WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

MODE I FRACTURE ENERGY OF HARDWOOD GLUELINES VIA TESTS

Martina Sciomenta[1], Antonios G. Stamopoulos [2]

ABSTRACT: Engineered wood products (EWPs) are characterized for a wide use of structural adhesives. The glue-lines between the board's faces play a key role to guarantee the stability and load-bearing features of structural elements. One of the most revealing properties to assess the bonding quality and behavior is the fracture energy (or toughness), which could be estimated by performing suitable tests. Previous works were focused on the bonding properties of structural adhesives with softwood species, nevertheless, the widespread interest on hardwoods and the major bonding issues of those species, led to focus on two of the most interesting species in Europe and Italy: beech and chestnut. The fracture toughness behavior of two different categories of adhesives for structural applications was investigated, namely melamine-urea-formaldehyde (MUF) and phenol-resorcinol-formaldehyde (PRF). The results revealed different fracture toughness behavior between the various adhesives and timber species. In particular, the adhesives combined with beech reached the highest values if both ultimate load and fracture toughness with increased performances recorded for melamine adhesive. Melamine combined with chestnut led to more stable crack propagations and fracture energy; Spruce behaved similarly with both melamine and phenolic adhesive. Softwood reached the minimum value of fracture energy when compared to hardwoods.

KEYWORDS: Timber, Wood adhesives, Hardwood, Mode I loading, Fracture Toughness

1 – INTRODUCTION

Timber has emerged as a widespread appreciated construction material in recent decades, primarily due to its high sustainability. The advancement of adhesive technologies for engineered wood products (EWPs) has significantly mitigated many of the limitations associated with sawn solid timber for construction purposes. This progress has led to a more efficient utilization of raw materials and, consequently, improved forest resource management. The main overcomes are the increased variability of cross section shape and length and the enhancing strength and stiffness properties

Ensuring the bonding quality of structural EWPs is critical for their load-bearing capacity and overall structural performance. Consequently, numerous researchers have undertaken experimental studies to evaluate bonding parameters [1], validate test methodologies, and develop novel eco-friendly and advanced adhesives for composite timber-based products.

The adhesive-wood interface is a highly complex mechanical system, where localized failures such as non-uniform cracking in the adherend/adhesive and fiber bridging may occur. The failure mechanisms of bonded timber joints often involve intricate delamination processes, in which the adhesive and timber may fail along the bond line in a brittle manner. Despite significant advancements in the science and engineering of wood adhesion, the accurate characterization and modeling of wood-wood adhesive bonding behavior remain an unresolved challenge. To date, only limited research has been conducted on this topic.

2 – BACKGROUND

Mechanical properties of wood adhesive bonds are typically assessed through mechanical testing, such as block shear tests or other standardized methods. A comprehensive review of various testing methodologies for characterizing adhesive bonding in timber structures is presented by Stoeckel et al. These [2], however, they have well-documented limitations, including non-uniform stress

[1] Martina Sciomenta, Department of Civil, Architecture and Building and Environmental Engineering (DICEAA), University of L'Aquila, L'Aquila, Italy, martina.sciomenta@univaq.it

[2] Antonios G. Stamopoulos, Department of Industrial and Information Engineering and Economics (DIIIE), University of L'Aquila, L'Aquila, Italy, antonios.stamopoulos@univaq.it

https://doi.org/10.52202/080513-0594

distribution and the simultaneous development of both normal and shear stresses. Additionally, certain methods require large specimen sizes, increasing the likelihood of brittle wood failure and limiting the assessment of bond line fracture energy.

Most adhesives have been found to bond wood effectively enough to cause wood/adherend failure, yet detailed data on adhesive bonding properties remain scarce. However, such properties can be determined through appropriate testing of bond characteristics in terms of fracture energy or fracture toughness. Fracture mechanics methods have gained prominence in recent years for evaluating adhesive bonding properties. Within this framework, fracture is assumed to occur when the energy release rate (G) reaches the critical fracture energy (G_c), which is considered a material property. The energy release rate corresponds to the release of stored energy within the structure and the work performed by applied loads per unit of created crack surface during crack propagation.

Three loading modes are considered in fracture mechanics:

- Mode I: The adherends separate perpendicularly to the adhesive layer.
- Mode II & III: Other shear-based fracture modes, though not as frequently tested in timber adhesives.

