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MODE I FRACTURE ENERGY OF AUSTRALIAN NATIVE HARDWOOD SPOTTED GUM AT VARIOUS MOISTURE CONTENTS

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ABSTRACT: While there is an industry drive to use Australian hardwood spotted gum (*Corymbia citriodora*) boards in the manufacturing of glulam beams, such beams frequently fail the delamination requirements in the Australian and New-Zealand standard AS/NZS 1328.1 (1998). Delamination likely occurs due to (a) the difficulty in gluing this species and (b) the combination of large shrinkage coefficients and high moduli of elasticity of the material, resulting in large moisture-induced stresses developing in the gluelines during the wetting and drying cycles of the delamination test. The paper forms part of a research aiming at finding mechanical solutions to reduce the moisture-induced stresses in the gluelines, allowing spotted gum glulam beams to pass the delamination requirements and land on the market. Especially, this paper introduces the reader to the overall project and focuses on measuring the Mode I fracture energy of the spotted gum material in the tangential-longitudinal crack system and of the glueline between spotted gum boards at 8%, 12% and 16% moisture contents. The relationship between the Mode I fracture energies and moisture content are then discussed and analysed statistically to determine whether fracture energy is sensitive to the moisture content for the analysed range.

KEYWORDS: Australian hardwood glulam, fracture energy, moisture content

1 INTRODUCTION

With the current drive towards sustainable and green construction, the demand for high-performance engineered wood products is increasing. This brings opportunities and challenges to Australia's hardwood industry, such as for native forest grown spotted gum (SPG - *Corymbia citriodora*), a dense hardwood with superior mechanical properties and durability [1]. Spotted gum occupies about 70% of the annual hardwood logs supplied by Queensland (QLD) native forests [2]. There is a drive to manufacture glulam out of this species to be used as beams, columns or bridge elements. However, for SPG glulam to be commercialised, the bond between boards must satisfy the delamination requirements in the Australian and New Zealand Standard AS/NZS 1328.1 (1998) [3]. The delamination test consists of vacuum water impregnation followed by a drying process. The parameters of these two processes depend on the service class of the final product, i.e., its intended environmental application. However, despite best efforts to improve the gluability of SPG [4], SPG glulam products commonly do not pass the requirements in [3] for external applications, with outcomes from a typical delamination test shown in Figure 1. This phenomenon is thought to be attributed to (1) the difficulty in gluing the species from little adhesive penetration [5] and (2) the high moisture shrinkage coefficients combined with high elastic moduli of the material, resulting in large moisture-induced internal stresses developing in the gluelines during the delamination test.

As delamination develops from over-stressed gluelines [6], reducing the internal stresses could represent an effective mechanical solution to prevent delamination. Several approaches may potentially achieve this. First, as the shrinkage and swelling coefficients of SPG (and timber in general) are different along the radial and tangential directions [7], designing the glulam with boards stacked in a specific grain orientation combination could improve results from the delamination test. Second, cutting stress relief grooves in the boards, with specific shape and arrangement, could also reduce the internal stresses [8]. Finally, adjusting the board geometry (width

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to thickness ratio) could also affect the internal stresses and thereby decrease the stresses imposed to the gluelines during the delamination test.

To study the delamination problem and find mechanical solutions to reduce the moisture-induced stresses in the gluelines, a numerical model that can reproduce (i) the heat-and-mass transfer in the timber during drying, (ii) the associated drying stresses and (iii) crack initiation and propagation in both the timber and gluelines, would represent an economical and efficient method to investigate potential solutions [8, 10]. The physical and mechanical properties of the SPG material and its associated gluelines need to be collected to establish such a model. The SPG physical properties, such as permeability, diffusion coefficient and desorption-isotherm, are already available in [7]. However, there is a lack of information regarding the mechanical properties, especially the fracture properties and their relationship with moisture content. This paper aims to determine the Mode I fracture energy of the SPG material and associated gluelines. As the mechanical properties of timber are moisture sensitive [9] and the SPG glulam moisture content varies during the delamination test in the AS/NZS 1328.1 (1998) [3], the fracture energies along the crack paths experienced during the delamination tests are determined in this paper at different moisture content, namely 8%, 12% and 16%. First, published fracture energy test methods for fracture Mode I are reviewed, and the most appropriate method for timber is selected. Second, the Mode I fracture energies of the timber with a Tangential (T)-Longitudinal (L) crack system, i.e., with the crack occurring in the RL plane and propagating along the longitudinal direction, and of the "glueline" crack system, i.e., with the crack normal to the glueline, at different moisture content are measured experimentally. Note that the timber orientation in the Tangential (T), Radial (R) and Longitudinal (L) directions is shown in Figure 2. The crack systems investigated are shown in Figure 3.

