FRACTURE ENERGY IN MODE I AND MODE II OF REINFORCED WOOD

Peer Haller [1] and Robert Putzger [1]
[1] Department of Civil Engineering, Technische Universität Dresden, 01062 Dresden, Germany

ABSTRACT

Textile reinforcement in timber constructions enables substantial improvement of load bearing behaviour. Failures in wood due to insufficient strength perpendicular to grain caused by anisotropy are reduced. Durability is increased during atmospheric exposure, too. We aim at guaranteeing high bond strength for a long period of time. Therefore, it is necessary to evaluate wood-textile compounds especially in consideration of long term effects. Results of all fracture tests (mode I and mode II) published in this paper follow the recommendation of RILEM TC-133. The tests confirmed stable crack growth also in glued joints for intermediate textile layers and provided a basis for using fracture energy G_f as a measure for the quality of bond strength. Fracture energy of glass fibre reinforced spruce could significantly be improved as compared to solid wood. The use of wood as a naturally grown material requires an accurate selection according to its intended application in timber constructions. This is an essential condition for a high quality wood-textile compound.

1 INTRODUCTION

In textile reinforced timber constructions, reinforcement is used on the one hand to improve weak strengths due to anisotropy of wood and on the other hand to get a better durability of especially unprotected outdoor applications. The laminate used for reinforcement consists of a textile which is embedded in a matrix and connected to the wood by an interface. These constituent parts are exposed to several physical and chemical factors, see figure 1 - left. In order to take advantage of high strengths of synthetical fibres or heavy textiles, it is necessary to obtain high bond strength.

Two methods, Haller [1,2], are used for assessment of wood-textile compound, as figure 1 - right shows. Peel force is determined according to ASTM D 3167 and serves for comparison of the influence of the environmental factors mainly among each other.

Fracture mechanics deliver a characteristic bond value independent of specimen geometry. The so-called fracture energy G_f can be used in analysis and design later. Two different specimens were tested in the laboratory by means of fracture mechanics. The DCB cleavage specimen is used in a tensile test and fails in mode I because of delamination. Unlike this, the TENF-specimen is examined in a three point bending test and fails in mode II - shear failure.

2 MATERIALS AND METHODS

All tests were conducted with specimens made of spruce. The boards where the DCB- and TENF-specimens were cut from had a thickness of 30 mm before planing. The oven-dry density was determined to approximately 0.44 g/cm³.

After machining the specimens were glued by hand. The climate in the laboratory was 20 °C and 35 % relative humidity. After manufacturing the specimens were kept under these dry conditions for some weeks. Therefore the moisture content of wood dropped to about 9 %.

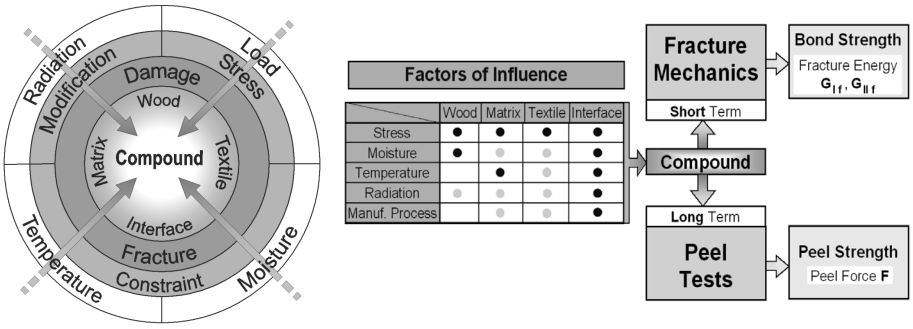

Figure 1: Factors of influence on bond strength and test methods used

The lamination process “wet in wet” was done in one step. After both parts of wood were painted with resin, the textile was placed on one part. Finally the remaining part was put on the other one. Before a PTFE foil were placed under the textile on one side of the specimen. Due to the foil it was possible to ensure a uniform initial crack of 11 cm length in the interface. Finally the specimens cured at room temperature and low pressure.

As adhesives there were used two component resins like epoxy (EP LN-1) and unsaturated polyester (Vicovoss i 25 B) with a one component polyurethane primer (VOSSCHEMIE G4). The following textiles were used for reinforcement: glass fabric 200 g/m², glass textile-complex 540 g/m², and aramid fabric 170 g/m². The textiles not only have a different weight but also have a various structure and are made of different fibre material.

Most specimens were made of wood with a fibre angle about 3 ° with respect to the bond line. This is important in order to hold the crack in the interface. The geometry of DCB- and TENF-specimen is quite similar, see figure 2 - left. The TENF-specimen got 5 cm next to the end with embedded foil additionally a tapered notch of 14 cm x 1.5 cm. The notch was done by band saw after protruding laminate of glued specimens was planed again. Before the tests, specimens were coated by means of airbrush support on both sides with brittle white colour. This is used for better visualisation of crack propagation during fracture tests.

