DCB- and TENF-Specimens - Made of Textile Reinforced Wood

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Abstract. The use of wood as a naturally grown material requires an accurate selection according to its intended application in timber constructions. Textile reinforcement in timber constructions enables substantial improvement of load bearing behaviour. 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. All fracture tests performed in Mode I and Mode II follow the recommendation of RILEM TC-133 [2]. 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 in Mode I of reinforced spruce is higher than that of solid wood. On the other hand investigations in Mode II showed similar values of fracture energy for both laminated specimens and wood.

Introduction

For assessment of wood-textile compound two methods are used as Fig. 1 shows. The Peel tests on the right hand side determine the peel force according to ASTM D 3167 [1] and serves for comparison of the influence of the environmental factors mainly among each other.

On the other side fracture mechanics deliver a characteristic bond value independent of specimen geometry. The 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.

The laminate used for reinforcement consists of a textile which is embedded in a matrix and connected to the wood by an interface. In order to take advantage of high strengths of synthetical fibres or heavy textiles, it’s necessary to obtain high bond strength.

Test methods, Materials and Manufacturing

All tests were conducted with specimens made of spruce *(Picea abies)*. The oven-dry density was determined to approximately 0.44 g/cm³. After sawing and gluing both parts of wood specimens were planed to get a smooth surface. Most specimens were made of wood with a fibre angle of about 3 ° with respect to the bond line and flat annual rings orientation in cross section. These facts are important in order to hold the crack in the interface. Like Fig. 1 shows, geometry of DCB- and TENF-specimen is quite similar. Both specimens are 50 cm long, 5 cm high and 2 cm thick. But 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.

Two methods were used to manufacture respectively to glue fracture mechanics specimens: DCB- and TENF-specimens were either made by hand or by means of RTM (Resin Transfer Moulding) method.

In case of manufacturing specimens by hand, 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. Then the remaining part was put on the other one. Before two layers of PTFE foil were placed under the textile on one side of the specimen. Due to the foil it’s possible to ensure a uniform initial crack of 11 cm length in the interface. Finally, the specimens cured at room temperature and low pressure. The climate in the laboratory was 20 °C and 35 % relative humidity.

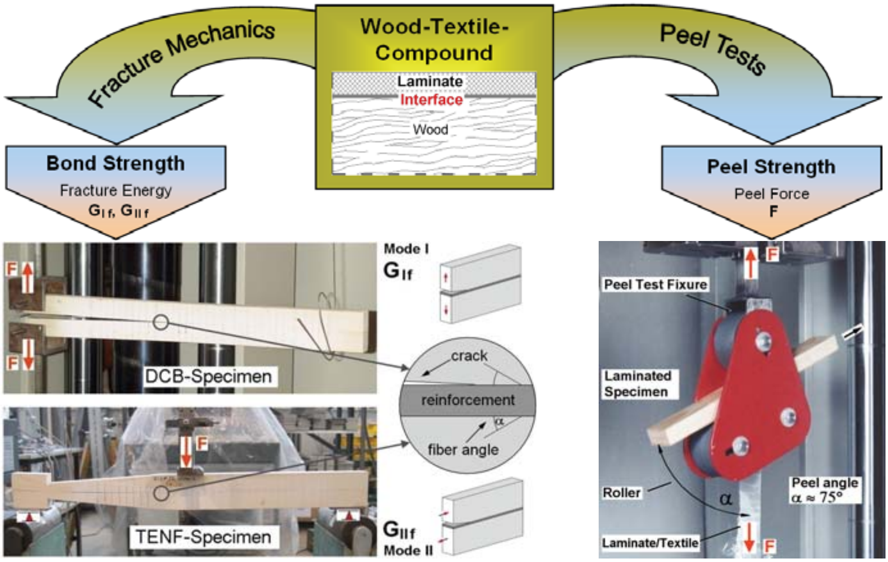


Fig. 1 Test methods for assessment of wood-textile compound

The first column in Table 2 gives an overview about investigated wood-textile compounds. As adhesives were used two component resins like epoxy (EP LN-1) and unsaturated polyester (Vicovoss i25 B) with the one component polyurethane primer (VOSSCHEMIE G4). For reinforcement textiles with various weight and structure as well as made of different kind of fibre material were used, too.

