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Bonding of FRP materials to wood using thin epoxy gluelines

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ABSTRACT

The use of fibre-reinforced polymers (FRPs) in the construction industry is becoming increasingly common. One application of these materials is in the stiffening and strengthening of glue-laminated timber. The research programme discussed in this paper examined the bonding of commercially available FRPs to wood using three commercial epoxy adhesives. The programme involved comparative testing of non-moisture cycled FRP–wood specimens, non-moisture cycled wood–wood bonded, and solid control specimens with moisture cycled FRP–wood specimens all manufactured using wood from the same boards. Findings showed that with specific adhesives, cost-effective thin bondlines have the capacity to resist severe hygrothermal stresses imposed at the FRP–wood interface. It was further noted that the integrity of the bond depended not only on the epoxy adhesive in question but also on the FRP type.

1. General Introduction

Fibre-reinforced polymers possess many advantages in civil engineering applications in comparison to conventional engineering materials. They are associated with higher strength and stiffness to weight ratios, as well as good fatigue and weathering characteristics. The construction industry appears to be gradually recognising the additional benefits offered by these materials.

In contrast, wood has been extensively used in construction for many decades and has many applications in structural engineering [1]. It is a renewable resource, is recyclable, is relatively inexpensive, has a high strength to weight ratio and is architecturally attractive. However, wood also has a number of disadvantages. It undergoes biological deterioration over time and is dimensionally unstable in alternating environmental conditions, and in flexural members it exhibits brittle tensile failures.

A number of research studies have examined the option of reinforcing wooden flexural members with pultruded fibre-reinforced polymers in laminate form. Significant strength and stiffness increases in comparison with unreinforced members have been reported by a number of researchers [2–8]. This technique can be easily and efficiently carried out and adds negligible depth and mass to the member that is being reinforced. In recent times, the commercialisation of an FRP-reinforced glulam structural beam in the USA has been reported [9].

1.1. Behavioural differences between FRP and wood

It is imperative that a reliable, good-quality connection is established in these hybrid members. Adhesive bonding is identified as the most efficient method of stress transferral between two materials as it avoids the stress concentrations that are associated with mechanical fasteners. Furthermore, few finishing operations are involved and assembly costs are lower. Dissimilarities in the materials include their moduli of elasticity, surface properties, reaction to creep loading and, most importantly, response to moisture and to alternating environmental conditions.

The environmental durability of FRP materials is known to depend on the polymer matrix type, laminate thickness, quality of production, method of curing, fibre volume fraction, fibre matrix interface and manufacturing process. It has been found that environmental aging reduces the flexural and tensile properties of pultruded E-glass fiber-reinforced vinyl ester matrix composites [10] and that moisture absorption in polymer resins results in microcavities [11]. Because wood is hygroscopic, fluctuations in both its mass and volume occur with change in the surrounding relative humidity. When significant fluctuations in moisture content occur, distortion and fracturing can result because of rapid dimensional changes, particularly in the directions perpendicular to the longitudinal grain direction [12]. Longitudinal shrinkage is not an important consideration in mature wood but is more significant in wood containing large juvenile proportions [13]. Therefore, because wood and FRP differ in their reactions to changes in humidity and temperature, an important consideration in the adhesive bond between the two materials is the shear stresses that result from differential shrinkage and swelling at the bond interface [14].

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1.2. FRP–wood bonds using epoxy adhesives

Epoxy adhesives are well established in applications involving the bonding of structural materials [15] and it is reported that they are generally considered to be the most suitable for the bonding of FRP materials [16]. They possess advantages such as good gap-filling characteristics and only require low clamping pressures. As a result, epoxy adhesives are often employed in anchoring bonded-in rods and bars in the upgrade or repair of timber members [17–19].

However, the use of epoxy resin for bonding wood remains limited because of concerns regarding product cost, the additional expense resulting from stringent health and safety restrictions imposed on their transport as well as the durability of the bond formed.

Starved joints were reported as being the principal cause for low bond quality when testing commercial epoxy formulations in one study [20]. It was found in another study [21] that an inadequate bond is formed between wood and epoxy resin and that in general the bond strength did not reach the strength of the timber used in the research. Well-regarded technical documentation on repairing glued laminated timber with epoxy adhesives cautions against their use without mechanical reinforcement [22]. In the same literature, inappropriate moisture content, poor adhesive mix, too great a planing tolerance on the bond surface of the timber, inadequate curing period or incorrect curing temperature are listed as possible reasons for loss of bond. One study found that for dry non-durability tested specimens, the epoxy–wood bonds exceeded the strength of the wood itself but after water soaking of the specimens, the bonds weakened more rapidly and poor wood failures were obtained [23]. In another study, wood failure greater than 90% was achieved by an epoxy adhesive in the dry condition but dropped to less than 20% for wet tests using the same adhesive [24]. Rowlands et al. [25] found that epoxy adhesives formed an excellent bond to glass, aramid and carbon fibre-reinforced products for dry conditions but that after being subjected to a severe moisture cycling procedure, they were unable to maintain even 50% of half their dry bond strength. Frihart [26] stated that because of the cross-linking of the adhesive polymers chains, the rigidity of the adhesive often prevents the integrity of the bond being maintained. This was because of the dimensional changes in the wood during swelling and shrinking of the material. Bulk cohesive failure of the epoxy as well as interfacial failure was reported after investigating epoxy bonded specimens subjected to a cyclic water soak, heat-drying procedure [27]. However, the main failure mechanism in the study was said to be in the wood and epoxy interface region. Another research programme examined the use of epoxy adhesives using thick bondlines in joints and directly compared their performance with that of solid specimens [28]. Of the 10 adhesive types studied, only two obtained dry shear strengths equal to or higher than that of the solid specimens as well as obtaining wet strengths that were greater than half those of the bonded dry specimens. However, the application of an appropriate coupling agent, such as hydroxymethlated resorcinol, to the surface of the wood has been seen to significantly increase the durability of epoxy adhesive bonds [29–33].

