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# TESTS ON FRP-STRENGTHENED TIMBER JOINTS

K.I. Crews
*(Professor, Centre for Built Infrastructure Research, University of Technology Sydney, Australia)*

S.T. Smith
*(Senior Lecturer, Centre for Built Infrastructure Research, University of Technology Sydney, Australia)*

## ABSTRACT
Surprisingly little research has been conducted on the strengthening of timber with fibre reinforced polymer (FRP) composites as opposed to the much more widely researched strengthening of concrete and to a lesser extent metallic structures. As with all FRP strengthening applications, the bond of the FRP to the substrate is of particular importance. A lack of understanding of the bond between FRP and timber is a major factor contributing to the reluctance of industry to utilise FRP for timber strengthening applications. This paper reports results of preliminary bond strength tests undertaken at the University of Technology Sydney (UTS) on FRP-strengthened timber joints. The aims of the tests were to observe the suitability of the test method, quality of the bond, bond strength and failure mode of the test specimens.

## KEYWORDS
FRP, Bond, Strengthening, Timber, External Bonding

## 1. INTRODUCTION

There are some interesting similarities between the properties of timber and those of FRP's, in that both have orthogonal properties as a consequence of having an inherent fibrous structure set in a matrix binder. It can be argued that FRP is a manufactured product of "perfect" timber – where the fibre strength rather than the occurrence of strength reducing characteristics that occur naturally in wood (e.g. knots), govern the strength of a structural member. It is therefore somewhat surprising that combinations of the two products have not been more widely researched and as a result the bond interaction between FRP and timber is not generally understood.

Most work on FRP-strengthened timber to date has focused on the bonding of FRP composites to selected faces of timber beams. Research by Meier (1995), Tingley et al. (1996), Chajes et al. (1996), Gilfillan et al. (2004), and Dagher (2005) has demonstrated that FRP bonded tension face plates (or tension and compression faces) can significantly increase the bending strength and stiffness of a timber beam, whilst Milner (1999) demonstrated the effectiveness of FRP's to overcome inherent weaknesses in the finger joints of glued laminated timber beams. Experimental work undertaken by Greenland *et al.* (1999) at UTS also explored this issue as part of a detailed program of research on the viability of externally bonded FRPs for improving the tensile capacity of stress laminated T system webs, but this same work also highlighted some of the difficulties associated with bonding failures which can occur between the FRP and the timber substrate.

## 2. PREVIOUS RESEARCH AT UTS

The work undertaken to date at UTS has focused on characterising the flexural performance of Australian Radiata Pine products strengthened with carbon FRP (CFRP) composites. Pilot tests have been conducted on solid (sawn) and reconstituted (Laminated Veneer Lumber - LVL) sections of Radiata Pine to determine the short term properties of the CFRP, the bending strength and stiffness of timber elements, and improved bending strength, stiffness and ductility, with reduced variability, of FRP-strengthened timber elements. Further pilot studies investigated the short term behaviour of T beams (for use in stress laminated timber decks) constructed of LVL webs and solid Radiata Pine flanges with and without FRP web strengthening (Greenland 2001). Whilst Greenland developed models for predicting linear-elastic and nonlinear behaviour of the FRP composite LVL beams as a structural system, the fundamental behaviour of the bond and the bond-slip relationship of the FRP-strengthened timber were not addressed.

## 3. TESTS ON BOND BEHAVIOUR OF FRP AND TIMBER

Vick (1997) investigated the durability of epoxy bonds and presented details of a primer system developed by the US Department of Agriculture (USDA) to improve epoxy durability. It was concluded that epoxy bonds develop bonds to timber that are as strong as the timber itself, as long as the bonds remain dry and that epoxy adhesives could equal the structural durability of resorcinolic adhesives when the USDA primer was used. The effectiveness of adhesion between FRP and timber was evaluated using a cyclic delamination test as noted in ASTM D2559-03 (2003) *Standard Specification for Adhesives for Structural Laminated Wood Products for Use Under Exterior (Wet Use) Exposure Conditions*. Once the specimens were exposed to the severe stresses from repeated water soaking and drying, the bonds tended to degrade and delamination occurred.