Test set-up for Double Cantilever Beam - Mode I

The one end of DCB-specimen with embedded foil is fixed into the tensile testing machine by means of pins. The other one is hanged up in a loop. Both Mode I and Mode II tests were displacement-controlled. At first specimens were loaded with a speed of 1 mm/min up to a cross head movement about 5 mm. Afterwards testing machine moves with a speed of 2 mm/min up to a displacement about 10 mm. After reaching the maximum displacement of approximately 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. All together loading and unloading one test takes about 10 minutes. Slower speeds of unloading show the same linear deflection back to the original position. But using higher unloading speed, test time will be reduced and viscous-elastic influences are excluded.

Test set-up for Tapered End Notched Flexure - Mode II

The TENF-specimen is tested in a three point bending test. Because of special geometry and the embedded foil it's intended to create a shear failure at the interface between wood and laminate.

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 to 7 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 up to 15 cm.

Contrary to Mode I crack propagation in Mode II is very difficult to be recognized visually. The exact crack length can be measured after the test only by splitting the TENF-specimen completely, e.g. with a wedge.

Results and discussion of fracture mechanics tests – Fracture energy G_f

Result of each test is a load versus deflection curve. Fracture energy in Mode I and Mode II can be determined by assuming stable crack growth. The fracture energy G_f is calculated as shown in Eq. 3, whereas W_{crack} (Eq. 1 or 2) is the work to create a new crack area A_{crack} .

$$W_{crack,I} = \oint F \cdot du \tag{1}$$

$$W_{crack,II} = \int_0^{u_{max}} F \cdot du - \frac{F(u_{max}) \cdot u_{max}}{2} \tag{2}$$

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

In Mode I deflection behaves almost linear elastically during unloading. For calculation of W_{crack} is integrated over total deflection in Eq. 1. In contrast to Mode I, recovery in Mode II is non-linear. Furthermore, there is a permanent deflection of the specimen when unloaded, see Fig. 2. Integration over total deflection would result in too high values for fracture energy. Thus, a method by Aicher [3] is used: For calculation of $G_{II\,f}$ in Eq. 2 is assumed that the unloading branch from maximum deflection down to the origin is linear elastic, too. In Fig. 2 the crack work that are used for calculation are shaded light in Mode I and dark in Mode II.

The right part of Fig. 2 shows a sample chart with a load-displacement curve in Mode I divided in three sectors. This is used for determination of fracture energy of some specimens in more detail. Table 1 contains the results of fracture energy determined by means of this method of solid wood (spruce) and two test series with textile reinforcement each with 3 specimens. Fracture energy based on crack work in sector I (displacement: 0 to 4 mm), sector II (4 to 7 mm) and sector III (7 to 10 mm) were calculated and compared to total value of energy. Table 1 shows also belonging crack length of each sector.

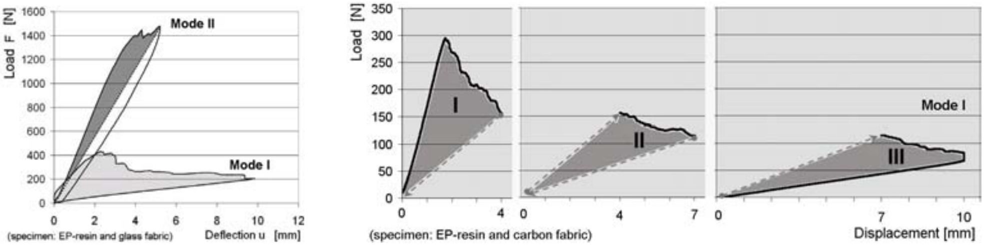


Fig. 2 Crack work shaded in load-deflection curves and segmentation of three sectors in Mode I

Table 1 Fracture energy with amount deviation and crack length in Mode I for each sector