Currently, there is no standardized method for quantifying the strain energy release rate of timber bond delamination. Several studies have focused on Mode I adhesive bonding testing using the Double Cantilever Beam (DCB) and Tapered Double Cantilever Beam (TDCB) methods. These techniques, widely adopted in other industries such as dissimilar material bonding and fiber-reinforced composite bonding, have been instrumental in examining the effects of geometric and environmental conditions on bond strength. Notable studies include:

Gagliano and Frazier [3], who tested the Mode I fracture energy of phenol-formaldehyde bonded wood using the DCB test. Veigel et al. [4], who determined the specific fracture energy of spruce wood-bonded joints via the DCB test. Davalos et al. [5], who employed the Constant-Taper Contoured Double Cantilever Beam (CTDCB) test to characterize Mode I fracture in wood-wood bonded interfaces, determining critical loads for crack initiation and arrest.

Given these findings, it is clear that testing methodologies developed for other materials could be adapted for assessing timber adhesive joints. The ASTM-D5528 [6] standard, originally designed for Mode I interlaminar fracture toughness testing of unidirectional fiber-reinforced composites, has frequently been modified for timber applications. This standard relies on DCB testing and employs three data reduction methods to calculate fracture energy release rate (G_I): *(i)* Modified Beam Theory (MBT); *(ii)* Compliance Calibration (CC) and (*iii*) Modified Compliance Calibration (MCC).

The accuracy of ASTM-D5528 [6] is highly dependent on precise monitoring of crack length, which is typically conducted using an optical microscope.

3 – PROJECT DESCRIPTION

Two structural adhesives were tested in the present study: *(i)* One bi-component liquid melamine-urea-formaldehyde (MUF) adhesive (Trevigiana Collanti TCM042 with hardener CK42) and *(ii)* One bi-component phenol-resorcinol-formaldehyde (PRF) adhesive (Trevigiana Collanti TCF017 with hardener CK26) for waterproof and heat-resistant applications.

The two adhesives were applied on lamellas cut from defect free sawn boards of three local timber species: European spruce (*Picea Abies*) with an average density of 450 kg/m^3, beech (*Fagus sylvatica L.*) with an average density of 704 kg/m^3 and chestnut (*Castanea sativa Mill.*) with an average density of 547 kg/m^3.Boards were cut into lamellas up to the dimensions of (length ×width × thickness/300 × 25 × 10 mm) corresponding to the L, B, and h directions respectively (Fig.1c). Lamellas were treated using a planer machine prior to the bonding in accordance with EN 301:2023 [7] prescriptions.

The adhesives were applied manually by using an electrical pneumatic dispensing system (DA 1000T) from DAVtech S.r.l. to guarantee a high spread precision and repeatability and to reproduce the industrial manufacturing process.

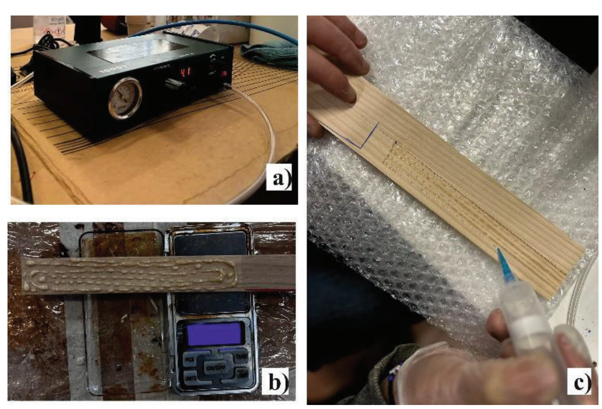

Figure 1. Specimen manufacturing: a) the glue spreading machine; b) the measuring of glue spreading rate, c) the glue line deposition

https://doi.org/10.52202/080513-0594

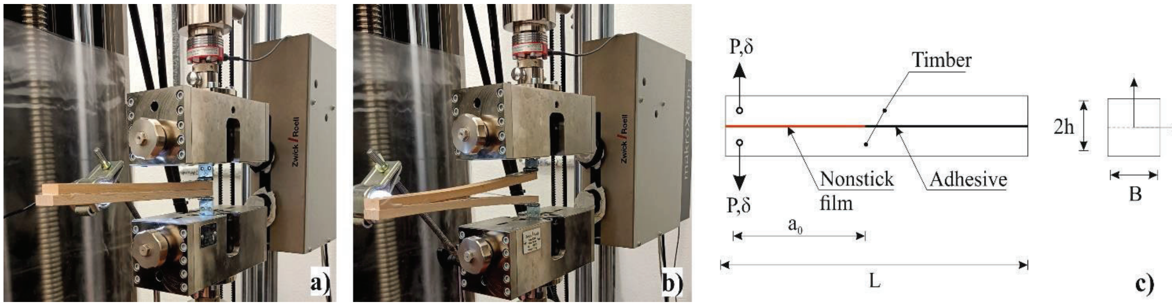

Figure 2. Specimen: a) starting point of DCB test, b) opening point of DCB test, c) geometrical features