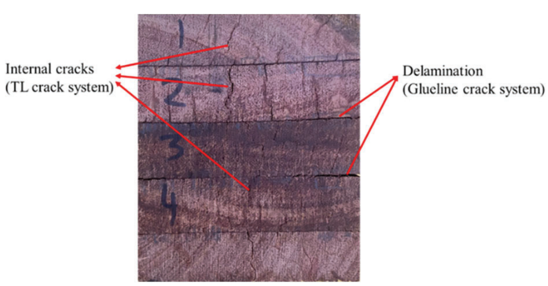

Figure 1: *Spotted gum glulam after delamination test*

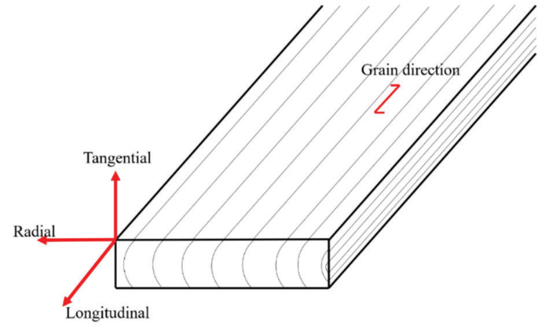

Figure 2: *Timber Tangential (T), Radial (R) and Longitudinal (L) directions*

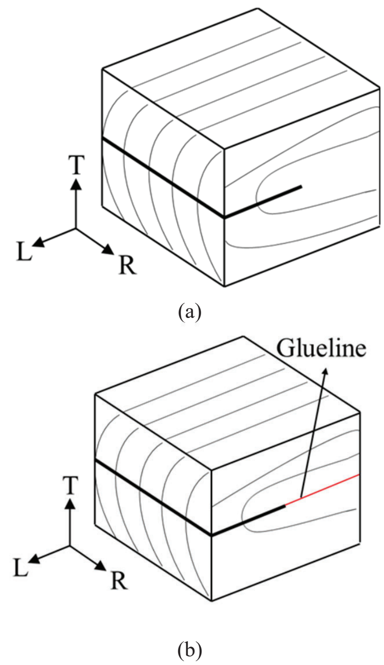

Figure 3*: Timber crack systems (a) TL and (b) glueline*

2 METHODOLOGY

The methodology to obtain the Mode I fracture energies consists of three main steps: (a) determining the test setup used for Mode I fracture energy experiment, (b) preparing the timber and glulam samples and (c) analysing the Mode I fracture energy results statistically by one-way ANOVA.

2.1 MATERIAL, GLUEING AND CONDITIONING

Australian's native forest SPG sawn boards, with the trees harvested in QLD, were used to investigate the Mode I fracture energy and its sensitivity to the moisture content. After the drying process of the delamination test [3], the cracks typically developed within the timber normal to the tangential direction and along the gluelines, as shown in

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Figure 1. Therefore, in view of modelling, the fracture Mode I energies in the TL and glueline crack systems were investigated in this study.

When boards needed to be glued to manufacture the samples, as detailed in Section 0, boards were bonded following the results in [4, 10-12] to maximise adhesion, consisting of face milling the boards to a thickness of 22 mm to activate the surface and using commercial resorcinol–formaldehyde adhesive (RF) manufactured by Jowat Adhesive. The gluing process consisted of: (1) mixing the resorcinol with formaldehyde by 4:1 for 5 mins and letting it stand for 10 mins, (2) face milling the surfaces to be glued with a Rotoles 400 D-S manufactured by Ledinek [5], (3) manually applying the adhesive on the milled surfaces, immediately after milling, at a glue spread rate of 450 g/m^2, and (4) pressing the boards together under a pressure of 1.4 MPa for a period of 12 hours.

After the gluing process was finished, the samples were put into different conditioning chambers with targeted equilibrium moisture content of 8%, 12% and 16%, corresponding to the conditioning chambers set at 20℃/40% relatively humidity (RH), 20℃/65% RH and 60℃/90% RH, respectively [13]. The moisture content were selected based on measurements on the glulam samples during delamination tests which reached moisture content up to 16% after vacuum impregnation and down to 8% after kiln drying.

Immediately after testing (Section 2.2), the actual moisture content of each sample was determined following the oven-dry method in the Australian standard AS/NZS 1080.1 [14].

