

VENEER-REINFORCED TIMBER

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ABSTRACT: This paper deals with the development of a novel veneer-reinforced timber product for load-bearing applications – veneer-reinforced timber. For this composite timber product, veneers are inserted vertically into a glulam cross-section to act as reinforcement for shear and tensile stresses perpendicular to the grain. By arranging the veneer layers between the glulam components at angles of 0° and 90°, the highly anisotropic strength and stiffness properties of glulam are homogenized. By means of numerical simulations and experimental investigations, the load-bearing behavior and the efficiency of veneer-reinforced timber are investigated.

KEYWORDS: timber composite, glued laminated timber (GLT), veneers, reinforcement, strength, stiffness, holes, notches, damage tolerance

1 INTRODUCTION

A known weakness of glued laminated timber (GLT) is the very low shear strength (only approx. 15 % of the bending strength) and tensile strength perpendicular to the grain (only approx. 2 % of the bending strength) [1]. The low strength properties often lead to cracks parallel to the grain. This applies to geometries or details such as curved beams, holes, notches, cross-connections and groups of fasteners. In addition, changing climate conditions lead to cracks caused by imbalanced shrinkage in glulam members [2,3]. The state of the art is to counteract these properties with local reinforcements, usually perpendicular to the grain direction of the wood component, e.g. by threaded rods or fully threaded screws [4]. Recent investigations [5,6,7] show a high performance of plane reinforcements over the entire beam length. Based on these investigations the objective of the research project presented is the further development of reinforced GLT.

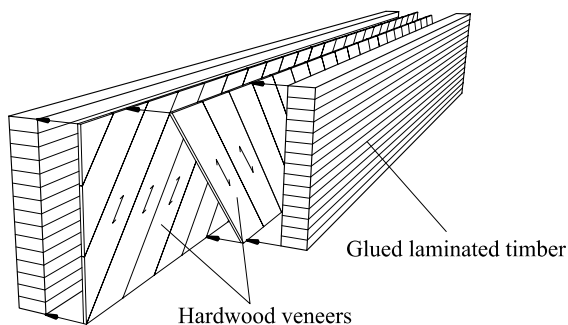


Figure 1: Veneer-reinforced timber (VRT)

The combination of glued laminated timber and hardwood (beech) veneers results in a novel composite timber

product with significantly improved strength and stiffness properties – veneer-reinforced timber (VRT) (Figure 1). The veneer layers represent a deformation-compatible reinforcement of glued laminated timber which can significantly increase the capacity in shear, tension perpendicular to the grain and around groups of fasteners. In addition this species-hybrid product supports the necessary efforts to enlarge the use of hardwoods in construction.

2 PARAMETRIC NUMERICAL MODEL

2.1 General

In order to determine the efficient cross section of veneer-reinforced timber, an extensive parameter study on veneer thicknesses and veneer inclinations was carried out using several 3-D FEM volume models. The degree of reinforcement $\delta = \Sigma t_{VP} / b$ was defined to describe the proportion of veneer plate (VP) in the cross section (Figure 2).

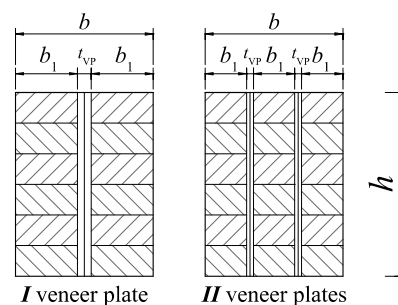


Figure 2: Cross section of veneer-reinforced timber (VRT)

Cross-sections with one veneer plate (I) and with two veneer plates (II) were investigated in the linear-elastic

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state. In the numerical model, the modulus of elasticity $E_{0,veneer}$ ($E_{0,v}$) was varied between 5.000-20.000 MPa. For glued laminated timber the stiffness values of GL28h of EN 14080 [1] were used.

2.2 TENSION PERPENDICULAR TO THE GRAIN

To investigate the influence of veneers on tension stresses perpendicular to the grain in glulam, small solids with a length $l = 100$ mm and a height $h_0 = 400$ mm and different veneer inclinations were modelled. The width b_1 was varied in 10 mm steps. The tension stresses perpendicular to the grain at $h/2$ on the surface of the GLT component of VRT were then extracted and compared with unreinforced glulam. Figure 3 shows the experimental setup of the FEM model.

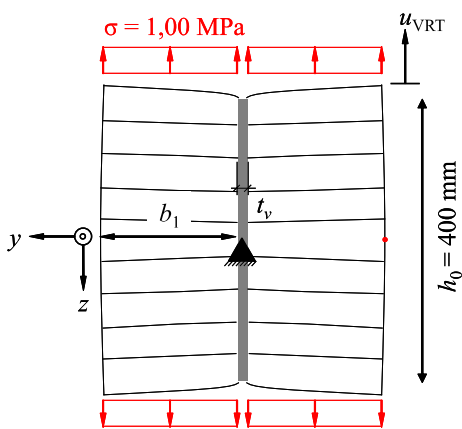


Figure 3: FEM test setup for the influence of the veneers on the tension stresses perpendicular to the grain in glulam

Figure 4 shows the reduction of the tension stresses perpendicular to the grain in the glulam component of VRT for four different veneer lay-ups and three widths b_1 (60 mm, 80 mm, 100 mm). The stresses with the index VRT are the stresses in the glulam components of VRT.