The adhesive spread rate as well as parameters related to the polymerization conditions of the adhesives were adopted from the manufacturers 'guidelines summarized in Table 1. In accordance with the reference standards EN 301:2023 [7] dealing with phenolic and amino-plastic adhesives, a bondline thickness of 0.15 mm was assessed and used for the specimens manufacturing. To guarantee the right thickness a plastic insert having a calibrated thickness equal to 0.15 mm and length a_0= 120 mm was placed on the free edge of the specimen (Fig.1c)

Table 1: Relevant specifications for adhesives

Adhesive	**Spread Rate**	**Pressing Duration**	**Applied Pressure]**	**Mixing Ratio**
Type	***[g/m²]***	***[h]***	***[MPa]***	***[-]***
MUF	300	8	0.5	100:20
PRF	300	3 ½	0.5	100:15

Five repetitions for each combination of adhesive type and timber species were realized in accordance with Table 2

Table 2: Combination of adhesive type - timber species and relative abbreviations

Adhesive	**Timber species**		
Type	***Beech***	***Chestnut***	***Spruce***
MUF	BM (5)	CM (5)	SM (5)
PRF	BP (5)	CP (5)	SP (5)

The number in the bracket represents the number of repetitions for each configuration

4 – EXPERIMENTAL SETUP

The lack of specific standards for testing the fracture toughness of timber adhesives and the great analogy among the failure of composites and past research on bondlines on timber samples, allow to follow the testing methods of the ASTM D5528 standard [6] specifically formulated for composite structures. Its principles regarding the basic the execution of the tests were taken into consideration. The double cantilever beam (DCB) test was used to evaluate fracture mechanical properties under Mode I opening. A schematic representation of the DCB test is shown in Fig. 1a, 1b. The specimen, which was composed of 2 symmetrical prismatic adherends, had a cross-section of *L* x *B*. The initial delamination length, a_0=100 mm, was the distance from the load line to the end of the lamination (Fig.1c). The Mode I fracture along the linear distance (L-a_0) was assumed to occur while applying the load through the piano hinges. The load was applied by a Universal Testing Machine model Z100 by Zwick Roell having a capacity of 100 kN applied force. The load, *P*, was originally applied perpendicularly to the bond line and transmitted to the specimen by two hinges at a distance *L* as shown in Fig. 2. The load was applied by a Universal Testing Machine model Z100 by Zwick Roell having a capacity of 100 kN applied force. The load, *P*, was originally applied perpendicularly to the bond line and transmitted to the specimen by two hinges at a distance *L* as shown in Fig. 2.

