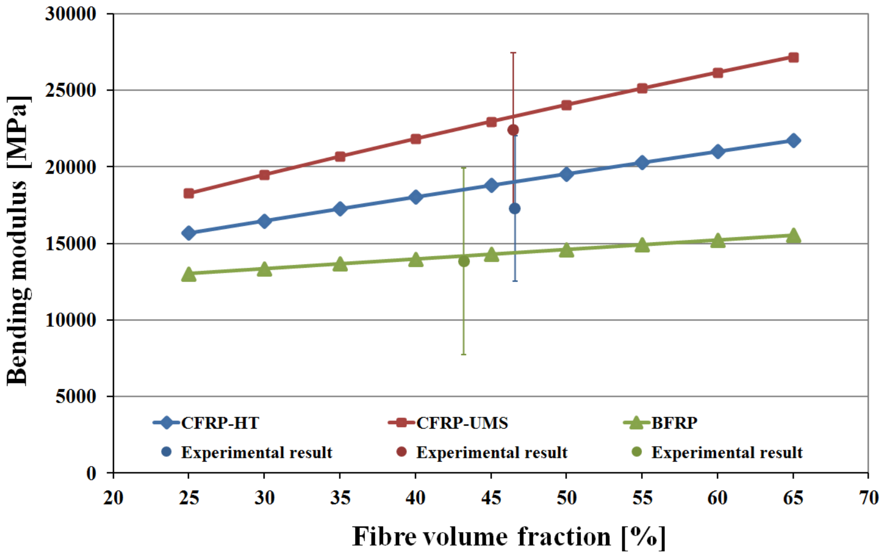

Figure 10: FEA simulation of a static 4-point bending test considering three different fibre materials for FRP with a varying of the fibre volume fraction

With help of the obtained simulation experience a dimensioning of real wood parts with FRP reinforcement can be carried out. However, for appropriate simulation results an extensive analysis of basic wood properties is necessary.

6 Summary

Based on experimental research two one-step infiltration processes to manufacture FRP reinforcements within wooden parts with small cross sections have been investigated. With help of extensive testing the achievable properties of wood-FRP composite structures have been analysed. Additionally, a FEA was carried out to consider further possible reinforcement parameters and to establish a basic design concept for future wood-FRP parts.

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