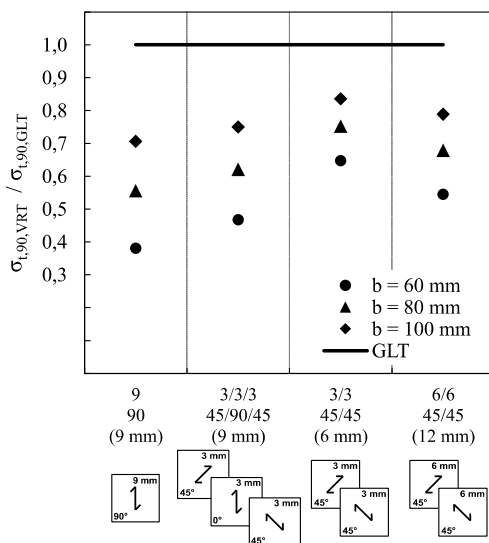


Figure 4 Influence of veneer angle and thickness on the tension stresses perpendicular to the grain in the GLT components of VRT

The veneers can reduce the tensile stresses perpendicular to the grain in the glulam section by 20-60 % in comparison to the pure GLT cross section. For this, a minimum reinforcement level of 10-15 % is required. With a glulam width b_1 of 60 mm (Figure 4) the tensile stresses perpendicular to the grain can be reduced up to 50 %. With increasing width b_1 the influence of the veneers decreases. With a width b_1 of 100 mm, the potential reduction is still 20 %.

2.3 SHEAR

The influence of the veneers on the shear stresses were investigated by means of a numerical model of a 3-point bending test. The model had a ratio $l/h = 5$ and the width of the VRT beam was 180 mm. The degree of reinforcement was gradually increased. As the degree of reinforcement increases, the stress reduction in the GLT decreases (Figure 5).

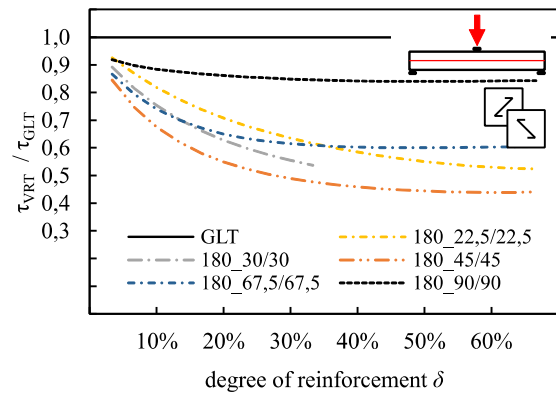


Figure 5 Shear stress reduction in the GLT component of VRT depending on the degree of reinforcement and veneer angle

A crosswise arrangement of the veneers at an angle of 45° (+45°/-45°) shows the best potential. The shear stresses in the glulam section can be reduced by 20-50 % using veneers. Figure 6 shows the bending tensile stresses in the GLT component as a function of the veneer angle and the degree of reinforcement.

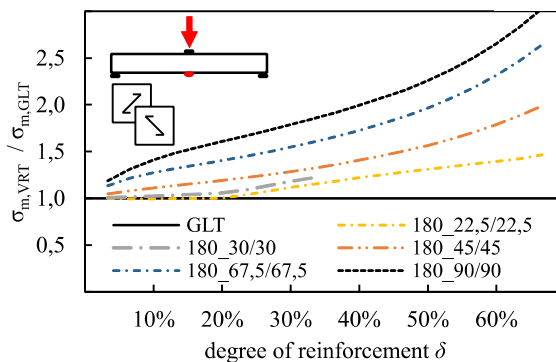


Figure 6 Influence of the angle of veneer inclination on the bending tensile stresses in the GLT component of VRT as a function of the degree of reinforcement

For a veneer angle between 0° and 22.5° (+22.5°/-22.5°) the bending stresses do not increase significantly.

2.4 MOISTURE

To estimate the influence of wood moisture changes on the tensile stresses perpendicular to the grain in the glulam part, a wood moisture change of 5 % (stationary analysis) was applied to the composite cross-section. This investigation showed that inclined veneer arrangements cause lower tensile stresses perp. to the grain compared to veneers oriented at 90° to the grain direction of GLT.

2.5 CONCLUSION

The FEM analyses show that the veneers reduce the shear and tension perp. to the grain stresses while having only a small negative effect on the bending stresses. The simulations revealed that the veneers should have a minimum modulus of elasticity $E_{0,v}$ of 10.000 MPa.

3 EXPERIMENTAL INVESTIGATION

3.1 TEST PROGRAM

The test concept has a multi-level structure. Each test specimen is first examined using non-destructive methods (vibration measurements) and then subjected to destructive testing. Three cross-sections types of VRT were produced for all experimental investigations of VRT, (Figure 11). Table 1 gives an overview of the current status of experiments.