Material	Sector Displacement [mm]		Fracture energy [Nm/m^2]						Crack length [cm]		
			I 0 to 4		II 4 to 7		III 7 to 10		I 0 to 4	II 4 to 7	III 7 to 10
I_Spruce	1	*total value*			*165,3*					*25,3*	
		sector value	**168,0**	+2 %	**156,0**	-6 %	**175,0**	+6 %	**9,5**	**9,6**	**6,2**
	2	*total value*			*169,2*					*26,3*	
		sector value	**196,0**	+16 %	**138,5**	-18 %	**167,2**	-1 %	**10,8**	**9,5**	**6,0**
	3	*total value*			*221*					*23,3*	
		sector value	**214,9**	-3 %	**213,8**	-3 %	**233,0**	+5 %	**7,7**	**7,9**	**7,8**
I_EP_GK_540	1	*total value*			*207,2*					*21,3*	
		sector value	**190,9**	-8 %	**207,4**	0	**245,9**	+19 %	**8,4**	**7,5**	**5,4**
	2	*total value*			*183,8*					*23,3*	
		sector value	**162,9**	-11 %	**169,1**	-8 %	**214,6**	+17 %	**8,8**	**9,4**	**5,1**
	3	*total value*			*234,5*					*20,5*	
		sector value	**294,2**	+25 %	**165,5**	-29 %	**253,0**	+8 %	**7,2**	**7,8**	**5,5**
I_EP_K_245_Vak	1	*total value*			*232*					*21,5*	
		sector value	**221,5**	-5 %	**233,9**	+1 %	**227,3**	-2 %	**8,4**	**7,0**	**5,9**
	2	*total value*			*207,2*					*28,7*	
		sector value	**198,7**	-4 %	**166,3**	-20 %	**165,6**	-20 %	**11,1**	**9,3**	**8,4**
	3	*total value*			*221,7*					*24,2*	
		sector value	**262,4**	+18 %	**169,0**	-24 %	**230,4**	+4 %	**7,7**	**10,6**	**5,9**

Based on these results the biggest difference between sector value and total value of solid wood is about 15 % and of reinforced specimens nearly 25 %. Despite existing deviation fracture energy on average is nearly equal and independent of observed scope of displacement of cross head. One possible assumption of higher values of fracture energy at beginning of tests because of higher load was not confirmed with these investigated specimens.

That is important for further interpretation of all fracture tests in Table 2, because that include also values of fracture energy calculated with only parts of load-displacement plots. More specimens could be used for evaluation, because not every specimen has to reject because of only instable crack growth at the end of test. The use of crack work of single sectors for evaluation of fracture energy is possible, provided that crack length of each sector is known.

The results of all fracture tests in Mode I and Mode II are summarised in Table 2. In Mode I fracture energy of textile reinforced specimens is about 30 % higher than fracture energy of test series without reinforcement. By means of RTM method fracture energy can be increased by another 10 %. All values of test series of laminated wood are higher than fracture energy of solid wood.

In contrast to Mode I evaluation of fracture energy in Mode II indicates a different performance. In this failure mode laminated specimens have only negligible higher fracture energy in comparison to unreinforced specimens. Even two of three test series with specimens manufactured by means of RTM method have up to 10 % lower values of fracture energy. Solid wood has with about 1000 Nm/m^2 the highest fracture energy in Mode II. Examination of all other specimens no matter whether reinforced or not and independent of manufacturing method results in lower values of fracture energy.

Investigated tests series with a matrix made of polyester resin and a primer result in higher fracture energy than those where an epoxy matrix is used. This general tendency is confirmed also by evaluation of peel tests [4]. An influence of textile with respect to textile weight or structure can not be observed.

Further on, Table 2 contains mean values of ultimate load of each test series. Obvious values of ultimate load are closely connected to values of fracture energy. That's why, on principle corresponding conclusions about fracture energy are valid for ultimate load, too. Therefore in Mode I higher loads are measured for reinforced specimens than for unreinforced wood. In Mode II there is no significant divergence in ultimate load between investigated test series.