Despite the above findings, epoxy adhesives remain the choice of researchers in FRP–wood bonded connections because of their good gap-filling properties, limited shrinkage during curing and their ability to achieve full cure at ambient temperatures. Furthermore, they do not release volatile waste products such as water upon chemical curing, which could result in poor bond quality or the development of adverse dimensional transformations in wood.

1.3. Bondline thickness effects

FRP plate reinforcement can be easily incorporated into the glue-laminating manufacturing procedure in contrast to bonded-in rod or bar connections, which require time-consuming routing procedures. When using plate reinforcement, the thickness of the adhesive bondline can be varied easily. It has been reported from an experimental investigation that a bondline thickness of 0.1 mm gave optimum joint strength in timber scarf joints after bondline tests on a thickness range between 0.05 and 1 mm [34]. Findings from a number of finite element model studies contradict these experimental results and report that thicker bondlines help to dissipate more easily the shear stresses induced on the adhesive interface [35,36]. However, a linear finite element analysis study reported by Gleich et al. [37] agrees with experimental results and showed that as the bondline thickness was increased, peak shear and peel stresses were seen to increase but that average adhesive stresses decreased. Adams and Peppiatt [38] stated that careful consideration should be given to increased porosity and micro-cracking in thicker bondlines as these factors are possible reasons for lower strength failures.

The common practice in industry and in research programmes that study FRP–wood composites is to use thick epoxy bondlines. This is because the stresses that are experienced in the adhesive layer, which result from the variation in the swelling and shrinking between the two materials, can be more easily dissipated in thick bondlines in the order of 2 mm. However, the cost involved in the production of an FRP-reinforced glulam beam would drop considerably if it was shown that thinner bondlines of approximately 0.5 mm thickness can form adequately strong and durable bonds at the FRP–wood interface.

1.4. Objectives of the present study

The objective of this study was to examine the bond quality developed between selected FRP materials and low-grade spruce when using thin epoxy gluelines with an approximate thickness of 0.5 mm. Assessment of the epoxy bonds was by means of a methodical approach whereby the performances of moisture cycled FRP–wood bonded specimens, non-moisture cycled FRP–wood bonded specimens, non-moisture cycled wood–wood bonded specimens and solid wood specimens all taken from the same board were directly compared by means of the block shear test. Both adherend failure percentage and the shear stress at failure were recorded for each specimen. Furthermore, the effect of the application of a specially formulated silane-based adhesion promoter (AP) was assessed during moisture cycling of the FRP–wood bond.

2. Materials

2.1. Fibre-reinforced plastics

Two pultruded fibre-reinforced composite materials were selected for the bond test programme based on their mechanical properties as given by the manufacturers and presented in Table 1.

It can be seen that both materials possess tensile moduli considerably greater than the mean tensile modulus reported for Irish-grown Sitka spruce tested at 12% moisture content reported in Section 2.2. The tensile strength of the Fulcrum material is much higher than that of this wood. Both FRP materials comprised glass fibres aligned unidirectionally in a matrix. E-glass was selected as the most appropriate fibre type because of its relatively low cost in comparison to other glass fibre types,

Table 1
Properties of FRP materials from manufacturers data sheets.

FRP type	Tensile modulus (N/mm^2)	Tensile strength (N/mm^2)
Fulcrum[a]	45 000	980
GFRP[a]	40 000	N.A.

[a] Rotafix UK Ltd.

carbon fibres and aramid fibres. The Fulcrum material was manufactured using an engineered thermoplastic polyurethane matrix with which it is possible to achieve fibre volume fractions as high as 70%. A further important advantage of this material is that it can be recycled. Vinylester was the matrix type used in the GFRP material. This resin type was chosen in preference to polyester and epoxy resins because of its capacity to withstand moisture absorption, which is important when bonding the material to wood.

The pultrusion process used in the production of the FRP materials is an efficient method for the production of fibre-reinforced plastics where a constant cross-section is required. Much improved mechanical properties can be obtained with this procedure due to higher fibre volume fractions than those achieved in labour-intensive manual lay-up procedures.

2.2. Wood species

Irish-grown Sitka spruce was the wood species used in the test programme. The timber was all plain sawn and was harvested from the same stand. Consequently, variability in the wood resulting from contrasting environmental conditions during growth was significantly reduced. An important concern was the high juvenile wood percentage in the material and as a result increased dimensional instability present in the longitudinal direction. The timber was kiln dried in the sawmill to approximately 18% moisture content, and upon delivery to the laboratory, the boards were transferred to a conditioned environment of 65±5% relative humidity and a temperature of 20±2 °C for 3 months. Average board density was recorded as 390 kg/m^3 after this conditioning period. A mean tensile modulus and a mean tensile strength of 8074 and 22.7 N/mm^2, respectively, were found after approximately 65 in-grade specimens at 12% moisture content were tested in accordance with EN408 [39].