Table 1: Current state of experimental investigations

Experiments	processing status
Tensile tests on veneers	✓
Bending	✓
Shear	✓
Notches	✓
Round holes	✓
Cross connections	✓
Tension perp. to the grain	✓
Compression perp. to the grain	✓
Moisture	in progress
Delamination	in preparation

In this paper the results of the test on veneers in tensile, bending and shear tests of reinforced cross sections as well as the load bearing behaviour of reinforced cross-sections with notches, round holes and cross connections are discussed. In addition, the current state of the moisture tests is outlined.

3.2 TENSILE STRENGTH OF BEECH VENEERS

3.2.1 Experiments

To determine the tensile strength and the modulus of elasticity ($E_{0,v}$) tensile tests according to EN 408 [8] were carried out on rotary-cut beech veneers $t_v = 1.5$ mm. The veneers for the test specimens were taken from three different tree trunks by one manufacturer. The density distribution of the veneers is shown in Figure 7. The average moisture content of the veneers of the three trunks was 9.6 % (COV 2.0 %).

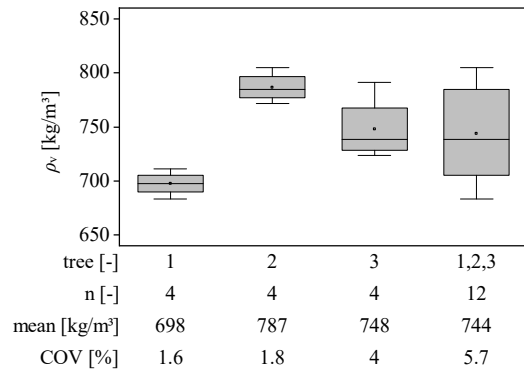


Figure 7 Density distribution of the 1.5 mm rotary-cut beech veneers per tree trunk

Test specimens were realized with I, II, IV and VI veneer layers. Glue resin Silekol® 262, a mixture of polycondensation products of urea and formaldehyde in water solution was chosen as the adhesive, as the project partner could only process this. In addition, three test specimens per tree with IV and VI layers and a phenol-resorcinol formaldehyde (PRF) adhesive were produced in the university test laboratory (MPA BAU). Figure 8 shows the test setup of the tensile tests.

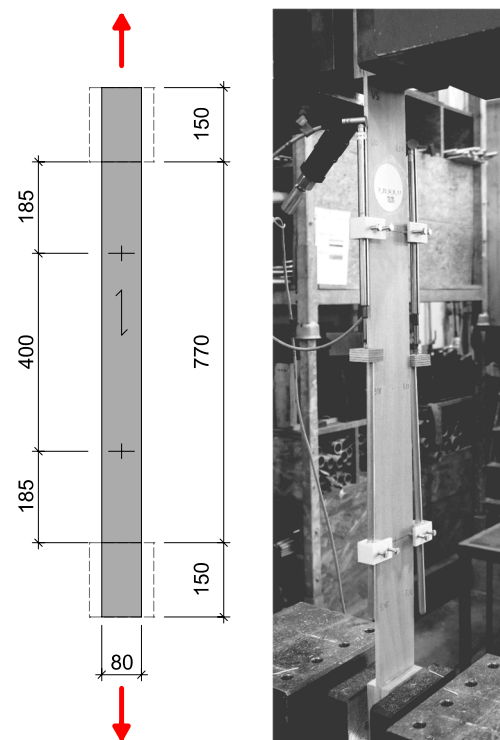


Figure 8 Test setup of the tensile tests of beech veneers

The deformation was measured with two displacement transducers, which were attached one on each side of the veneer.

3.2.2 Results

The results of the tensile tests show a strong homogenization effect for several parallel veneer layers (Figure 9).

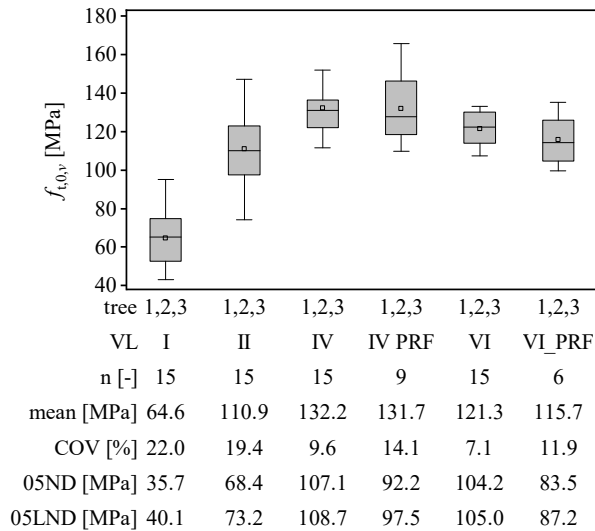


Figure 9 Tensile strength of beech veneers with different layers (I, II, IV, VI)

Tensile strengths $f_{t,k}$ of 100 MPa were achieved for the VI-layer specimens. The scattering of ($E_{0,v}$) decreases with increasing number of veneer layers (Figure 10).

