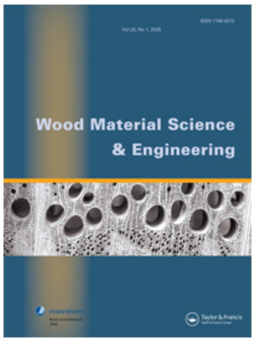

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BRIEF ORIGINAL

Mode I fracture energy release rates of European beech wood-adhesive bonds

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ABSTRACT

This paper presents mode-I fracture energy release rates (G_I) of European beech wood (*Fagus sylvatica*) adhesive bonds for three common types of adhesives pressed with two levels of pressure and glued with three spread rates. Flat double cantilever beam tests with a shear corrected compliance method were used to derive G_I. A high pressing pressure of 1.0 versus 0.1 MPa resulted in higher G_I-values for phenol resorcinol formaldehyde and melamine urea formaldehyde adhesive systems (not significant), but did not affect the polyvinyl acetate system. A low adhesive spread rate of 50 g m^{-2} clearly resulted in lower G_I-values for all three systems, while no clear differences were found between spread rates of 100–200 g m^{-2} for the formaldehyde systems. The herein presented G_I-values of beech adhesive bonds can be used to further evaluate the suitability of beech in glued load-bearing timber structures and promote optimising beech wood-adhesive systems for high G_I.

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Shear corrected compliance method; *Fagus sylvatica*; flat double cantilever beam (DCB) test

Introduction

The availability of beech wood and interest to exploit this material as structural timber in various engineered wood products (EWPs) is increasing in Europe (Brunetti *et al.* 2020, Pramreiter and Grabner 2023). To evaluate its use in such glued load-bearing timber structures, it is important to study the fracture behaviour of beech wood-adhesive bond lines. Specifically, fracture characterised by strain energy release rate in opening mode (G in mode I, G_I) is of primary interest. This measure of the energy required to propagate a crack by unit area provides essential input for calculating the load-bearing capacity of glued joints in timber and EWPs, for example through numerical modelling (Sørensen 2010), and is often governing the joint's capacity – G_I is typically much lower compared to G in mode II and III (River 1994).

G_I-values can readily be determined from a mode I cleavage test using a flat double cantilever beam (DCB) specimen (Gagliano and Frazier 2001). The advantage of this test is easy specimen preparation and straightforward data reduction by using the so-called *shear corrected compliance* method (Gagliano and Frazier 2001). Cyclic loading and in-situ crack length measurements provide test data to calibrate beam stiffness to provide a more reliable calculation of G_I. Other tests, such as compact tension (CT), single edge-notched three-point bending tests (SEN-TPB) and other DCB variants, and other data reduction schemes, such as 'area', 'beam theory' and 'displacement' method and other types of 'compliance' methods are available each with their pros and cons (Blackman *et al.* 1991, Sørensen 2010, Pečnik *et al.* 2023, Sciomenta *et al.* 2024). These methods should give identical results as long as linear elastic behaviour is observed during loading and unloading at any given crack length (Blackman *et al.* 1991). Nevertheless, for solid beech wood fractured along the grain, a difference in G_I-values from DCB versus CT tests was reported: 860 versus 260–730 J m^{-2}, respectively (both tests used *area* method as data reduction scheme) – a difference that was explained by the much smaller fracture surface in the CT tests (Ammann and Niemz 2015).

The current literature presenting G_I data for beech wood-adhesive bonds is limited. Effects of environment has been studied, and G_I-values were reported of 1200 J m^{-2} for beech-PVA bonds (Takatani et al. 1984 in River 1994), 500 J m^{-2} for beech-MUF (SEN-TPB test, *area* and *compliance* method (Pečnik *et al.* 2023)), and 860 and 230 J m^{-2} for beech-PRF and beech-PUR, respectively (DCB test, *area* method (Ammann and Niemz 2015)). A study on the impact of basic gluing parameters pressure and spread rate on G_I of beech wood-adhesive bonds is missing in the literature. Such a study has been conducted during 2001 as part of a PhD thesis on wood-adhesive bonding (Sterley 2012), but has until now not been published.

The aim of this work was, therefore, to present the G_I of wood-adhesive bonds with European beech (*Fagus sylvatica*) and common types of adhesives pressed with different levels of pressure and glued at different spread rates, based on the experiments conducted in 2001. Comparisons and evaluation of test methods and data reduction schemes were out of scope.