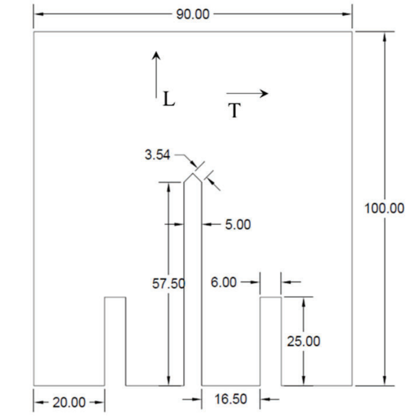
2.2 FRACTURE MODE I TEST SETUP

Different test methods have been adopted in the literature to measure the Mode I fracture energy of timber specimens. Ostapska and Malo [15] applied to timber the wedge splitting test method that was proposed by Brühwiler and Wittmann [16] for concrete. However, this test method is complex and laborious if only fracture energy is required [15]. Franke and Quenneville [17] applied the compact tension shear (CTS) test setup, which was proposed by Richard and Benitz [18], to Radiata Pine Laminated Veneer Lumber (LVL) and sawn timber. The advantage of the CTS is that either Mode I, Mode II or mixed Mode fracture energies can be measured with one test rig by changing the angle of the applied load. However, the CTS specimens must be carefully prepared with high accuracy to avoid that unsymmetrical loading occurs which would significantly affect the applied stress and resulting fracture energy [17]. In addition, De Moura et al. [19], applied the double cantilever beam (DCB) test for fracture Mode I to Pinus pinaster sawn timber and stable crack propagations were achieved.

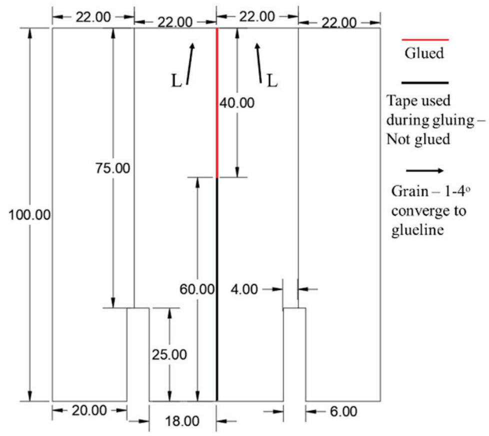
The most adopted method to measure the Mode I fracture energy of timber samples was proposed by Gustafsson [20] and was used in [17, 21, 22]. It is referred to as single end notched beam specimen (SENB). A notched specimen is glued to two pieces of timber to form a beam. The specimen is loaded in three-point bending, forcing the crack to open and propagate. Due to the gluing involved in preparing the specimens, the manufacturing process is time-consuming if a large number of tests are required. Ardalany et al. [21] improved the setup and replaced the side timber pieces with steel sections to which the notched timber specimens can easily be connected to, significantly simplifying the manufacturing process. A counterbalance weight is placed on each steel section to offset the effect of the self-weight of the test rig into the calculations of the fracture energy. This method was used herein due to its simplicity and its common adoption for timber.

The Mode I tested samples are presented in Figure 4 (a) for the TL crack system and Figure 4 (b) for the glueline crack system. In Figure 4 (a), 100 mm deep × 90 mm wide × 44 mm thick samples were produced. To produce the 44 mm thick samples from the 22 mm thick boards, two SPG pieces, cut from the same board, were face glued together. All boards were selected for grain orientation so that the cracks developed in the chosen system, with the orientation shown in Figure 4 (a). For each sample, (1) a 5 mm thick × 60 mm deep notch was cut by a V-shaped blade in the middle of the sample from which the crack can initiate and (2) two 25 mm deep side notches were cut to connect the sample to the test rig shown in Figure 5 (photo) and Figure 6 (schematic).

In Figure 4 (b) for the glueline crack system samples, four 22 mm thick pieces were glued together to form an 88 mm thick glulam. The two middle pieces came from the same sawn board and were selected to have the grain orientation relative to the glueline making an angle of 1-4 degrees and converging towards the glueline. This configuration encourages the crack to propagate along the glueline as explained in [23, 24]. A thin adhesive tape was positioned over 60 mm on the two middle pieces before gluing to prevent adhesion and create a notch equivalent to the samples shown in Figure 4 (a) and from where the crack can propagate. The produced samples were 100 mm deep × 88 mm wide × 44 mm thick sample with the orientation shown in Figure 4 (b). Two 25 mm deep side notches were cut to connect the sample to the test rig as shown in the figure.