2.3. Adhesives

Three commercially available structural epoxy adhesives were used in the bond test programme. All were two-component, room-temperature cure, gap-filling, thixotropic adhesives and were specially formulated for the structural bonding of FRP to wood. A base resin and curing agent comprised the two parts of the adhesives. The adhesives were also reported to exhibit high-quality weathering characteristics as well as good creep and chemical resistance. Both Epoxy 1 and Epoxy 2 were supplied by Rotafix Ltd. and the products' commercial names were Timberset and CB10T Slow Set, respectively. CB10T Slow Set comprises Part-A epoxy resin (diglycidylether of bisphenol "A", DGEBA) with reactive diluent diglycidylether and is filled with silica fume particles, which cross-link with polyetheramines after mixing with the hardener Part-B. Timberset is a formulation of the base adhesive CB10T Slow Set, but with the addition of clay particles. Epoxy 3 was Sikadur 31 Normal, a well-recognised civil engineering two-component thixotropic adhesive and was supplied by Sika Ireland Ltd. Young's moduli of Epoxy 1, Epoxy 2 and Epoxy 3 adhesives were 5000, 1100 [40] and 8000 N/mm^2, respectively. The technical advice contained in the adhesive data sheets and that given by the manufacturers were followed closely during preparation of the test specimens.

2.4. Adhesion promoter

The adhesion promoter used involved a one-part composition of silanes supplied in a dilute aqueous solution. Although silanes predominate as adhesion promoters, the formulation was designed by the manufacturer, Rotafix Ltd., to enhance adhesion of the dissimilar substrates. The aim was to improve the chemical reaction of the adhesive and to attribute good surface wetting properties to the two substrates. This material was included in the bond test programme on the recommendation of the FRP supplier as a means of improving the performance of the moisture cycled FRP–wood bonded interface.

3. Experimental methods

The experimental programme that was undertaken to examine the bond interface quality between the timber and the two FRP materials, bonded with the three epoxy resins both with and without the adhesion promoter, is discussed in the following sections.

3.1. Substrate surface preparations

Correct pre-treatment of the bond surface is critical to the durability of the bond formed [41]. It is believed that this is particularly true when using cold cure epoxy adhesives to bond FRPs.

The expected service environment of an FRP-reinforced glulam beam is 65±5% relative humidity and 20±2 °C temperature and, therefore, the FRP materials were initially conditioned in this environment for at least 40 days prior to use. The surfaces of the FRP materials were maintained free from contamination by storing in a cling-film wrapping.

A range of FRP surface preparations was investigated and selection was made based on cost-effectiveness, practicality and the durability of the bond that could be achieved. Information was collected both from the technical advice provided by the suppliers of the FRP materials and that reported in the literature. Although, peel plies are an effective technique for preserving a contaminant-free surface on the FRP and no release agents are used in their manufacture, they are not regarded as being cost-effective for FRP materials that incorporate glass fibre reinforcement. The use of gritblasting on FRP materials can cause unevenness even with the use of extremely fine particles. Also, capital investment is required for the blast cabinet, contamination may easily occur from recirculated media and, therefore, regular media replacement and cabinet cleaning are required. Furthermore, skilled technicians are needed to operate the equipment in a safe manner. Sanding is a practical, cheap and convenient surface preparation procedure. Vick reported that sanding of the bond surface was seen to increase the resistance to delamination [28]. More information on the surface preparations for adhesively bonded composite joints is available in the literature [42].

The surface of the GFRP material was gently abraded using 320 grade wet and dry emery paper so that the top layer of the material, which was likely to contain release agents used in the manufacturing process and possibly other contaminants, was removed. Subsequently, the abraded surface was wiped clean with a cloth, which was wetted fresh with methylated spirits for each wipe in order to minimise a residue of grease remaining on the adherend surface prior to bonding. Methylated spirits were chosen as the solvent as it is cheap, readily available, and is associated with reduced hazardous risks in comparison to other solvents such as acetone. The production of the Fulcrum thermoplastic polyurethane did not require the use of any demoulding waxes or other release agents and therefore any residues present on the surface of this material were removed by simply wiping clean with a cloth wetted with methylated spirits. Furthermore, this material is associated with an inherently coarse surface and did not require any abrasion as a result.

Clear wood pieces were selected from the wood stock so that irregularities such as knots, fissures and resin pockets, which would inhibit the formation of a quality bond, were omitted. Knife planing was the preferred choice of surface preparation of the wood as research has shown that abrasively planed surfaces do not maintain the integrity of the bond to the same degree [43]. This process removes both chemical and physical contaminants that might be present on the surface of the wood and exposes the porous cellular structure of the wood so that the adhesive can penetrate into the microstructure. The adhesive was applied within 2 h of planing in order to limit oxidation of the wood surface. Abrasive planing procedures disrupt the bond surface by the crushing of the surface and subsurface wood cells in comparison to a uniform and smooth surface being formed by the knife planing process. Although the wettability of the wood is increased by knife planing, research has shown that it can be further increased in association with more complex procedures [44]. However, the objective of this research was to identify an inexpensive and commercially viable surface treatment technique that was capable of producing durable bonds.

Upon completion of the first set, a second set of specimens was fabricated including the silane-based adhesion promoter. This was applied by gently rubbing the bond surfaces of the adherends with a cloth soaked in the silane solution after they had been cleaned with the methylated spirits as described above. The adherend surfaces were ready for adhesive application after 1–2 h.

3.2. Bond specimen fabrication

The steps specified in ISO 6238 [45] were followed during the manufacturing and testing phases of the shear bond specimens. From the timber stock of approximately 200 boards, clear wood laminations, approximately 310 mm long × 60 mm wide × 20 mm thick, were prepared so that the test bars of the type shown in Fig. 1 could be manufactured. The fabrication programme for the wood–wood bonded test bars was initially executed.