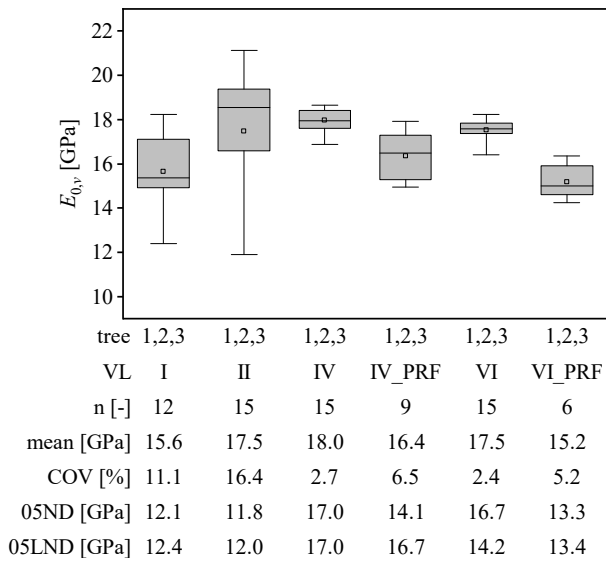


Figure 10 Modulus of elasticity (MOE) determined from the tensile tests of beech veneers as a function of the number of veneer layers

The mean MOE of PRF glued veneers is about 10 % lower than veneers with urea glue.

3.3 BENDING STRENGTH AND STIFFNESS

3.3.1 Experiments

To determine the bending behaviour of veneer-reinforced timber, three cross-sections types (Figure 11) each with three test specimens were tested in 4-point bending tests. In addition, one GLT cross-section per type was tested as a reference test specimen without veneers. The test setup followed the specifications of test standard EN 408 [8]. The span of the four-point bending tests was $18 \times h$, with a height of the beam $h = 320$ mm.

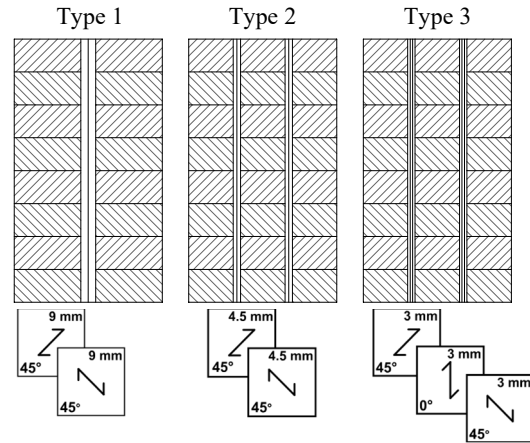


Figure 11 Cross-sections (layups) of VRT test types

The load was applied at two points at a distance of $6 \times h$ from the supports. Two hydraulic cylinders with a maximum load of 250 kN each were used. All configurations feature a degree of reinforcement of 10 %. Specimens were manufactured from GL28h, 1.50 mm rotary-cut beech veneers and PRF adhesive.

3.3.2 Results

The VRT test specimens tend to have a more localized bending fracture behavior compared to the GLT reference specimens. The resulting bending strength of the GLT and VRT test specimens was calculated according to EN 408 [8] applying the full width b (Figure 12).

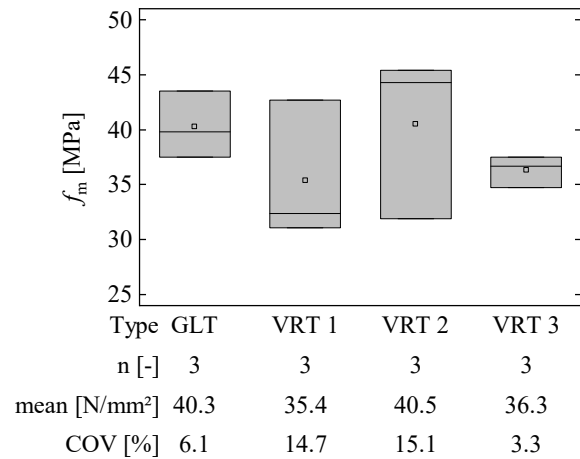


Figure 12 Determined bending strength of VRT and GLT

The mean values of the bending strengths (f_m) of VRT type 1 and 3 are approx. 10 % lower than the average value of the GLT test specimens. The behaviour is due to the degree of reinforcement ($\delta = 10$ %). Inversely, this means that the veneers do not increase the bending strength. The mean value of VRT type 2 is at the same level as that of the GLT test specimens. The reason for this is the low number of test specimens. In a test series with more test specimens, VRT type 2 is expected to behave similarly to type 1 and 3. The local and global modulus of elasticity was determined according to EN 408 [8] (Figure 13, Figure 14).