Table 2 Experimental results of fracture tests with coefficient of variation (COV in %)

	Material	Textile weight [g/m²]	**Mode I** - DCB Specimen				**Mode II** – TENF Specimen			
			Number of valid specimens	Number of rejected specimens	max Load [N]	Fracture energy [Nm/m²]	Number of valid specimens	Number of rejected specimens	max Load [N]	Fracture energy [Nm/m²]
	Spruce, massive wood	-	11	0	**244** (13)	**188** (12)	13	3	**2206** (18)	**934** (38)
	Epoxy, no textile	-	15	5	**251** (13)	**209** (22)	9	3	**1785** (18)	**575** (20)
	unsat. Polyester, no textile	-	4	1	**208** (4)	**215** (14)	7	0	**1933** (7)	**681** (21)
Made by Hand	Epoxy with glass fabric	200	23	8	**270** (17)	**250** (32)	18	8	**1812** (12)	**753** (26)
Made by Hand	Epoxy with glass textile-complex	540	19	7	**261** (21)	**231** (29)	12	11	**1774** (15)	**768** (35)
Made by Hand	unsat. Polyester with glass fabric	200	10	5	**255** (12)	**252** (24)	5	10	**1860** (10)	**821** (25)
Made by Hand	Epoxy with aramid fabric	170	10	7	**273** (16)	**222** (27)	6	8	**1796** (9)	**692** (34)
Made by RTM	Epoxy with glass fabric	200	-	-	-	-	5	2	**1821** (9)	**698** (15)
Made by RTM	Epoxy with glass textile-complex	540	8	12	**321** (9)	**268** (17)	5	2	**1746** (7)	**548** (4)
Made by RTM	Epoxy with aramid (A) fabric	170	15	0	**356** (7)	**390** (7)	-	-	-	-
Made by RTM	Epoxy with carbon (C) fabric	245	9	1	**306** (14)	**264** (23)	-	-	-	-
Made by RTM	Epoxy with hybrid (A/C) fabric	205	7	0	**293** (11)	**230** (22)	-	-	-	-

The number of specimens is also included in Table 2 and shows that fracture energies of few test series are 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. In general the COV of ultimate load is smaller or equal than that of fracture energy. Because of crack length respectively crack area are only little varying within a test series, the reasons for high COV of G_f have to be explained by determination of crack work. 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 is given in RILEM TC 133 Report [2, 3]. 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 % no matter testing specimens in Mode I or Mode II.

Crack growth during fracture test

In Mode I as well as Mode II the maximum displacement of cross head movement is limited to final crack length of investigated material. It depends strongly on bond strength at interface. Because of test set up and specimens geometry the crack length usually in Mode I should be about 25 cm respectively 15 cm in Mode II.

During the test is running crack growth in Mode I can be observed easily because of continuously opening at the crack tip. But to measure crack growth in Mode II it's necessary to draw a scale of several pencil lines perpendicular to the interface respectively crack path on the TENF-specimen. Because of crack propagation the upper part of specimen slides on the lower one. Thus lines are displaced against one another and indicate that way the position of the crack tip. Even this method enables to measure crack length during the test.

Table 3 Crack growth in *Mode I* with Coefficient of Variation (COV in %)