After knife planing of the wood was complete, the adhesive under examination was mixed. A bondline thickness of 0.5 mm was obtained at the shear bond interface by the placement of shims at both ends as well as at the centre of the test bar. Although epoxy adhesives generally require only sufficient clamping pressure to eliminate voids and squeeze out any excess glue, a uniform pressure of 0.7 N/mm^2 was applied to the assembly for a period of 24 h at a temperature of approximately 20 °C. This process was consistent with the production of glue-laminated beams. Squeeze-out of the excess epoxy resin indicated that sufficient quantity was spread along the interface.

Fabrication of the FRP–wood test bars followed the same procedure as that for the wood–wood bonded test bars except that an FRP plate was incorporated adjacent to the centre line of the test bar. The thicknesses of the GFRP and Fulcrum plates that were used were 4 mm and 1.4 mm, respectively. In order to obtain a consistent 40 mm depth of test bar, a wood backing piece of the required thickness was bonded to the FRP plate in order to facilitate correct application of compressive load during the shear specimen testing phase. A bondline thickness of 0.5 mm was also incorporated for the FRP–wood specimens. Once the clamps were removed, the bonded test bars were placed in a conditioned environment of 65 ± 5% relative humidity and a temperature of 20 ± 2 °C for a minimum period of 40 days in order for the adhesives to reach full cure. Five double-notched test specimens were cut from each test bar as shown for a GFRP–wood test bar in Fig. 1.

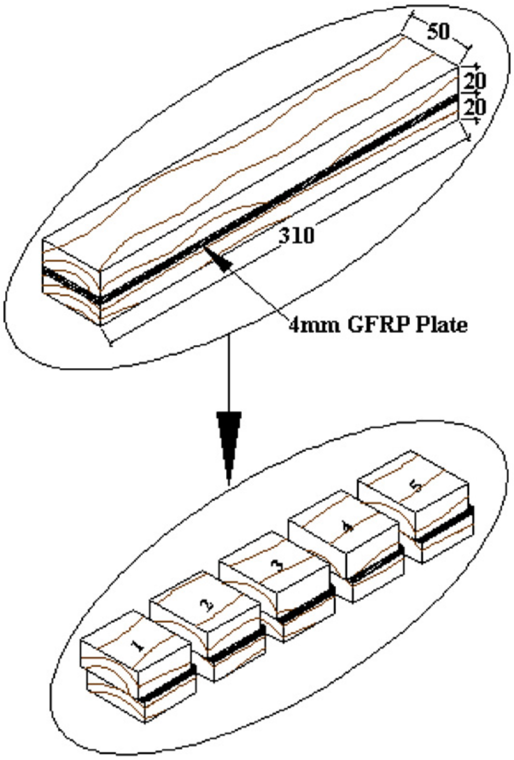

Fig. 1. Typical GFRP–wood test bar and test specimens.

The bond shear test specimens were cut to obtain a notch of 5 mm on each loading face and were associated with a bond interface area of approximately 40 mm × 50 mm. The theoretical shear plane was measured using a vernier caliper with a precision of 0.01 mm. A typical Fulcrum–wood test specimen is shown in Fig. 2.

3.3. Solid wood specimen testing

Shear tests on solid wood specimens used the same double-notched geometry as that stated in the ISO 6238 standard. This shape was based on a recommendation by Okkonen and River [46]. However, because of a restriction in size of the boards from which the solid specimens were cut, they were constrained to 40 mm in width in comparison to 50 mm used in the bonded specimens. Notches were located at either end such that shearing parallel to the grain could be facilitated. All solid specimens were non-moisture cycled and were conditioned to an environment of 65 ± 5% relative humidity and a temperature of 20 ± 2 °C. A typical solid specimen and its associated geometry are shown in Fig. 3.

3.4. Moisture cycling

The moisture cycling of the FRP–wood bonded specimens followed an adjusted EN 391 procedure [47]. Specimens were initially transferred from the conditioning chamber to a pressure

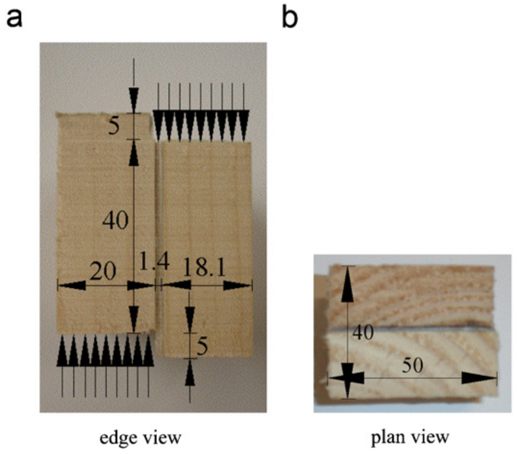

Fig. 2. Fulcrum–wood test specimen.

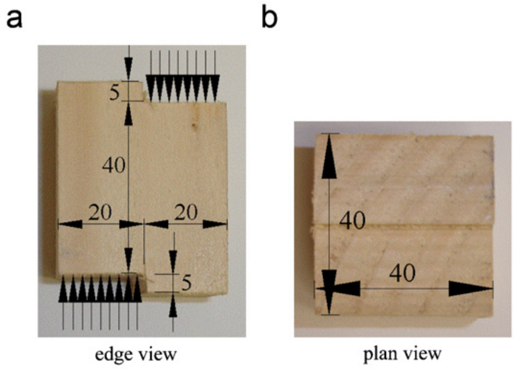

Fig. 3. Solid control test specimen.