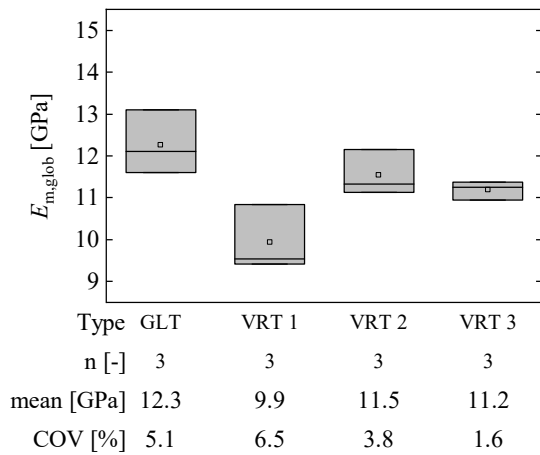


Figure 13 Global modulus of elasticity of the VRT type 1-3 and GLT test specimens

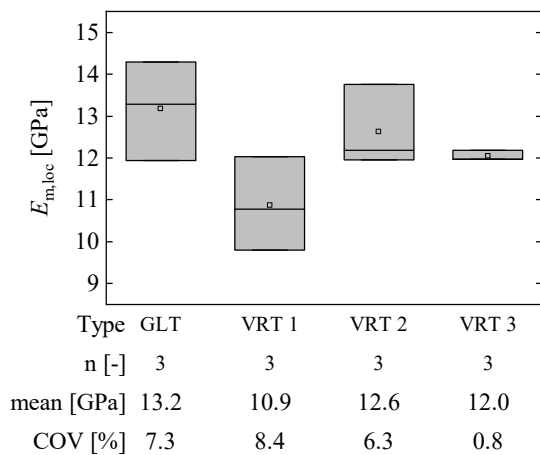


Figure 14 Local modulus of elasticity of the VRT type 1-3 and GLT test specimens

The evaluation of the measurements shows that the MOE of VRT type 1 is reduced by 20 % compared to the GLT specimens. In contrast, the modulus of elasticity of VRT type 2 is reduced by 5 % and that of type 3 by 10 %. This represents a first tendency that it is possible to insert inclined veneer plates into a glulam cross-section without significantly changing the modulus of elasticity and consequently the bending stiffness compared to glulam. However, the validity is limited by the small number of test specimens.

3.4 SHEAR STRENGTH AND STIFFNESS

3.4.1 Experiments

Compact 3-point bending tests (3PB) were carried out to investigate the shear strength (Figure 15). Furthermore, bending tests as single-span beam with cantilever were tested as 4-point bending test (4PB) according to [9,10] (Figure 16). The veneer structure and the cross-section of the shear test specimens were the same as the bending tests (Figure 11) except for the height ($h = 400$ mm). The length of the test specimens was 3000 mm.

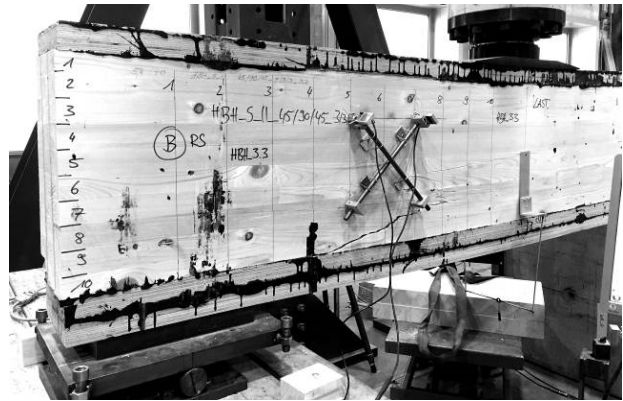


Figure 15 Setup for 3-point bending (3PB) test to determine the shear strength

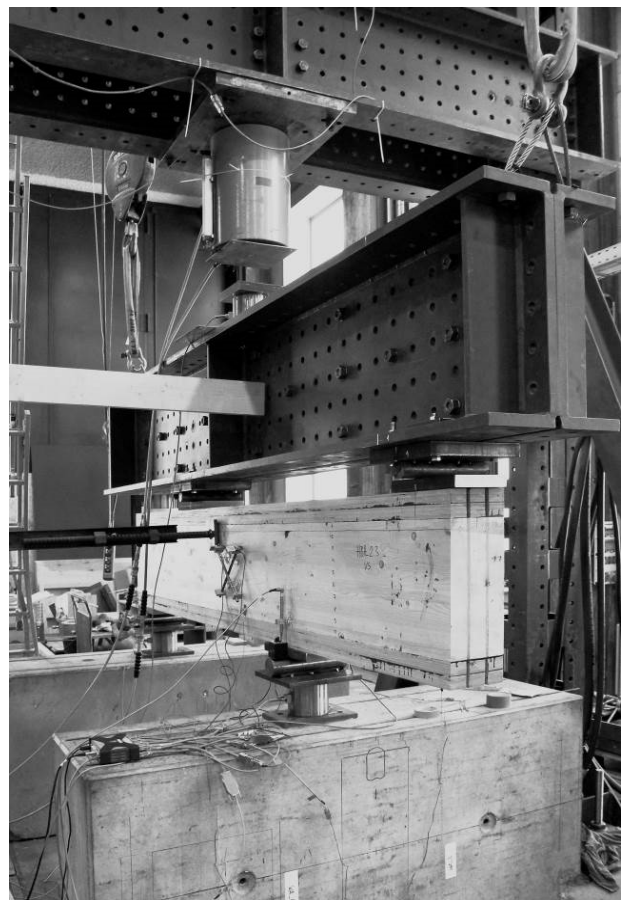


Figure 16 Setup for 4-point bending (4PB) test to determine the shear strength

As reinforcement in bending, two lamellas (80 mm each) of BauBuche S (BB, Z-9.1-838 [11]) were glued on the upper and lower beam edge. In the course of the tests the thickness of the BauBuche reinforcement was adjusted. The length of the stressed shear field $l_s = 650$ mm was the same for both test setups.