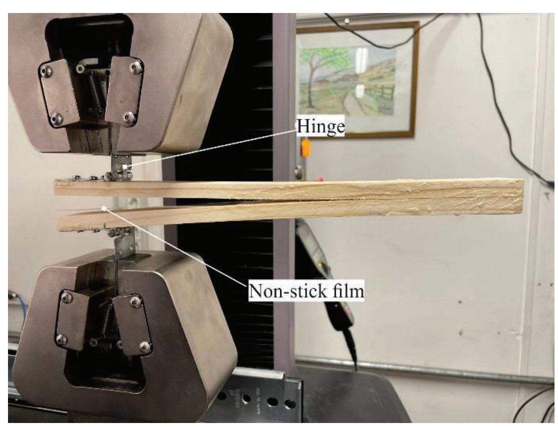

Figure 2. Specimen and hinges

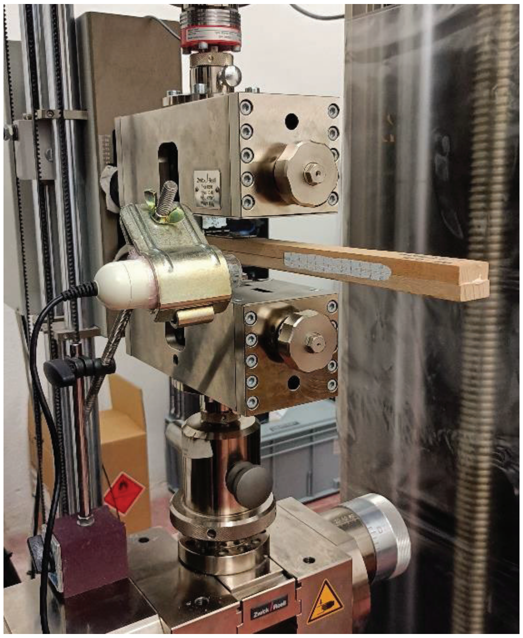

Figure 3. Setup including testing machine and optical microscope

According to ASTM D5528 standard [6] the crosshead speed was set to 1 mm/min that corresponds to the lowest value of the static test. A critical aspect is the observation of the crack front evolution optically. This task was performed using a Dino-Lite AM2111 portable optical microscope with 200x magnification capacity that was mounted in a movable base fixture, as seen in Fig.3. This practise is typical for monitoring the crack initiation and propagation in such kind of fracture toughness tests as seen in previous works [8]. To improve the visibility of the crack front on the side surface it has been clean, painted with white spray-ink, and marked with ticks 5 mm spaced each other to correlate the expansion of the crack with the testing machine load and crosshead displacement. The values of applied load, crosshead displacement are correlated with the visual observation of the crack extension at each tick (VIS).

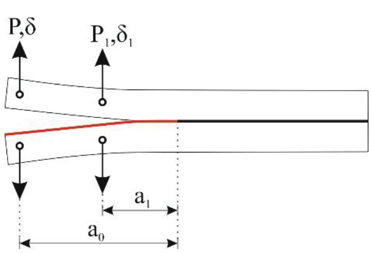

Figure 4. Determination of the root rotation correction factor Δ.

Two loading stages were conducted on each DCB specimen tested for mode I fracture energy determination, one pre-loading stages with a_1=10 mm initial crack lengths and one complete loading process up to failure with a_0=100 mm initial crack length as presented in Figure 4. The pre-loading on the DCB specimen was carried out prior to loading up to failure to obtain a sharp initial crack tip, leading to 2–5 mm crack propagation.

Measurement of the Machine Compliance

The tensile testing machine with associated grips and pins don't have an infinite stiffness and hence the compliance associated with the machine set-up should be determined and considered in the calculations. In our case the compliance is achieved by adopting the Modified Beam Theory (MBT). The compliance, C, is the ratio of the load point displacement to the applied load, δ/P. Δ was be determined experimentally by generating a leasts squares plot of the cube root of compliance, $C^{1/3}$, as a function of delamination length (Fig.5).

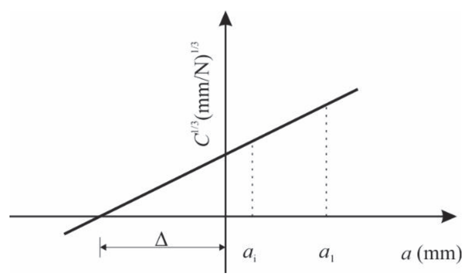

Figure 5. The definition of the Δ parameter of the modified beam theory

The correcting factor Δ will be added to the delamination length a to take account of the deflections in the loading system in the calculation of the fracture toughness

5 – STATISTICAL ANALYSIS

After the fracture energy was obtained, a two-factor ANOVA statistical analysis was conducted to determine the effect of the parameters taken into consideration, namely the adhesive type and the timber species and their combinations, on the critical energy release rate G_{IC}. α was kept equal to 0.05.

6– RESULTS

The results, in terms of Load-Crosshead displacement are presented in Fig.5 and Fig.6. In terms of applied load, the melamine adhesive combined with beech reached the maximum values of mean applied load (124.5 N) which is 21% higher than the mean maximum load achieved by combining beech with phenolic adhesive. Chestnut and Spruce bonded with melamine reached approximately the same mean value of maximum load equal to 63.6 N and

https://doi.org/10.52202/080513-0594

61.2 N respectively. The same condition was recorded by using phenolic adhesive; in this case slightly higher mean maximum load were reached (66.2 N for chestnut and 64.1 for spruce). The major maximum load scattering was recorded for chestnut bonded with melamine glue, which was twice the scattering recorded with phenolic adhesive.

When employed with hardwood species, melamine adhesive demonstrated superior values of both applied load and machine displacement required for opening the crack. Additionally, the crack propagation, resulted much more stable, especially with chestnut. Differently, phenolic adhesive with chestnut highlighted a crack propagation predominantly unstable delivering a sudden load drop to the corresponding curves (Fig.6b).