One of the variables that affects the behaviour of a composite FRP/timber element, are the shear properties of the bond/interface. Because the transfer of stress between timber and the fibre composite is achieved via the development of shear stresses in the adhesive bond, it is important that the strength properties of the adhesive in shear be understood and quantifiable for use in numerical models. In particular, the way in which load is transferred between the FRP and timber needs to be understood, namely; will the behaviour of the strengthened section be governed by the strength of the timber or FRP, or is it governed by the ability of the adhesive to transfer shear stresses from the timber into the FRP?

The strength properties of adhesive bonds in shear can be determined using either compression or tension methods. The majority of studies on the bond between timber and fibre composites have involved testing the shear strength of the adhesive through a (modified) compressive method, based on ASTM D905-03 (2003): *Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading*.

While ASTM D905-03 (2003) is primarily concerned with obtaining the shear strength of an adhesive, it is arguable that the critical factor in developing reliable bonds in FRP-to-timber composites is to ensure that the failure mode occurs as a wood fibre failure, rather than in the adhesive itself. This would be evident by the proportion of wood on the failure surface – a high amount of wood on the failure surface indicating that the adhesive itself may be less critical than other factors. Given that high proportions of wood failure are desirable, the results of such tests do not necessarily indicate the true value of the shear strength of the adhesive, since ASTM D905-03 specifically notes that wood failure is very common in joints made with strong adhesives, and when high proportions of wood are evident on the failure surface, the measured strength is lower than the true adhesive strength.

Preliminary tests on 10 specimens have been undertaken at UTS using specimens (as indicated in Figure 1) made from the following materials:

- Radiata pine (solid, sawn timber, dressed surface finish)
- ATL type I prefabricated carbon fibre composite
- ATL epoxy "Techniglue CA"

The ATL type I composite carbon fibre, consisted of 2 layers of a 580g/m$^2$ unidirectional carbon fibre prepreg plates which, when cured, formed 1.6mm thick carbon fibre laminates. When tested in accordance with the 1995 version of ASTM D3039 (2006) *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, the following properties were obtained from testing of 10 specimens: average ultimate strength 726 MPa, with a coefficient of variation (CoV) of 4.1%; and average Modulus of Elasticity 78,200 MPa with a CoV of 10.3%.

The cut timber and fibre composites were glued together using ATL Techniglue CA epoxy adhesive after the bonding surfaces of both the pine and fibre composites were lightly sanded in accordance with the adhesive manufacturer's directions. The test specimens were 50mm wide blocks, with a set up similar to that in Figure 1 where the block on the left side is fixed while load is applied to the block on the right side.

Whilst the tests methods used for the determination of strength properties in shear were primarily sourced from the 1994 version of ASTM D905-03 (2003), cross reference was also made to AS1321.3 (1976) *Bond Strength of Cured Wood-to-Wood Adhesives in Shear* and to the block-shear test method specified in the 1987 version of AS1328

(1998) *Glued-Laminated Structural Timber*. The ASTM D905-03 (2003) test method for specimens containing the FRP required some modifications, which was the same as those made by some other researchers testing the interface properties between various timbers and fibre composites (e.g. Davalos et al. 1992).

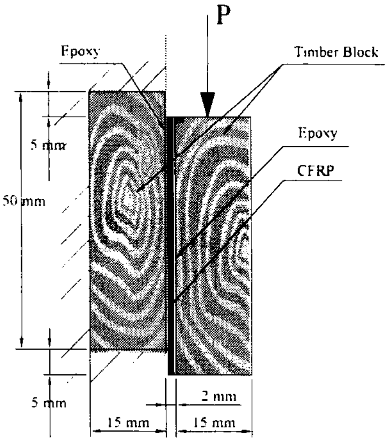


Figure 1. Side elevation of a typical test specimen

Table 1. Test results

| Specimen | Ultimate Load (kN) | Shear Stress (MPa) |
|---|---|---|
| S03-1 | 21.1 | 10.6 |
| S03-2 | 16.75 | 8.4 |
| S03-3 | 10.8 | 5.4 |
| S03-4 | 12.2 | 6.1 |
| S03-5 | 20.4 | 10.2 |
| S03-6 | 20.4 | 10.2 |
| S03-7 | 9.0 | 4.5 |
| S03-8 | 14.0 | 7.0 |
| S03-9 | 16.4 | 8.2 |
| Average | | 7.8 |
| Standard Deviation | | 2.2 |
| CoV (%) | | 28.4% |
| 5% exceedence | | 4.9 |