The shear stiffness was determined by measuring the shear field according to EN 408 [8]. The shear modulus was also determined as a result of the bending tests (Chapter 3.3).

3.4.2 Results

The failure of the test specimens can be categorised into four main failure types (FT). In the case of the GLT reference test specimens, shear failure (FT 1) could be achieved by the selected test setup (3PB). In contrast, two of the VRT test specimens (VRT_S_1.1, VRT_S_1.2) failed in shear in the transition area between GLT and BauBuche (FT 2). The remaining VRT test specimens (VRT_S_2.1, VRT_S_2.2) failed in bending tension (FT 3) in the GLT component and the test specimen (VRT_S_3.3) failed in shear in the first two border lamellas (FT 4). The remaining test samples (VRT_S_1.3 / 2.3 / 3.1 / 3.2) were tested with the test setup (4PB), see Figure 16. By this process, the shear force in the shear field could be increased. Only VRT_S_3.2 failed in shear (FT 1), the other specimens had failure type two and four. Taking the BB reinforcement into account, the shear stresses at the failure crack (τ_{crack}) and the maximum shear stresses (τ_{max}) were determined in relation to the full cross section width (b) on the basis of the maximum shear forces (V_{max}). The results are shown in Table 2.

Table 2: Results of the 3PB and 4PB shear tests

Type	test setup	FT	V_{max} [kN]	τ_{crack} [MPa]	τ_{max} [MPa]
GLT	S_1	3PB	315	4.6	4.6
	S_2	3PB	328	4.7	5.1
	S_3	3PB	392	5.8	6.1
VRT	S_1.1	3PB	360	2.8	5.3
	S_1.2	3PB	330	2.5	4.9
	S_1.3	4PB	376	4.7	5.6
	S_2.1	3PB	341	5.8	5.8
	S_2.2	3PB	429	6.8	6.8
	S_2.3	4PB	510	3.9	7.6
	S_3.1	4PB	472	3.6	7.0
	S_3.2	4PB	577	7.4	8.6
	S_3.3	3PB	457	5.2	7.2

FT 1 shear | FT 2 shear BB-GLT | FT 3 bending | FT 4 shear border lamellas

The determined shear stresses of failure types 1 are to be evaluated as shear strengths. All other calculated shear stresses (FT 2-4) only represent lower boundaries. Comparing the mean value of the GLT test specimens with the shear force of VRT_S_3.2, the shear force could be increased by 67 %.

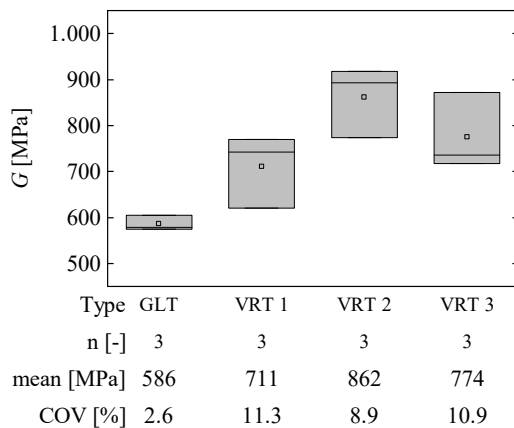


Figure 17 Shear modulus G according to EN 408 [8]

The shear modulus determined on the basis of the bending tests according to EN 408 [8] are shown in Figure 17. Compared to the GLT reference test specimens, the mean value of the shear modulus of VRT type 1 could be increased by approx. 20 %, the type 2 by approx. 50 % and the type 3 by approx. 30 %.

4 Notches, round holes and cross connections

4.1.1 Experiments

The undamaged parts of the bending test specimens were used to make test specimens for notches, round holes and cross connections. All types of VRT were investigated. The test setups are shown in Figure 18.

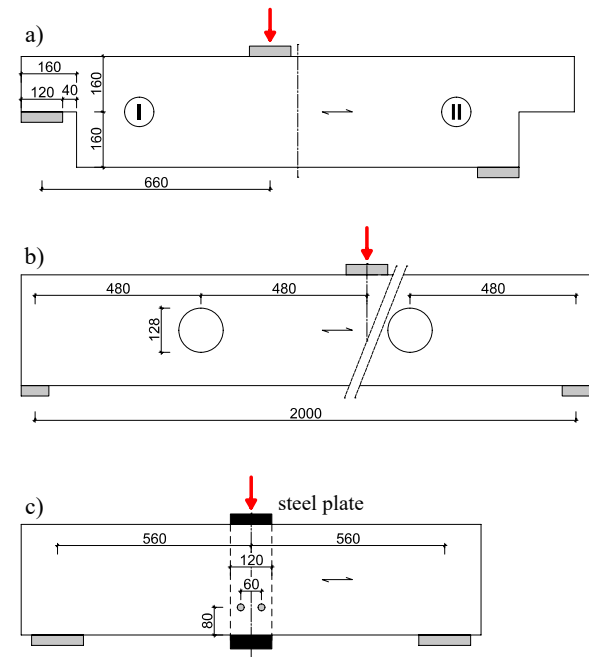


Figure 18 Test setups for notches (a), round holes (b) and cross connections (c)