In terms of the critical energy release rate G_{IC}, the average values three specie both with melamine and phenolic adhesives are presented in the histogram of Fig. 7 along with the standard deviation of each adhesive type. Melamine demonstrated the highest fracture toughness combined with beech adherend. For chestnut, despite reaching similar level of ultimate load, the melamine adhesive reached higher value of G_{IC} and a lower instability.

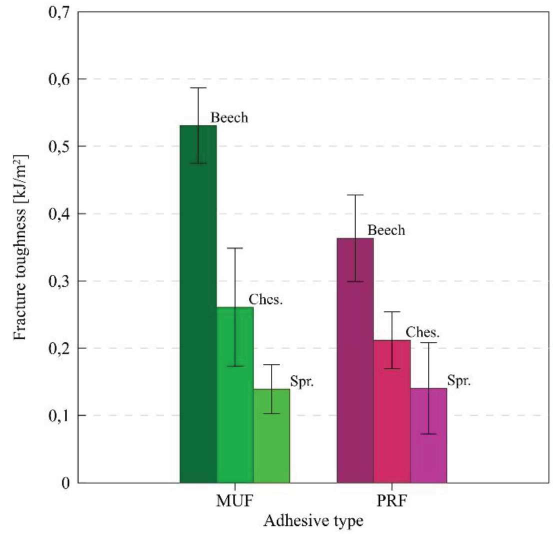

Figure 7. Histogram for the comparison of G_{IC}

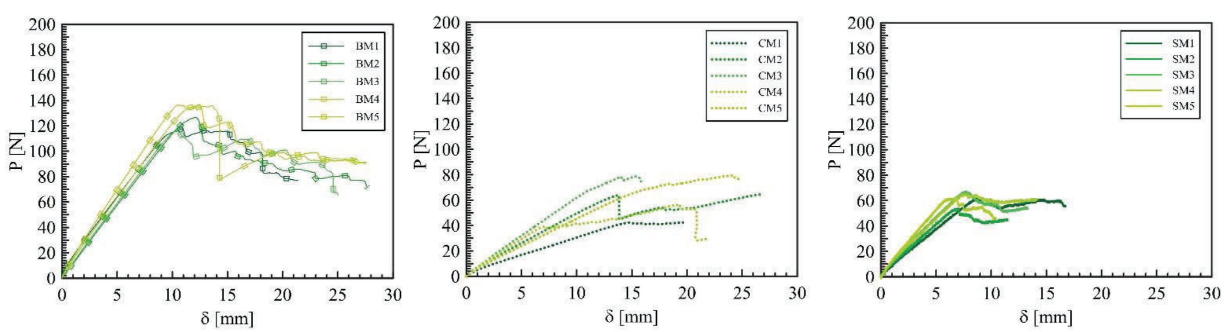

Figure 5. Load- Crosshead displacement for specimens with melamine adhesive: a) Beech; b) Chestnut; c) Spruce.

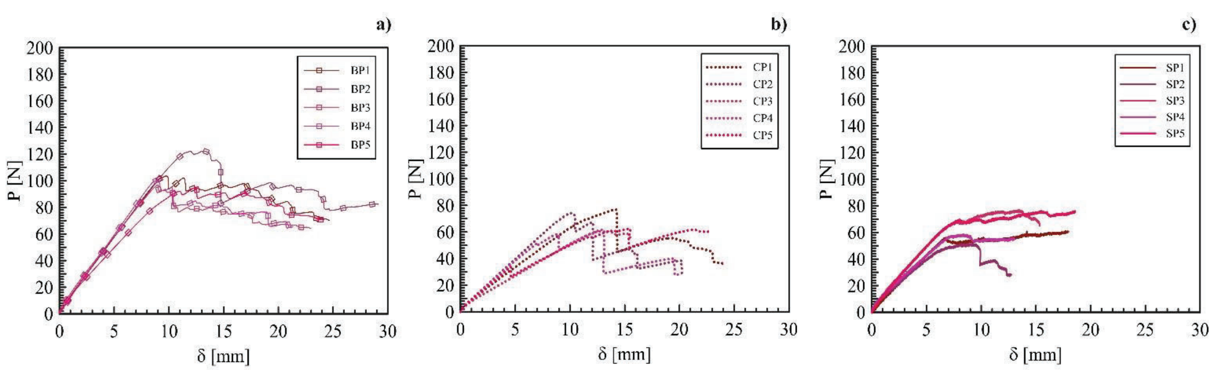

Figure 6. Load- Crosshead displacement for specimens with phenolic adhesive: a) Beech; b) Chestnut; c) Spruce.