(a)



(b)

Figure 4: *Sample geometry for (a) TL and (b) glueline crack systems (unit in mm)*

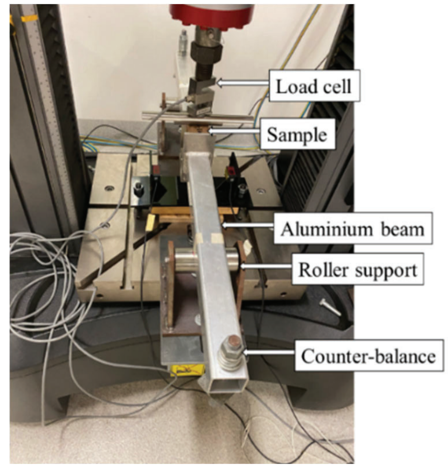


Figure 5: *Experimental setup for fracture Mode I*

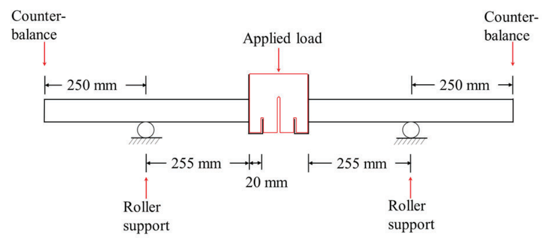


Figure 6: *Fracture Mode I test setup sketch*

The samples were then connected to two aluminium beams, as shown in Figure 5 (photo) and Figure 6 (schematic) to form a beam. The beam was positioned on two roller supports to be loaded in 3-point bending in a 100 kN capacity INSTRON universal testing machine fitted with a 2.5 kN load cell. A half-round was connected to the load cell to load the specimens at mid-span. Counterbalance weights were also used at the extremity of the aluminium beams to offset both the self-weight of the timber samples and the beams themselves.

A loading rate of 8 mm/min and 1.2 mm/min were selected for TL and glueline crack system samples, respectively, to target failure in 3-5 mins.

The Mode I fracture energy G_{If} was calculated as [22, 25], as.

$$\boldsymbol{G_{If}} = \frac{\boldsymbol{Q}}{\boldsymbol{h_c b}} \tag{1.}$$

where Q is the work performed to fully fracture the sample and calculated from the load-displacement curve, h_c is the measured depth of the specimen above the crack tip and b is the measured specimen thickness. Note that despite the displacement provided by the testing machine may different to the actual displacement of the specimens, as outlined in [26], the testing machine behaves linearly and the work performed by the testing machine is equal to the work needed to fully fracture the samples.

2.3 STATISTICALLY ANALYSIS

After the fracture energy was obtained, a one-way ANOVA statistical analysis was conducted to determine whether there was a statistically significant difference between the mean of various moisture content groups.

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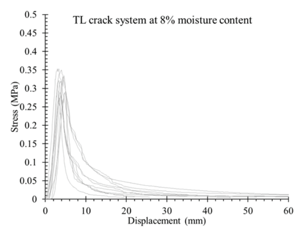
3 RESULTS AND DISCUSSION

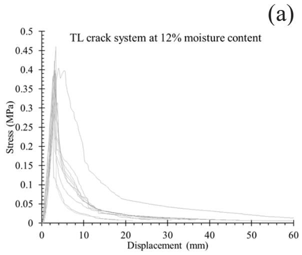
3.1 FRACTURE MODE I TEST RESULTS

The stress-displacement curves for all the fracture Mode I tests relative to the different crack systems and moisture contents are presented in Figure 7. Nominal and actual moisture content, average measured fracture energies, with associated coefficient of variation (CoV), are summarised in Based on test results presented in Table 1, the Mode I fracture energy in the TL crack system is about four times higher than the fracture energy of the gluelines. This likely reflects the difficulty in gluing this species [5] and indicates that the fracture would propagate faster in the glueline than the timber.