Contrary to mode I crack propagation in mode II is very difficult to be recognized visually. The exact crack length can only be measured after the test by completely splitting the TENF-specimen, e.g. with a wedge. The fracture surface developing in failure mode II is of different nature as the one that resulted of manual splitting afterwards. This is used to determine the crack length visually. This requires a little angle between observer and surface of break as well as sufficient illumination. However, contrary to solid wood specimens, the different light reflexions on fracture surfaces of smooth laminate or glue surfaces are considerably more difficult to be recognized.

2.1 Test set-up and procedure for DCB-specimen (Mode I)

The test specimen is fixed into the machine (Zwick Z250) by means of pins. All tests were displacement-controlled. The specimens were loaded with a speed of 1.5 mm/min. After reaching the maximum displacement of approx. 10 mm a break of 30 seconds is following. In this time the crack lengths on both sides of the specimen are marked. Finally the specimen is unloaded with a rate of 5 mm/min.

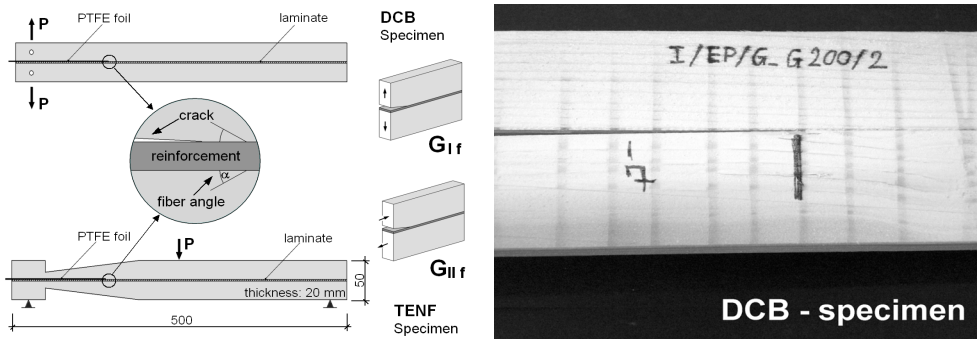

Figure 2: Geometry of fracture mechanics specimens; Crack tip in mode I

Slower speeds of unloading show the same linear deflection back to the original position, as in figure 3 - right. But using higher unloading speed, test time will be reduced and viscous-elastic influences are excluded.

2.2 Test set-up and procedure for TENF-specimen (Mode II)

Between load and support points as well as specimen body small steel plates were placed in order to reduce wood deflections. The supports are situated in a distance of 45 cm. The round shape of the supports guarantees a free rotation of specimen during bending test. The cross-head moves with a constant speed of 1 mm/min.

After a deflection of approximately 5 mm the specimen is unloaded with a speed of 4 mm/min. Some tests series with large crack propagation were examined with smaller final deflection, in order to limit crack length to about 7 cm.

3 RESULTS AND DISCUSSION

The result of each test is a load versus deflection curve. Fracture energy in mode I and mode II can be determinated by assuming stable crack growth. The fracture energy G_f is calculated as shown in eqn. (3), whereas W_{crack} is the work to create a new crack area A_{crack} eqn (2).

In mode I deflection behaves almost linear elastically during unloading. That is why for calculation of W_{crack} eqn. (1a) is integrated over total deflection. In contrast to mode I, recovery in mode II is non-linear, as can be seen in figure 3 - right. There is a permanent deflection of the specimen when unloaded. Integration over total deflection would result in too high values for fracture energy. Thus, a method by Aicher [4] is used: For calculation of $G_{II\,f}$ is assumed that the unloading branch down to the origin is linear elastic, too, see eqn (1b).

$$W_{crack,I} = \int_{u} F \cdot du \qquad \text{resp.} \qquad W_{crack,II} = \int_{0}^{u_{max}} F \cdot du - \frac{F(u_{max}) \cdot u_{max}}{2} \qquad (1.a/1.b)$$

$$A_{crack} = b \cdot \frac{a_1 + a_2}{2} \qquad \begin{array}{l} \text{a: final crack length (left and right side of specimen)} \\ \text{b: specimen width (constant 2 cm)} \end{array} \qquad (2)$$

$$G_{I/II\,f} = \frac{W_{crack,I/II}}{A_{crack}} \qquad (3)$$

Table 1: Experimental results of all fracture tests with coefficient of variation (COV in %)

Specimens	DCB (Mode I)				TENF (Mode II)			
	Number of valid specimens	Number of rejected specimens	max P [N]	Fracture energy [Nm/m²]	Number of valid specimens	Number of rejected specimens	max P [N]	Fracture energy [Nm/m²]
Spruce, massive wood	5	0	232 (12)	179 (11)	4	1	1815 (15)	737 (28)
Epoxy, no textile	6	3	223 (11)	185 (10)	3	2	1464 (17)	485 (26)
unsat. Polyester, no textile	4	1	207 (4)	215 (14)	-	-	-	-
Epoxy with glass fabric	13	5	270 (23)	235 (39)	15	11	1817 (12)	988 (25)
Epoxy with glass textile-complex	4	1	310 (19)	284 (33)	3	4	2169 (3)	923 (37)
unsat. Polyester with glass fabric	7	4	252 (13)	247 (17)	5	10	1859 (9)	1128 (19)
Epoxy with aramid fabric	4	3	288 (16)	258 (27)	5	2	1836 (8)	686 (38)