Table 3: Combination of adhesive type - timber species and relative abbreviations

	SS	*df*	*MS*	*F*	*p-value*
Adhesive types	0,03846	1	0,0384	8,15	0,0087
Species	0,4942	2	0,247	52,36	1,76E-09
Inter	0,037	2	0,018	3,97	0,032
Within	0,1132	24	0,004		
Total	0,6834	29	0,023		

The outcome from ANOVA analysis are summarized in Table 3. Since the p-value (adhesive types) = .0087< .05 = α, we can reject the Factor B null hypothesis and so conclude (with 95% confidence) that there are differences between the effectiveness of the two adhesives. Additionally, since the p-value (timber species) = 1,76E-09 < .05 = α so conclude (with 95% confidence) that there are significant differences between the effectiveness of the employed species. We also see that the p-value (interactions) = .03 < .05 = α and so conclude there are differences (weak) in the interaction between species and adhesives.

6 – CONCLUSION

This study analyzed the fracture behavior of MUF and PRF adhesives when combined with different timber species: beech and chestnut as hardwood and spruce as softwood.

The results demonstrated different fracture toughness by varying adhesive types and timber species. Notably, adhesives combined with beech exhibited the highest values for both ultimate load and fracture toughness, with melamine adhesive showing the best performance (G_{IC}=0.53 kJ/m^2). When paired with chestnut, melamine provided more stable crack propagation and a slightly higher fracture energy than the phenolic adhesive. Spruce displayed similar behavior with both melamine and phenolic adhesives (G_{IC}=0.14 kJ/m^2). Overall, softwood recorded the lowest fracture energy compared to hardwoods. Future research could explore the long-term durability of these adhesives under varying environmental conditions to enhance their practical applications in construction and engineering.

Overall, this work contributes to a deeper understanding of adhesive behavior in engineered timber products and offers guidance for selecting materials that ensure reliability and strength in structural applications. To conclude with, the mode I fracture toughness tests using the principles of the ASTM D5528 standard, especially for the basic considerations, the assumptions, and the test execution, has proven to be an effective method for qualifying the adhesive bonding of the timber structures and for characterizing their behavior under this particular load/crack opening.

8 – REFERENCES

This work was funded by CRESTIMB project which is supported under the umbrella of ForestValue2 (Horizon Europe GA no. 101094340). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the ForestValue2. Neither the ForestValue2 nor the granting authority can be held responsible for them. The following granting authorities are acknowledged: Ministry of Agriculture, Food Sovereignty and Forests of Italy (MASAF) (D.M. no. 150074 del 29/03/2024 - CUP no. E13C24000270006).

7 – REFERENCES

[1] Sciomenta M., Paoletti A., Stamopoulos A.G, Experimental investigation of the mode I fracture toughness behaviour of timber adhesive joints: The synergistic effect of the adhesive type and the bondline thickness, International Journal of Adhesion and Adhesives, Volume 130, 2024, 103652, ISSN 0143-7496

[2] F. Stoeckel, J. Konnerth, W. Gindl-Altmutter, Mechanical properties of adhesives for bonding wood—A review, Int. J. Adhes. Adhes. 45 (2013) 32–41.

[3] J.M. Gagliano, C.E. Frazier, Improvements in the fracture cleavage testing of adhesively-bonded wood, Wood Fiber Sci. 33 (2001) 377–385.

[4] S. Veigel, J. Follrich, W. Gindl-Altmutter, U. Müller, Comparison of fracture energy testing by means of double cantilever beam-(DCB)-specimens and lap joint testing method for the characterization of adhesively bonded wood, Eur. J. Wood Wood Prod. 70 (2012) 3–10. https://doi.org/10.1007/s00107-010-0499-6.

[5] J.F. Davalos, P. Madabhusi-Raman, P. Qiao, Characterization of Mode-I fracture of hybrid material interface bonds by contoured DCB specimens, Eng. Fract. Mech. 58 (1997) 173–192.

 https://doi.org/10.52202/080513-0594

[6] ASTM D5528-01, Standard test method for mode I interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites, Am. Stand. Test. Methods. 03 (2014) 1–12.

[7] European Committee for Standardization (CEN), EN 301:2023 Adhesives, phenolic and aminoplastic, for load-bearing timber structures - Classification and performance requirements.

[8] K.A. Blackman B., Fracture Mechanics Testing Methods for Polymers Adhesives and composites, Polym. Test. 21 (2001) 225–270.