Table 1



(a)



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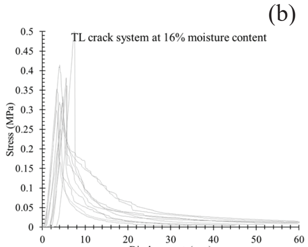
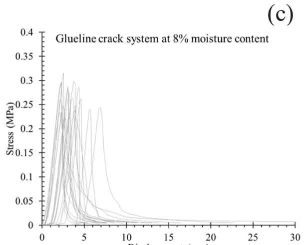
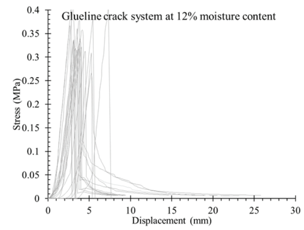


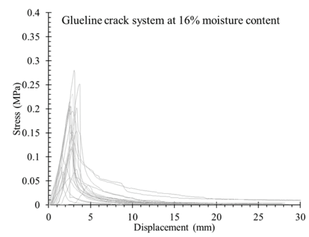
(c)



(d)



(e)



(f)

Figure 7: *Load-displacement curves for the Mode I fracture energy tests for TL crack system at (a) 8%, (b) 12% and (c) 16% moisture content, and glueline crack system at (d) 8%, (e) 12% and (f) 16% moisture content*

Based on test results presented in Table 1, the Mode I fracture energy in the TL crack system is about four times higher than the fracture energy of the gluelines. This likely reflects the difficulty in gluing this species [5] and indicates that the fracture would propagate faster in the glueline than the timber.

Table 1: *Fracture Mode I test results*

Crack system	Moisture content *(%)*			Fracture energy G_{If}		
	Nominal	Actual	CoV *(%)*	No. of tests	Mean *(N/mm)*	CoV *(%)*
TL	8	8.3	2.2	10	1.99	44.4
	12	12.5	2.3	10	2.02	55.5
	16	15.8	2.0	10	2.31	42.6
Glueline	8	8.2	3.5	20	0.46	38.1
	12	12.4	1.9	20	0.56	32.0
	16	16.1	1.6	20	0.42	49.6

The results from one-way ANOVA statistical analyses between the different moisture content groups show that for the fracture energies of (1) the TL crack system: $F(2,27) = 0.318$, $p = 0.7301$, and (2) the glueline crack system: $F(2,57) = 1.913$, $p = 0.157$. This implies that there was no statistically significant difference between group means for both TL and glueline crack systems, and therefore that the Mode I fracture energy is independent of the range of moisture content analysed for both crack systems. This result also indicates that the fracture energy does not seem to follow the same trend as the “common” mechanical properties which vary with the moisture content. According to [27], the difference in mechanical properties between 8% and 16% would be of 27%.

Since it is found statistically that the Mode I fracture energy in both TL and glueline crack systems for SPG is not sensitive to moisture content, the average fracture energy of the three moisture content groups would be taken as future numerical model input.

Figure 8 shows the typical failure modes for the Mode I fracture tests. The cracks initiated either at the tip of notch or non-glued area, and propagated up straight or along the glueline for the TL and glueline system samples, respectively.

(a) (b)

Figure 8: *Fracture Mode I typical failure for (a) TL system and (b) Glueline system*

3.2 COMPARISON TO OTHER STUDIES

Table 2 compares the fracture test results to published studies.

Leka [28] applied the same test setup to the same material presented in this paper and found an average fracture energy 37.9% lower than the one in Table 1. Leka [28] tested both TL and RL crack systems, all together (i.e., with no distinction between the two systems), which could explain the above difference. Franke [17] measured the Mode I fracture energy of softwood Radiata Pine in the TL crack system, which resulted in a fracture energy 74.4% lower than this study. Ammann [24] conducted European beech hardwood glulam glueline fracture tests, with boards bounded with RF as in the present study. The fracture energy presented in Table 1 was only about half compared to Ammann’s [24] tests, with 50% of the tests failing in timber rather than glueline in [24].

Table 2: *Mode I fracture energy from other studies*

Species/ type	Test setup	Crack system	Fracture energy (N/mm)	Reference
SPG sawn boards	Three-point-bending	TL	2.11	This study
SPG sawn boards	Three-point-bending	TL/RL	1.53	[28]
Radiata Pine LVL	CTS	TL	1.21	[17]
SPG Glulam	Three-point-bending	Glueline	0.48	This study
European beech Glulam	DCB	Glueline	1.00	[24]

4 CONCLUSIONS

The Mode I fracture energies of SPG sawn timber in the TL crack system and associated gluelines at various moisture contents were measured in this paper. The sensitivity of the fracture energy to the moisture content was analysed statistically. It was found that the average Mode I fracture energies were of 2.11 N/mm and 0.48 N/mm for the TL and glueline crack systems, respectively. The statistical analysis (one-way ANOVA) showed that the Mode I fracture energy of the analysed crack systems was not sensitive to moisture content variation. Therefore, a unique value can be considered for future numerical models which simulate crack initiation and propagation of SPG glulam during the delamination test.

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