vessel in which they were completely submerged in de-aired water, which was maintained at a temperature of 20 °C. It was ensured that sufficient space was left between the specimens so that their end grains could be infiltrated by the water. A vacuum pressure of 70 kPa was drawn for approximately 2 h so that air that was trapped in the voids of the wood was extracted. A back pressure of 600 kPa was subsequently applied in the vessel for a minimum of 30 min so that complete saturation of the specimens could be obtained. Drying of the specimens was then undertaken in an environment of 25 ± 5% relative humidity and to 35 ± 5 °C temperature. This cycle of wetting and drying was repeated five times. The specimens were then transferred to a conditioning chamber, which was maintained at 65 ± 5% relative humidity and a temperature of 20 ± 2 °C, for a period of at least 15 days prior to testing. This methodical procedure allowed for the direct comparison of the mechanical performance of the moisture cycled specimens with that of the non-moisture cycled specimens, and hence, by reconditioning the specimens to their original in-service moisture content, evaluated only the effect of the hygrothermal stresses imposed on the adhesive bonds during moisture cycling.

3.5. *Specimen testing*

A guillotine-type tool was used to carry out the shearing of the test specimens. Prior to placement in the tool, the loading faces of the specimens were sanded square with 100 grit sandpaper so that possible eccentricities that might have been incurred during testing would be eliminated. A 100 N preload was applied to each specimen after placement in the shearing apparatus so that its correct position could be maintained prior to load application.

The target failure time for execution of each test was 60 ± 20 s [45]. The specimens were tested at a constant loading rate, in preference to a constant stroke rate (crosshead displacement), as a more progressive application of the load is achieved by this procedure. It was shown in previous research that the rate at which the load was applied had no effect on the failure strengths of bonded specimens [30].

A previous study using a numerical model illustrated that friction in the block shear test set-up can be a concern [48]. As a result, grease was applied at the contact locations between the specimen and the shear tool so that the contribution from friction would be negligible. After each specimen was tested, a visual assessment of the percentage adherend failure was executed, to the nearest 5%, using a superimposed grid after each specimen was tested. An FRP/adhesive combination was attributed a "Pass" if the mean adherend failure percentage obtained was greater than or equal to 80%. A high adherend failure percentage indicates a strong bond has been formed and that the adherend in question was the weakest link at the bond interface.

The compressive shear strength of each specimen was determined by dividing the ultimate load of the failed specimens by the measured dimensions of the theoretical shear plane. This approach assumes an instantaneous failure and a uniform stress distribution across the theoretical shear plane. While this is the accepted approach to determine the shear strength, the actual shear stress distribution is characterized by peaks at the end of the bonded length. Findings from three-dimensional nonlinear finite element analyses have demonstrated the existence of stress concentrations adjacent to the loading edges beside the notches as well as the presence of tensile peel stresses perpendicular to the shear plane in both single-notched [49] and double-notched [50] block shear specimens. The stiffness inbalance that arises from the bonding of dissimilar materials was noted as being an important consideration in the shear stress distribution in other studies [51,52]. Furthermore, when two materials of different stiffness are bonded together, numerical modelling has shown that the maximum shear stresses occur at the free end of the adhesive region close to the adherend of the higher stiffness [36].

3.6. *Test programme*

The test programme involved testing the three epoxy adhesives with the two FRP types both with and without the adhesion promoter applied. For each test combination examined, 10 non-moisture cycled solid control specimens, five non-moisture cycled wood–wood bonded specimens, 20 non-moisture cycled FRP–wood bonded specimens and 10 moisture cycled FRP–wood specimens, which were all taken from the same board, were tested. The most important aspect of this approach is that a direct comparison can be made between the shear strength of solid wood and a bonded specimen fabricated from the same board. Variations in wood properties such as ring width, orientation of the grain, latewood percentage and density are considerably reduced as a result. One wood–wood bonded test bar was manufactured for each FRP/adhesive combination and five wood–wood bonded test specimens were cut from this test bar accordingly. Six FRP–wood bonded test bars were manufactured for each combination in the test programme. From five of these six FRP–wood bonded test bars made, four test specimens were non-moisture cycled and the remaining one was moisture cycled. All the specimens from the sixth FRP–wood test bar were moisture cycled. By this approach, 20 non-moisture cycled FRP–wood bonded specimens and the 10 moisture cycled FRP–wood bonded specimens were fabricated and tested.

4. Results and discussion

In the following sections, the results from the testing of the shear specimens are discussed with regard to hygrothermal fracture failures, adherend failure percentages and shear strengths at failure.

4.1. Moisture cycling failures

A number of FRP–wood bonded specimens failed prematurely during the saturating and drying phases of the moisture cycling procedure. The specific stages where the fracturing occurred and the cycle number in question are shown in Tables 2 and 3. The specimens that demonstrated the worst performance are listed from the top of the tables. In general, these hygrothermal fracture failures consisted of adhesion failure to the FRP, although Epoxy 3 bonded specimens demonstrated cohesive (within the resin) failures.

It can be seen in Table 3 that for the GFRP–wood moisture cycled fracture results all the epoxy bonded specimens that did not incorporate the adhesion promoter experienced at least one failure. The application of the adhesion promoter appeared to prevent or delay fracturing during the moisture cycling process of Epoxy 1 and Epoxy 2 FRP–wood bonded specimens.

Three Epoxy 1 bonded Fulcrum specimens that did not include the adhesion promoter experienced failure during moisture cycling as shown in Table 3. Two of these specimens fractured in the first drying phase and the third failed in the second drying phase. These failures that occurred early in the moisture cycling phases demonstrate the weakness present in these specimens.