Materials and methods

Fifty-four 200 mm long flat DCB specimens – 3 per test series – were prepared and tested according to Gagliano and Frazier

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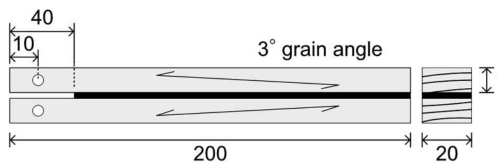

Figure 1. DCB specimen (after Gagliano and Frazier (2001)).

(2001). With help of the annual ring pattern, grain angle was at an 3 degree inward angle to force fracture towards the bond line, providing radial-longitudinal (RL) fracture (Figure 1). The test series included three adhesive types', phenol resorcinol formaldehyde (PRF), melamine urea formaldehyde (MUF) and polyvinyl acetate (PVA), two pressing pressures, 0.1 and 1 MPa, and three spread rates, 50, 100 and 200 g m^{-2}. The obtained glue line thickness for each combination of pressing pressure and spread rate was neither controlled nor recorded. The wood's average density was 700 kg m^{-3} at 10% moisture content, both during gluing and testing. The 40 mm long pre-crack was made with a paraffin wax release agent.

Specimens were loaded on an Instron screw-driven test machine. The cyclic loading procedure, 'displacement controlled loading' – 'holding after 3% load drop' – 'unloading to zero displacement', until complete specimen failure from Gagliano and Frazier (2001) resulted in 5–15 load cycles per specimen (Figure 2). Crosshead displacement was used. In the present work, a 180 s holding time was used instead of 45 s to ensure the load became quasi-stable (i.e. the load at crack arrest). The initial loading rate of 1 mm min^{-1} was adapted for each successive cycle to maintain a constant strain rate at the crack tip. During testing, crack lengths were manually delineated on the specimen. Employing a magnifying glass, the operator observed crack tip propagation and conducted manual measurements of crack lengths.

Results from each load cycle included: (1) maximum load (P_{max}), (2) crack length (a) at crack initiation, (3) load at crack arrest (P_{arr}), and (4) a at P_{arr}. Crack length remained constant after reaching P_{max} for PRF and MUF samples, i,e, a at crack initiation and arrest were similar. No crack arrest was observed for PVAc samples with a spread rate of 200 g m^{-2}, while for the other PVAc samples, cracks were not fully arrested. In addition, the herein used test method and data reduction schemes assume perfect linear elasticity (Gagliano and Frazier 2001). Inelastic behaviour was presumably significant for the thermoplastic type PVA adhesive with exceptional toughness. Hence, interpretation of the PVA data should be done with caution. After testing, based on the fracture surface appearance, failure type was classified manually as 'cohesive' (fracture in glue), 'adhesive' (fracture in interface) and 'substrate' (fracture in wood). Results from substrate failure were not included.

The mode I energy release rate G_I was calculated using the shear corrected compliance method as (Gagliano and Frazier 2001):

$$G_I = \frac{P_c^2(a+x)^2}{b(EI)_{eff}}$$

where P_c is a critical load, b is the width of the specimen, $(EI)_{eff}$ is the effective flexural rigidity of the DCB specimen and x the shear correction factor. $(EI)_{eff}$ and x were obtained from the slope m and intercept d of a linear fit between the cube root of compliance $C^{1/3}$ and crack length a as, $(EI)_{eff} = 2\ /\ (3m^3)$ and $x = d\ /\ m$ (Figure 3) (Gagliano and Frazier 2001). Inserting both P_{max} and P_{arr} for P_c in the above equation gave fracture energy release rates at initiation/maximum (i.e. the energy needed to initiate crack growth) and arrest (i.e. the energy level at which crack grown was stopped), respectively.

Results and discussion

Fracture energy values are shown in Table 1. In total, around 120 measurement values were calculated from 29 specimens both for crack initiation and arrest – two specimens and eight measurement values per test series on average. Twenty-five (25) specimens were discarded because of wood fracture (∼35% of total) and unstable crack propagation (∼10% of total).

Initiation/maximum fracture energies were typically higher than those measured at crack arrest, as expected (Gagliano and Frazier 2001), with values ranging between 94–1774 J m^{-2} and 38–895 J m^{-2}, respectively. Figure 4 illustrates fracture energy is highest for PVA followed by MUF and PRF adhesive systems (significant), is higher for high than low pressure (not significant), and highest for an intermediate spread rate of 100 g m^{-2} (significant). The results in Table 1 are in agreement with the literature for beech-PVA and beech-MUF systems (River 1994, Pečnik *et al.* 2023). For the beech-PRF system, G_I-values were about half of what has been reported previously

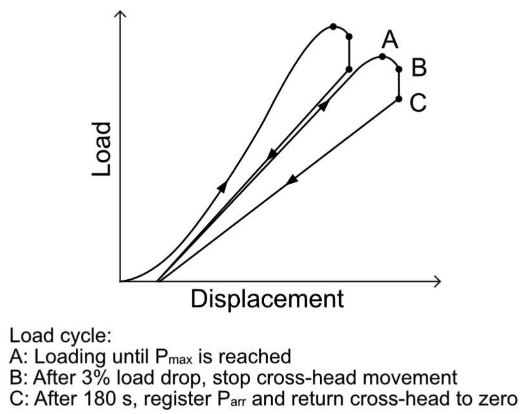

Figure 2. Load cycle.