The purpose of this test is to determine the strength of the adhesive-to-timber interface, assuming that the shear stress is constant throughout the depth of the "glue line". Whilst some effort was made for the wood specimens to be fabricated so as to avoid significant growth characteristics, such as knots, the inherent variability of timber is still reflected in the test results. This simplification will need to be addressed in future tests with larger pieces of timber that will inevitably include knots, since such a "smeared" average, will not consider the effects of knots. Failure modes can be described as brittle.

## 4. RESULTS AND DISCUSSION

The results of the preliminary tests are presented in Tables 1 and 2. In Tables 1 and 2, the shear block test result for the FRP-timber specimens are given as well as a typical shear strength of the timber and manufacturers data for the epoxy alone in Table 2. It is evident the shear strength of the timber and epoxy are higher thus leading to failure at the FRP-to-timber interface in the timber.

Table 2. Summary results of shear block tests

| **Summary** | **Shear Test Result** | **Timber** | **Epoxy** |
|---|---|---|---|
| Average Shear Stress (MPa) | 7.8 | 14 | 10 - 12 |
| Standard Deviation | 2.2 | 1 | - |
| CoV (%) | 28% | 7.1% | - |
| $5^{th}$ Percentile (MPa) | 4.9 | 12.7 | - |

Failures of the block shear specimens can be characterised into three types of failure: Failure within the glueline, failure within the wood, and failure partly within and partly adjacent to the glueline in the wood. The main type of failure that occurred in these tests was the third one, with a significant proportion of the failure surface showing wood failure. The results of the shear tests indicate that the shear strength of the timber-to-FRP interface is less than the shear strength of the (solid) timber and the epoxy. However, it must be noted that only a very small number of specimens were tested and a far greater number of specimens would need to be tested to report conclusively. Due to the high variability of these test results, conclusions about the shear strength of the bond, in particular whether the bond is likely to be a critical influence on limit state behaviour of reinforced beams, are difficult to draw with confidence based on the small number of specimens tested. However, failure surfaces typically showed greater proportions of wood failure than adhesive failure indicating that the properties of the bond are controlled by the properties of the Pine tested rather than the properties of the adhesive used. Other influences on the results are: surface preparation, knots, and size effects of knots on small test specimen

It should be noted that most glued timber products that are used in high performance structural applications (e.g. plywood, glulam and LVL), rely upon mechanical interlock of the glue with the timber fibres, occurring at a microscopic level. In the manufacture of plywood and LVL the sheets of ply are heated (to activate the resorcinol glue and also soften the timber) and squeezed together under a pressure of 1MPa in order to force the epoxy into the microfibres of the timber. This results in what is really a mechanical bond, rather than adhesion, between the glue and the timber. Such glue lines tend to be very thin as a result and gap filling glues or expoies are seldom used in structural applications. Therefore, in applying FRP strengthening to timber, we need to recognize that the same type of structural bond is not possible and as a result the connection is predominantly adhesive rather than mechanical. Furthermoore, it is possible that some of the natural growth charactersitcs of timber, such as knots, may in fact act like aggregate in concrete, and in doing so, create difficulty for the epoxy to penetrate the substrate material. These are all issues that will need to be addressed in future research.

## 5. FUTURE RESEARCH

Considerably more tests will need to be conducted in the future to systematically characterise the influence of many variables (e.g. species of timber, grade of timber, surface preparation, moisture condition etc) on the FRP-to-timber bond strength. The test set-up outlined in this paper appears adequate for conducting future testing. Ultimately a bond-slip relation of FRP-strengthened timber joints that can be used in numerical simulations is required. Such a relation may be best determined by fitting strain gauges at the epoxy-timber interface. Care must be taken to ensure the strain gauges do not disturb the distribution of bond stresses.

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