In general, an adhesive of lower modulus is known to lower the stress concentration in the bondline and subsequently a joint of higher strength can be obtained. Several bi-adhesive studies, which have employed an adhesive of lower modulus in a higher stressed zone, have obtained measurable increases in strength in comparison to those where one single adhesive was used over the full bondline length [53–55]. However, in the present study, no obvious link was established from the results between Young's modulus of the adhesive and the hygrothermal resistance of the bond.

Table 2
Hygrothermal fractures—GFRP.

Adhesive	Sat 1	Dry 1	Sat 2	Dry 2	Sat 3	Dry 3	Sat 4	Dry 4	Sat 5	Dry 5
Epoxy 3 –AP	–	–	1	–	1	–	–	–	–	–
Epoxy 2 –no AP	–	–	–	1	–	–	–	1	–	–
Epoxy 1 –no AP	–	–	1	–	–	–	–	–	–	–
Epoxy 3 –no AP	–	–	–	1	–	–	–	–	–	–
Epoxy 1 –AP	–	–	–	–	1	–	–	–	–	–

Table 3
Hygrothermal fractures – fulcrum.

Adhesive	Sat 1	Dry 1	Sat 2	Dry 2	Sat 3	Dry 3	Sat 4	Dry 4	Sat 5	Dry 5
Epoxy 1 –AP	–	2	–	1	–	–	–	–	–	–

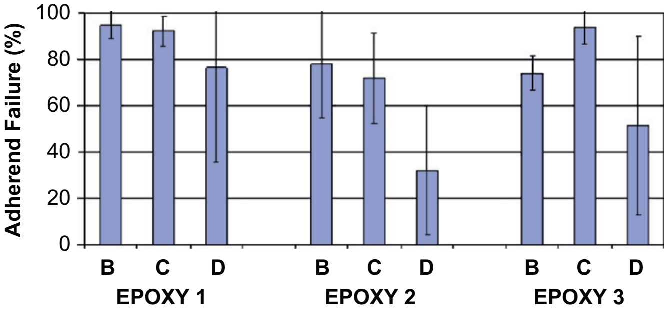

Fig. 4. Adherend percentage failure vs. adhesive GFRP with epoxy adhesives. Keys: A = solid specimens; B = non-moisture cycled wood–wood bonded specimens; C = non-moisture cycled FRP–wood bonded specimens; D = moisture cycled FRP–wood bonded specimens; I = standard deviation; AP = adhesion promoter.

4.2. Adherend percentage failures

Results from the assessments of adherend failure percentages for both FRP materials are discussed in the following paragraphs.

4.2.1. GFRP

Of the three epoxy adhesives tested, Epoxy 1 bonded moisture cycled specimens performed the best with regard to the mean adherend percentage failures (Fig. 4). However, this adhesive still marginally failed the 80% wood failure criterion. Furthermore, the result was associated with a high standard deviation, which demonstrated the degree of variation in the bond quality that was formed for these specimens. This was in contrast to the wood–wood bonded specimens and non-moisture cycled FRP–wood specimens, with both passing the 80% adherend failure criterion and having good reliability as shown by the short standard error bars (Fig. 4). The moisture cycled results for Epoxy 2 and Epoxy 3 were discouraging with both adhesive types failing to obtain even 60% average adherend failure percentages. Epoxy 2 bonded wood–wood specimens and non-moisture cycled FRP–wood specimens as well as Epoxy 3 bonded wood–wood specimens failed to pass the 80% adherend failure criterion.

The most favourable result in the GFRP bond test programme was obtained with the adhesion promoter in the bond tests to the GFRP plate when using Epoxy 1 (Fig. 5). All three specimen types for this adhesive passed the 80% adherend failure criterion. This was in contrast to Epoxy 2 and Epoxy 3 bonded specimens, which still exhibited a poor performance even when the adhesion promoter was applied. High variability was also associated with the moisture cycled specimens for these adhesives.

4.2.2. Fulcrum

Both Epoxy 1 and Epoxy 3 adhesives performed well in the Fulcrum bond test programme (Fig. 6). The mean result for the moisture cycled specimens with these adhesives passed the 80% failure criterion. Indeed, the moisture cycled Epoxy 1 bonded specimens achieved a higher mean adherend percentage failure than the wood–wood bonded specimens taken from the same board. The gap-filling characteristics of the epoxy adhesives were considered to be important in the formation of a high-quality durable bond to this coarse material. This was identified as a cause of poor bond quality in a previous test programme that examined bonding with conventional laminating adhesives possessing limited gap-filling properties [56]. However, all three types of Epoxy 2 bonded specimens failed the 80% wood failure criterion and the performance for the moisture cycled specimens was particularly poor.

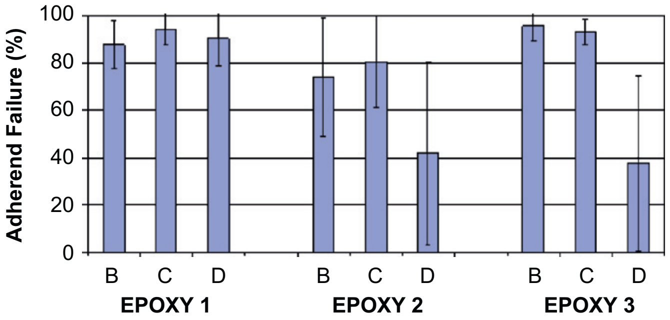

Fig. 5. Adherend percentage failure vs. adhesive—GFRP with epoxy adhesives (AP). Keys: A = solid specimens; B = non-moisture cycled wood–wood bonded specimens; C = non-moisture cycled FRP–wood bonded specimens; D = moisture cycled FRP–wood bonded specimens; I = standard deviation; AP = adhesion promoter.