Material		Crack length [cm] with COV [%] in Mode I																							
		Foreside												Backside											
Displacement [mm]		2	2,5	3	3,5	4	4,5	5	6	7	8	9	10	2	2,5	3	3,5	4	4,5	5	6	7	8	9	10
I_Spruce	Crack	1	4	5	7	10	11	13	16	18	21	24	26	2	3	6	8	10	11	14	16	18	21	24	26
	COV	22	12	8	11	13	15	12	12	11	9	6	5	51	30	17	16	13	16	12	9	12	11	8	6
I_EP_no textile	Crack	2	3	5	7	9	9	12	14	16	18	20	21	2	2	5	6	9	10	12	14	16	18	20	22
	COV	44	46	28	27	28	24	20	15	19	14	12	11	81	60	37	31	30	29	21	17	18	15	12	11
I_UP_no textile	Crack	5		7		9		12	13	16	18	19	21	3		6		9		11	12	15	17	18	20
	COV	61		24		7		11	6	13	14		18	31		26		13		13	1	12	11		11
I_EP_G200	Crack			4		8		11	13	16	17	25	21			4		7		11	11	16	16	24	21
	COV			39		23		20	23	18	8	11	17			42		31		20	25	18	12	7	18
I_UP_G200	Crack			2		6		6	11	11	16	14	19			3		5		5	10	10	15	14	18
	COV			126		65		40	40	24	22	12	18			113		68		36	41	27	26	10	18
I_EP_GK540	Crack			5		9		12	16	17	20	22	23			5		8		11	16	16	20	22	23
	COV			25		17		16	13	9	12	10	11			36		16		13	11	8	7	9	11
I_EP_A170	Crack			5		8		12	15	17	20	23	24			5		9		12	15	17	19	23	24
	COV			27		11		15	10	10	12	11	12			26		9		12	12	10	12	14	13
I_EP_GK540_Vaku	Crack			4	7	9	12	12	15	17	19	24	24		3	4	7	8	11	11	12	17	19	24	23
	COV			44	44	33	9	31	22	20	18	6	16			34	20	33	10	25	22	21	21	0	19
I_EP_A170_Vaku	Crack			2		5		8	11	13	16		19			2		5		8	12	13	16		18
	COV			46		38		23	21	11	16		8			40		25		18	10	10	8		8
I_EP_K245_Vaku	Crack			4		8		11		17		23	23			4		8		11		17		23	23
	COV			35		26		22		15		6	14			30		18		17		14		8	12
I_EP_Hybrid_Vaku	Crack			4		8		12		17			23			4		8		11		17			23
	COV			38		26		19		20			16			60		34		24		18			15

For all tested materials in Mode I Table 3 shows the mean values of crack growth in Mode I for movement of cross head from 2 to 10 mm displacement: There is a good agreement between crack length for both foreside and backside. The values of final crack length are closed together independent of material and manufacturing method. Unreinforced wood displays with about 26 cm one of the biggest crack length at 10 mm displacement. At cross head movement smaller than 2 mm it's not possible to measure crack length visually.

The results in Table 3 presents with increasing crack length a decrease of coefficient of Variation. That means in course of fracture test crack growth will be more stable. The COV averages only 50 % or less in the last part compared to high values of the first part.

The charts in Fig. 3 show crack growth in Mode I and for one selected example in Mode II. The added trend lines represent in a good way linear behaviour of crack growth. Obviously in Mode I the extension of trend lines intersect the point of origin. In Mode II scattered trend lines intersect axis of abscissas at about 3 or 4 mm displacement.

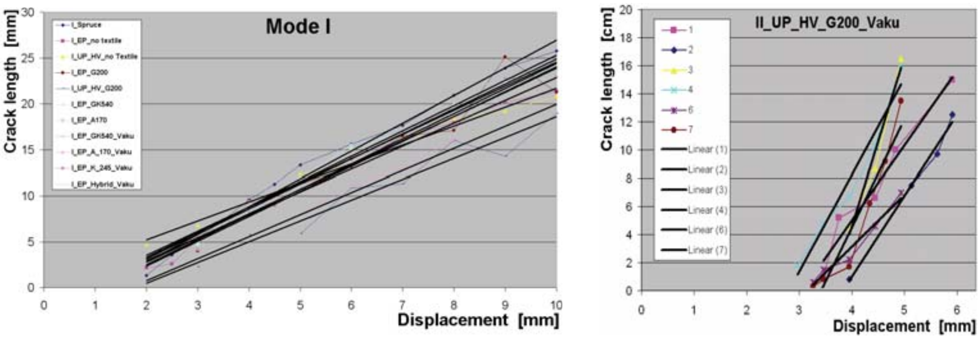
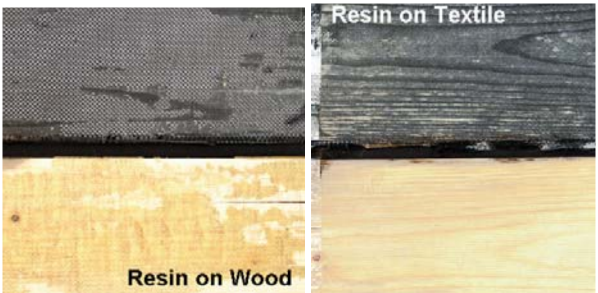