The test specimens of the notches were tested twice (I, II). The round holes were selected at $0.4 \times h$ in accordance with the maximum possible diameters according to DIN EN 1995-1-1 [12]. For the tests on cross connections, dowels $d = 20$ mm (S355) and steel plates $t = 10$ mm (S235) were selected. For VRT type 1, two steel plates were placed at a distance of 30 mm from the veneer plate each and for type 2 and 3 one steel plate was placed in the middle. The relative connection height α was 0.25.

4.1.2 Results

The results of the notched VRT test specimens show a load increase factor up to five compared to unreinforced GLT reference specimens [13]. In the tests for round holes, the load was doubled in comparison to unreinforced GLT reference test specimens [14] and tripled in the case of cross connections [15]. A significantly more ductile failure was observed in all three loading situations. Figure 19 shows typical failure modes of the VRT types.

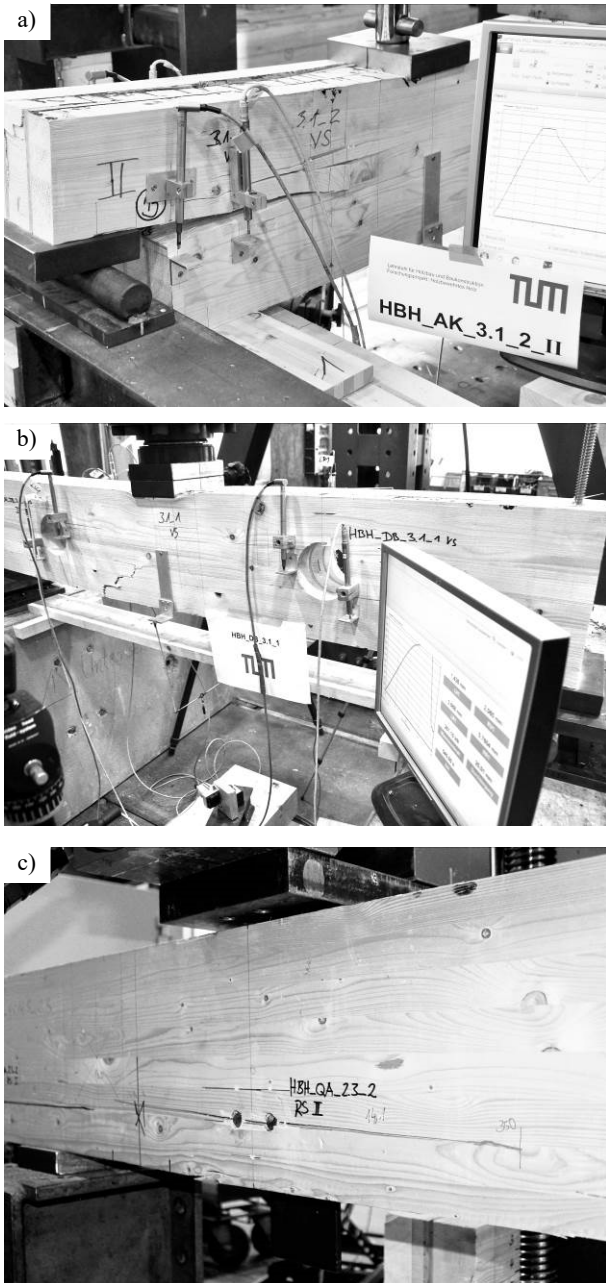


Figure 19 Typical failure modes of VRT for notches (a), round holes (b) and cross connections (c)

A detailed evaluation of the tests is currently still in progress.

5 Moisture

5.1.1 Experiments

In October 2019 18 test specimens ($l = 500$ mm, $b = 180$ mm, $h = 400$ mm) were placed in a climatic chamber (Figure 20), one GLT and three VRT test specimens per VRT types (Figure 11) [16]. In addition, two further types (F_I_90 and F_II_90) were produced. Each with three test specimens and a veneer inclination of 90° to the grain direction of the GLT components, the degree of reinforcement is also 10 %.