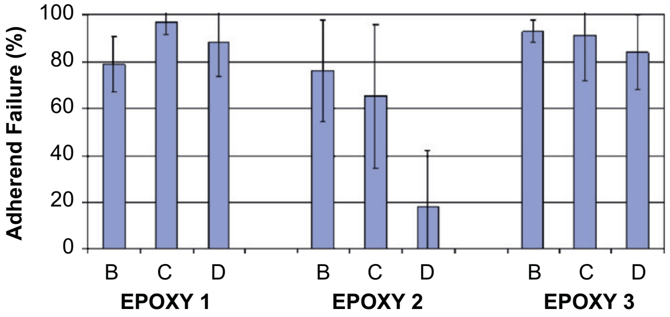

Fig. 6. Adherend percentage failure vs. adhesive—Fulcrum with epoxy adhesives. Keys: A = solid specimens; B = non-moisture cycled wood–wood bonded specimens; C = non-moisture cycled FRP–wood bonded specimens; D = moisture cycled FRP–wood bonded specimens; I = standard deviation; AP = adhesion promoter.

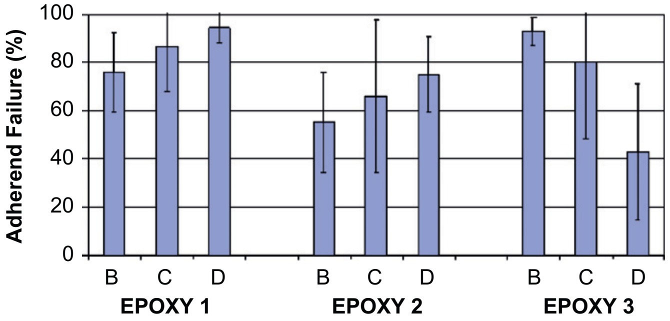

Fig. 7. Adherend percentage failure vs. adhesive—Fulcrum with epoxy adhesives (AP). Keys: A = solid specimens; B = non-moisture cycled wood–wood bonded specimens; C = non-moisture cycled FRP–wood bonded specimens; D = moisture cycled FRP–wood bonded specimens; I = standard deviation; AP = adhesion promoter.

Application of the adhesion promoter improved the performance of Epoxy 1 and Epoxy 2 bonded moisture cycled Fulcrum–wood specimens (Fig. 7). The mean adherend percentage failure of the moisture cycled Epoxy 1 bonded specimens was seen to outperform the non-moisture cycled FRP–wood bonded specimens and wood–wood bonded specimens taken from the same board. Although a significant performance increase is seen for Epoxy 2 bonded moisture cycled specimens, these specimens as well as the non-moisture cycled Fulcrum–wood and wood–wood bonded specimens all failed the 80% criterion. No improvement was recorded for the Epoxy 3 bonded specimens with the adhesion promoter. In fact, the moisture cycled specimens showed a marked deterioration in performance.

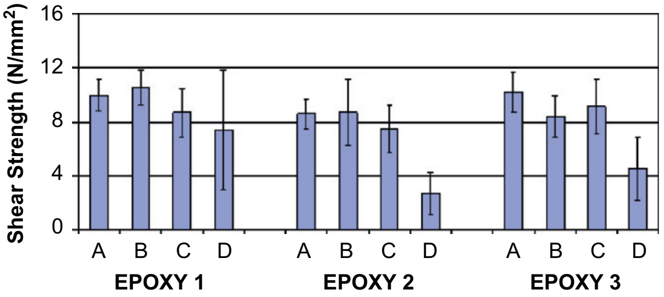

Fig. 8. Shear strength vs. adhesive—GFRP with epoxy adhesives. Keys: A = solid specimens; B = non-moisture cycled wood–wood bonded specimens; C = non-moisture cycled FRP–wood bonded specimens; D = moisture cycled FRP–wood bonded specimens; I = standard deviation; AP = adhesion promoter.

4.3. *Shear strength results*

The shear strength results relating to the three epoxy adhesives and the two FRPs both with and without the adhesion promoter are discussed below.

4.3.1. *GFRP*

It can be seen from the results in Fig. 8 that Epoxy 1 bonded moisture cycled GFRP–wood specimens performed the best of the three adhesives when the adhesion promoter was not applied. However, a high standard deviation indicates the variability associated with the results and the effect that the moisture cycling had on the bond in comparison to the non-moisture cycled specimens, wood–wood bonded specimens and solid control specimens taken from the same board. The shear strength magnitudes obtained for the moisture cycled Epoxy 2 and Epoxy 3 specimens were low in comparison to the other specimen types.

For the GFRP–wood specimens, to which the adhesion promoter was applied, Epoxy 1 bonded moisture cycled specimens exhibited best improvement (Fig. 9) and closely matched the performance of the non-moisture cycled specimens despite the severe swelling and shrinking stresses that would have been imposed on the bondline. Furthermore, the standard deviation associated with the results is much lower in comparison to when the adhesion promoter was not applied. The hygrothermal resistance for Epoxy 2 bonded FRP–wood moisture cycled specimens that included the adhesion promoter still performed poorly in comparison to non-moisture cycled specimens taken from the same board. No improvement was recorded with regard to Epoxy 3 bonded GFRP–wood specimens when the adhesion promoter was included in the fabrication of the specimens.

4.3.2. *Fulcrum*

The shear strength results for the Fulcrum material show that for Epoxy 1 and Epoxy 2 adhesives, the moisture cycled specimens underperformed considerably in comparison to the non-moisture cycled Fulcrum–wood specimens, wood–wood bonded specimens and solid control specimens (Fig. 10). The moisture cycled Fulcrum–wood specimens that were bonded using Epoxy 3 performed considerably better in comparison to the solid control specimens, wood–wood bonded specimens and non-moisture cycled specimens taken from the same board.