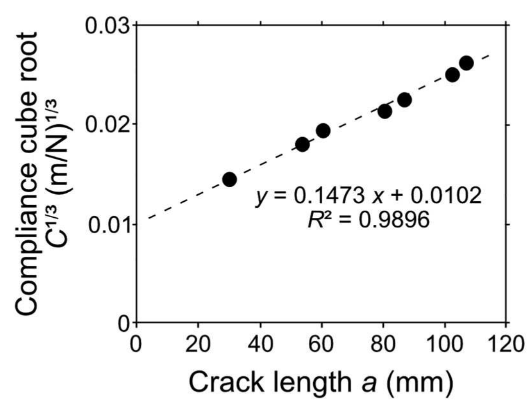

Figure 3. Representative plot of $C^{1/3}$ versus a with slope $m = 0.1473$ and intercept $d = 0.0102$.

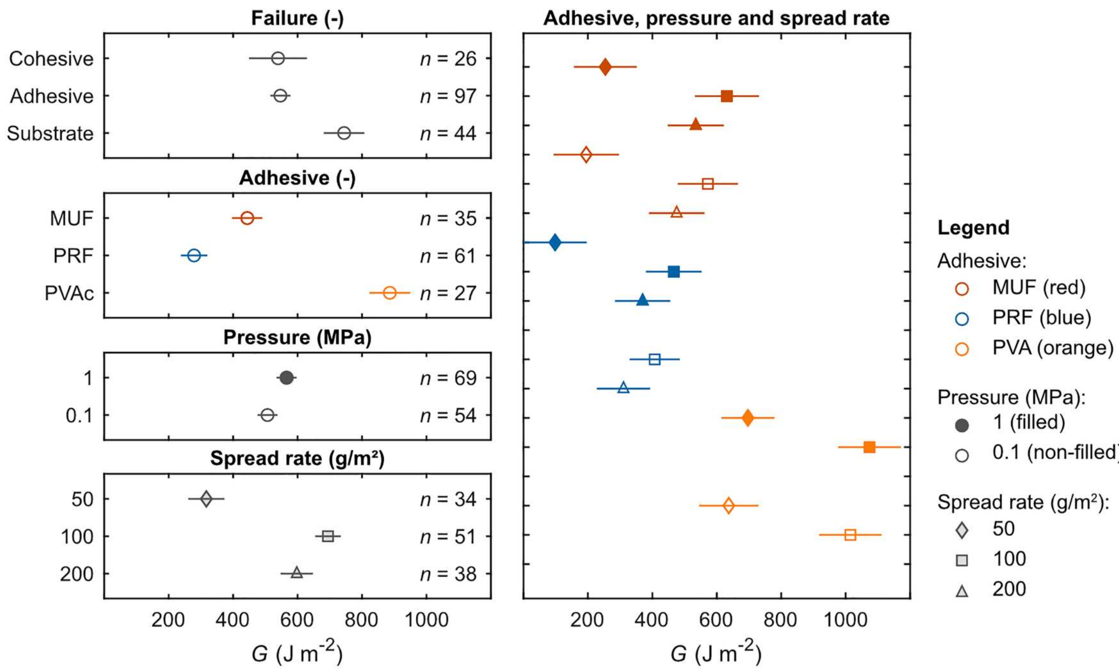

Figure 4. Multi-range significant test with 95% Tukey HSD intervals for crack initiation energies (Legend in figure, *n* is number of specimens, colour version available online).

Table 1. Initiation/maximum and arrest fracture energy release rate (J m^{-2}) [mean ± std (COV)$^{\text{no.specimens − no. data points, note}}$].