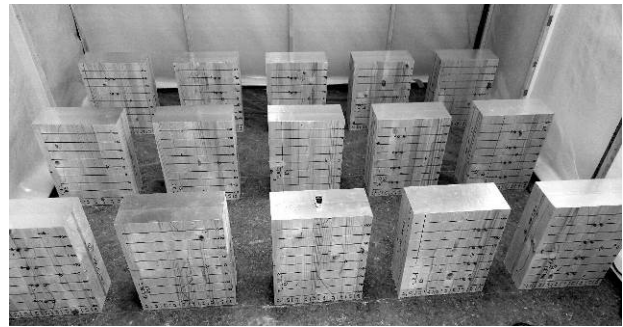


Figure 20 VRT moisture test specimen in the climate room

The relative humidity (RH) is reduced by 5 % per month at constant room temperature until a level of 30 % RH is reached. Every week, the wood moisture content of the test specimens is determined by the resistance method at different depths (15, 25, 40 and 70 mm), the volume changes are measured and any cracks that occur are recorded. In addition, each specimen is photographed every week. This approach follows [17].

5.1.2 Results

At the beginning of the climatic tests the wood moisture was determined by means of ram in electrodes at a depth of approx. 15 mm. The mean value ($u_{\text{mean},15 \text{ mm}}$) of the initial moisture content was 13.8 % (COV 3.4 %). Subsequently, the test specimens were conditioned during the first three months and the operation of the climate chamber was optimized. Afterwards the humidity was lowered for the first time (Figure 21). The weekly peaks of the curves are caused by entering the climate chamber for measurement.

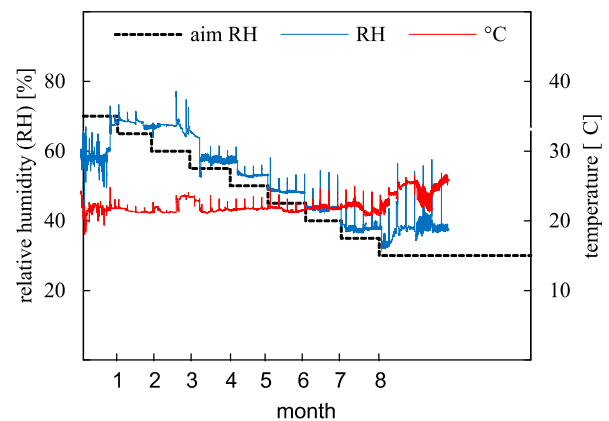


Figure 21 Course of relative humidity and temperature in the climate chamber (08.2020)

The dehumidifier used is at its capacity limit and can produce a minimum relative humidity of 35-37 % (08.2020). Measures are currently being examined to further reduce the RH. The wood moisture near the surface ($u_{15 \text{ mm}}$) was reduced by approx. $\Delta u = 5.5$ % in five months (Figure 22). As a presuming result it can be stated a clear influence of the veneer direction on the crack formation in the glulam components can already be observed.

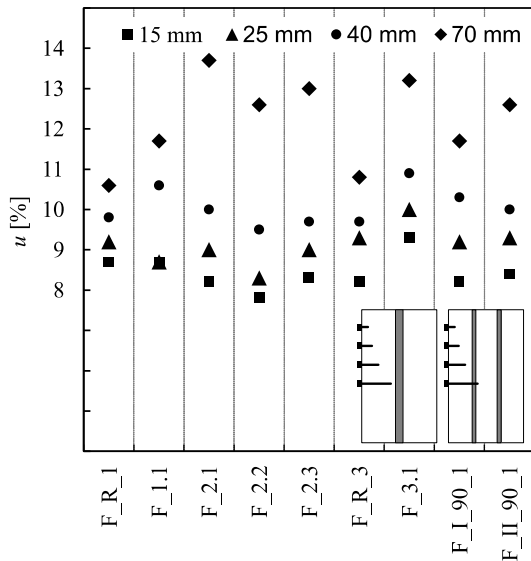


Figure 22 Status of wood moisture in GLT parts of VRT and GLT at different depths (08.2020)

6 CONCLUSIONS

Veneer-reinforced timber is a new type of wood building material based on glulam from spruce and veneers from beech. With VRT a new material with significantly improved properties perp. to grain and in shear will be available. The main outcomes of the research project so far are:

- In the case of several layers of veneers bonded in parallel, the strength increases and a clear homogenisation effect can be seen. Tensile strengths $f_{t0,k}$ up to 100 MPa can be achieved. The average values of the modulus of elasticity $E_{0,v}$ are on the same level as common hardwood products (BauBuche).
- The bending strength of VRT is reduced by the degree of reinforcement $\Sigma t_{VP} / b$. The average bending stiffness of type 2 and 3 is approximately at the same level as GLT.
- The 3PB test set-up is not suitable for determining the shear capacity of VRT. Using the 4PB test, a shear failure could be generated for one VRT test specimen of type 3. The shear force could be increased by 67 % compared to GLT and the shear modulus could be increased by up to 50 % (type 2).
- The load carrying capacity of notches could be increased by the factor of five, doubled for round holes and tripled for cross connections compared to unreinforced GLT
- Inclined veneers cause fewer cracks from restrained shrinkage in the glulam component of VRT compared to veneers oriented 90°. A detailed evaluation of the shrinkage behaviour will be carried out after completion of the climate tests.

VRT proves to be an effective alternative for the reinforcement of timber elements with geometries, in which high shear stresses or stresses perpendicular to

grain occur. The next step is to develop an economic production method for VRT.

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