It is seen that when the adhesion promoter was applied (Fig. 11), improvements occurred in the epoxy bonded moisture cycled specimens in relation to the performance of the

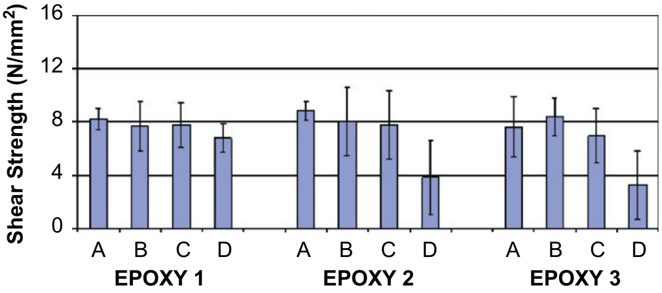

Fig. 9. Shear strength vs. adhesive—GFRP with epoxy adhesives (AP). Keys: A = solid specimens; B = non-moisture cycled wood–wood bonded specimens; C = non-moisture cycled FRP–wood bonded specimens; D = moisture cycled FRP–wood bonded specimens; I = standard deviation; AP = adhesion promoter.

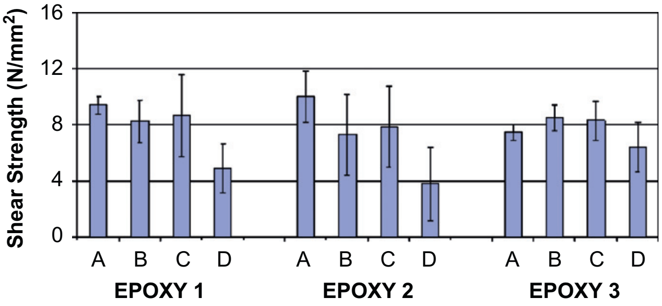

Fig. 10. Shear strength vs. adhesive—Fulcrum with epoxy adhesives. Keys: A = solid specimens; B = non-moisture cycled wood–wood bonded specimens; C = non-moisture cycled FRP–wood bonded specimens; D = moisture cycled FRP–wood bonded specimens; I = standard deviation; AP = adhesion promoter.

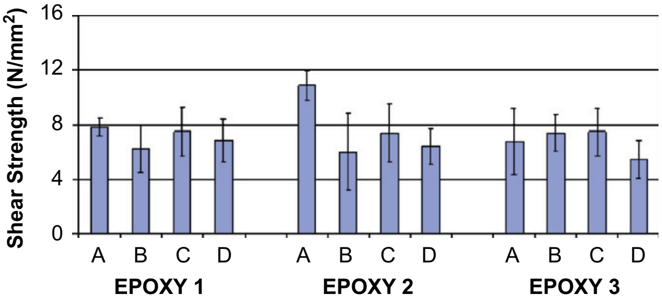

Fig. 11. Shear strength vs. adhesive—Fulcrum with epoxy adhesives (AP). Keys: A = solid specimens; B = non-moisture cycled wood–wood bonded specimens; C = non-moisture cycled FRP–wood bonded specimens; D = moisture cycled FRP–wood bonded specimens; I = standard deviation; AP = adhesion promoter.

wood–wood bonded specimens and non-moisture cycled Fulcrum–wood specimens taken from the same board. The biggest performance enhancements were recorded for Epoxy 1 and Epoxy 2 bonded specimens.

5. Conclusions

The test programme discussed in this paper has demonstrated that certain epoxy adhesives using a bondline thickness of approximately 0.5 mm can form strong durable bonds between wood and FRP materials depending on the FRP material in question. This bondline thickness is much less than that normally used to dissipate the hygrothermal stresses that are encountered in industrial applications where FRP–wood bonds are present. Both pultruded glass fibre-reinforced polymer types studied in the test programme have good mechanical properties relative to the timber under examination and as a result are considered to have strong commercial potential for the reinforcement of timber. For the more successful adhesive FRP combinations in this study, FRP–wood specimens, which were subjected to a severe 5-cycle vacuum pressure, soaking-drying cyclic procedure and subsequently tested in the block shear test apparatus, obtained shear strengths and adherend failure percentages as high as those of non-moisture cycled FRP–wood specimens, wood–wood bonded specimens and solid control specimens fabricated from the same board. However, another important finding from the study is that the quality of the epoxy bond depends not only on the epoxy adhesive under examination but also on the FRP substrate.

Application of the silane-based adhesion promoter prior to application of the adhesive was seen to increase the delamination resistance for two of the three epoxy adhesives that were examined. As a result, premature fracturing of the bond was postponed. Significant improvements in the mean shear strength and mean adherend failure percentages of the moisture cycled specimens were also noted for particular adhesive/FRP combinations when this material was applied to the bond surfaces.

The moisture cycling of the bonded specimens in this study was a severe process and the hygrothermal stresses to which the FRP–wood specimens were subjected to were considered extreme. It is believed that an FRP–wood beam in an internal service environment would never experience such excessive swelling and shrinking stresses on its bondlines. Consequently, the results presented in this paper represent a thorough evaluation of bond quality between the wood and FRP materials.

The results of this experimental programme suggest that thin bondlines with certain epoxy adhesives can give strong and durable bonds between FRP and wood. This finding gives further grounds for optimism in the development of cost-effective FRP-reinforced timber produces for use in the construction industry.

Acknowledgments

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