Fig. 3 Trend lines of crack growth in *Mode I* (all series) and in *Mode II*



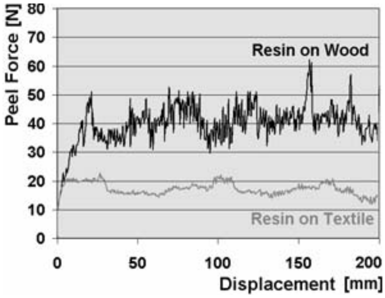


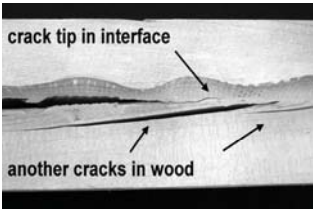
Fig. 4 Interface failure modes RoW and RoT with corresponding Peel Force – Displacement plot

Failure modes of laminated specimens

Besides fracture tests as well peel tests were performed [4]. It's used for assessment of wood-textile compound especially under consideration of long term effects. The result of each test is a peel force versus displacement curve. Fig. 4 shows two plots for peel specimens with different kind of failure modes made of carbon fabric. Obvious, the peel forces are connected with the failure modes. The correlation between failure mode and bond strength is observed also to specimens of fracture mechanics tests. For a better understanding of failure modes the interface of wood-textile compound has to be divided in two layers: First in the interface between wood and resin and second in the interface between resin and textile.

Fig. 4 contains two photos of tested peel specimens with typical failure modes of wood-textile compounds. The left picture shows resin on wood after delamination. That means during examination the textile was peeled up and resin remains on wood surface (RoW). This kind of failure in the interface between resin and textile requires high forces and leads to relative low distribution of test results. The right picture shows the failure of the interface between wood and resin (RoT). In this case resin is still bonded to textile and during crack propagation some fibres are splitted off wood surface. This failure creates a smooth surface. It requires low loads and leads further more to a wide distribution of test results. Also typical is splitting of wood or shear failure of wooden specimen. Because of determination of wood-textile compound this kind of failure is unwanted and specimens in each case will be rejected. The laminate itself did never break.

Of altogether 304 conducted tests, 211 examined specimens could be used for evaluation. The reasons for rejecting one third of specimens are of different nature. Fig. 5 gives an example of unwanted failure types because of development of multiple cracks in process zone. Sometimes low strength perpendicular to grain direction caused small additional cracks near the crack tip and leads to wood splitting at all. A further reason for rejecting specimens could be the low moisture of wood. The moisture content of 10 % and below leads to brittle material behaviour that was harmful to fracture tests.



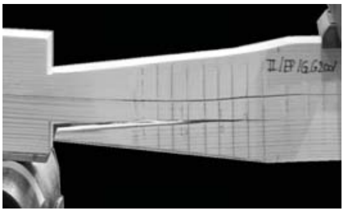


Fig. 5 Multiple cracks in process zone of DCB- and TENF-specimens

Summary

The fracture mechanics investigations in this study have confirmed stable crack propagation in Mode I and Mode II as well for intermediate textile layers. But for successful testing a careful wood selection with a wood fibre inclination of about 3 ° to the bond line is of great importance in order to hold crack in interface between wood and laminate.

The fracture tests provided a basis for using fracture energy G_f as a measure for the quality of compound. The examination of DCB- and TENF-specimens is suitable to characterize the interface between wood and textile reinforcement.

Based on peel tests, the expectations of good bond strength of textile reinforced wood are met and confirmed by high values of fracture energy. As result of strengthening fracture energy in Mode I is up to 30 % higher compared to solid wood. However fracture tests in Mode II resulted in approximately same values of fracture energy for reinforced wood as well as solid wood.

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