The results of all fracture mechanics tests are summarised in table 1. By means of textile reinforcement it was possible to increase fracture energy by approximately 40 % in mode I and by 25 % in mode II respectively. An exception is the laminate of epoxy resin and aramid fabric. In this case fracture energy in mode II was lower in comparison to specimens made of solid wood. Tests series with polyester resin matrix resulted in higher fracture energy than the one where an epoxy matrix was used. This general tendency was confirmed also by evaluation of peel tests, Haller [1,2]. An influence of textile with respect to textile weight or structure could not be observed.

Further on, table 1 contains mean values of ultimate load of each test series. The number of specimens is also included in table 1 and shows that fracture energies were based on a small average sample number with a partially high coefficient of variation. This has to be considered in the interpretation of the results.

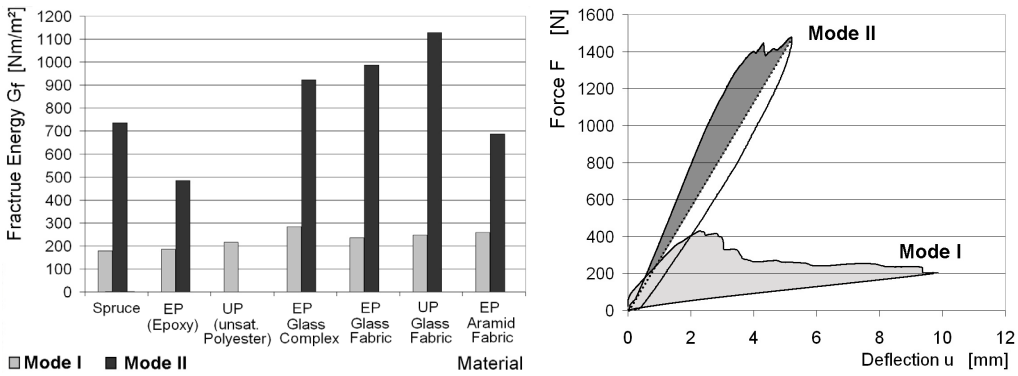

Figure 3: Summary of fracture energy and exemplary load-deflection curve in mode I and II

Besides the determination of the crack length the loading process is also important. As a limit for the stability of crack growth a maximum load drop of 3 % per second was given in RILEM TC 133 Report [3, 4]. This strict criterion could only be met in approximately half of all test specimens. Some specimens still were included in the evaluation up to a load drop of approximately 10 %.

Of altogether 120 conducted tests, 78 examined specimens could be used for evaluation. Apart from bending failure in mode II, it came to crack propagation from the laminate into the wood because of irregular grain formation in cross section or inferior wood quality. A further reason for rejecting specimens could be the low moisture of wood. The moisture content of 10 % and below was quite low and led to brittle material behaviour that was adversarial in fracture mechanics tests. The laminate itself did not beak in any of the tests.

4 CONCLUSIONS

The fracture mechanics investigations have confirmed a stable crack growth as well for intermediate textile layers. But for successful testing a suitable wood selection is of great importance.

The tests provided a basis for using fracture energy G_f as a measure for the quality of compound. Based on peel tests, the expectations of good bond strength of textile reinforced wood were met and confirmed by high values of fracture energy. As result of strengthening the fracture energy could significantly be improved compared as to solid wood.

5 REFERENCES

[1] Haller, P.; Birk, T.; Putzger, R.: Physikalische und mechanische Untersuchungen an textilbewehrtem Holz und Holzbauteilen. Technische Universität Dresden: Eigenverlag, 2002 – Arbeitsbericht des SFB 528, S. 283-322

[2] Haller, P.; Putzger, R.; Curbach, M. (Editor): Charakterisierung der Verbundfestigkeit und Dauerhaftigkeit von textilbewehrtem Holz. Technische Universität Dresden: Eigenverlag, 2003 – Proceedings of the 2nd Colloquium on Textile Reinforced Structures (CTRS2), S. 247-258

[3] Aicher, S.; Boström, L.; Gierl, M.; Kretschmann, D.; Valentin, G.: Determination of Fracture Energy of Wood in Mode II. In: RILEM TC 133 Report, SP Swedish National Testing and Research Institute, Building Technology, SPReport 1997: 13. Boras, 1997

[4] Aicher, S.; Gustafsson, P. J. (Editor); Haller, P.; Petersson, H.: Fracture mechanics models for strength analysis of timber beams with a hole or a notch – A report of RILEM TC-133. Structural Mechanics, Lund University, Sweden, 2002