Pressure (MPa)	0.1			1		
Spread rate (g m^{-2})	50	100	200	50	100	200
Initiation/maximum						
MUF	300 ± 182 (61%)$^{2-7}$	409 ± 192 (47%)$^{1-4}$	459 ± 39 (8%)$^{1-4}$	293 ± 54 (18%)$^{1-4}$	728 ± 46 (6%)$^{2-5}$	475 ± 137 (29%)$^{2-11}$
PRF	–$^{0-0, *}$	359 ± 137 (38%)$^{3-17}$	303 ± 95 (31%)$^{3-13}$	163 ± 66 (41%)$^{2-7}$	437 ± 82 (19%)$^{3-14}$	452 ± 108 (24%)$^{2-10}$
PVA	678 ± 86 (13%)$^{1-4}$	1,163 ± 207 (18%)$^{2-5}$	–$^{0-0, *}$	565 ± 183 (32%)$^{3-12}$	1,186 ± 409 (34%)$^{1-6}$	–$^{0-0, *}$
Arrest						
MUF	175 ± 83 (47%)$^{2-7}$	199 ± 87 (44%)$^{1-4}$	358 ± 19 (5%)$^{1-4}$	236 ± 23 (10%)$^{1-4}$	589 ± 24 (4%)$^{2-5}$	392 ± 125 (32%)$^{2-11}$
PRF	–$^{0-0, *}$	212 ± 114 (54%)$^{3-17}$	188 ± 62 (33%)$^{3-13}$	68 ± 29 (43%)$^{2-7}$	288 ± 68 (24%)$^{3-14}$	249 ± 59 (24%)$^{2-10}$
PVA	391 ± 53 (14%)$^{1-3}$	624 ± 154 (25%)$^{2-5}$	–$^{0-0, *}$	263 ± 132 (50%)$^{3-12}$	689 ± 194 (28%)$^{1-6}$	–$^{0-0, *}$

*No measurements because of unstable crack propagation.

by Ammann and Niemz (2015), but in the same range as those reported by Gagliano and Frazier (2001) for a poplar-PF system. Coefficient of variation (COV) was higher than expected (Gagliano and Frazier 2001) – up to 61%. This high COV might be caused by unstable crack growth and substrate surface inhomogeneities, since substrate failures were excluded and bending stiffness variation along specimens was small and accounted for. It should also be noted that no crack tip propagation could be observed during the holding phase of load cycles, whereas such propagation was recorded on DCD tests of poplar-PF bonds when using a coupled camera system (Gagliano and Frazier 2001).

Although pressing pressure had no significant effect on G_I, fracture energy values were in general higher for 1 MPa pressure for MUF and PRF (Table 1). These differences were largest at an intermediate spread rate of 100 g m^{-2}. For PVA, the effect of pressing pressure on G_I was ambiguous and PVA-beech bonds appear insensitive to changes in gluing pressure between 0.1 and 1 MPa.

A lower spread rate of 50 g m^{-2} clearly resulted in lower fracture energies for all three adhesive systems (Table 1 and Figure 4). The influence of spread rate was not clear for spread rates 100 and 200 g m^{-2}, and in general, the highest spread rate did not improve G_I but rather led to a small reduction (not significant). This may imply that there is no need to overdose beech-MUF and -PRF adhesives systems to obtain optimal G_I.

The results in Table 1 also show that cracks could be arrested at higher levels of energy for MUF than for PRF adhesive and the difference was more important for bonds glued with a high pressure. This may indicate a better capability of MUF adhesive to stop crack propagation in the adhesive joint than PRF adhesive.

Conclusions

Double cantilever beam tests on beech wood-adhesive bonds with MUF, PRF and PVA showed fracture energy release rates are generally higher for MUF and PRF systems when a high pressing pressure of 1 versus 0.1 MPa was used (not significant), while no such effect was seen for the beech-PVA system. Lower adhesive spread rates of 50 g m^{-2} clearly resulted in lower fracture energies for all three adhesive systems, but at the same time the results showed no clear difference between spread rates of 100–200 g m^{-2} indicating that there is no need to overdose beech-MUF and -PRF systems to obtain high fracture energy values. The herein presented G_I-values of beech adhesive bonds can be used to further evaluate the suitability of beech in glued load-bearing timber structures and promote optimising beech wood-adhesive systems for high G_I.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data is available upon request.

Author statement

Conceptualisation, Magdalena Sterley (M.S.) and Joran van Blokland (J.v.B.); Methodology, M.S.; Validation, M.S. and J.v.B.; Formal Analysis, M.S. and J.v.B.; Investigation, M.S.; Resources, M.S. and J.v.B.; Data curation, M.S. and J.v.B.; Writing – Original Draft Preparation, M.S. and J.v.B.; Writing – Review & Editing, M.S. and J.v.B..; Visualization, M.S. and J.v.B.

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