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FRP reinforcement of low-grade glulam timber bonded with wood adhesive

Gary M. Raftery [a,*], Peter D. Rodd [b]

[a] Department of Civil and Environmental Engineering, Faculty of Engineering, The University of Auckland, New Zealand
[b] Civil Engineering, College of Engineering and Informatics, National University of Ireland, Galway, Ireland

HIGHLIGHTS

- Low-grade glulam is reinforced using PRF bonded FRP plates.
- No premature delamination or slip at the interface is determined.
- Enhancements for stiffness and ultimate moment capacity are reported on.
- Strong agreement between finite element model predictions and experimental data.
- The use of expensive epoxy adhesives at the FRP–wood interface can be avoided.

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ABSTRACT

The commercial development of composite reinforced timber beams manufactured using low-grade laminated wood would be considerably enhanced if the same adhesive was permitted to be used both at the wood–wood bond interfaces as well as the FRP plate–wood bond interface. This paper describes a programme of tests undertaken to assess the structural performance of low-grade glued laminated timber reinforced with glass fibre reinforced plate (GFRP) bonded using the conventional wood laminating adhesive, phenol resorcinol formaldehyde (PRF). The use of a practical reinforcement percentage of 1.86% of the cross-sectional area resulted in a moderate stiffness enhancement of 18% and considerable improvements in the ultimate moment capacity of 31%. Strain profiles demonstrated that utilisation of the compressive behaviour of the timber was improved in the reinforced beams. Most importantly, at no stage during testing of any of the reinforced beams was the quality of the FRP–wood bond compromised. The results from a nonlinear finite element model showed excellent agreement with the experimentally determined ductile load–deflection behaviour of the reinforced beams. Furthermore, satisfactory comparisons are obtained between the predicted and measured failure loads and strain profile behaviour. Slip at the FRP–wood interface, bonded using a wood laminating adhesive, was considered negligible. The research proposes an improved alternative whereby the same adhesive is permitted to be used for all bond interfaces in the reinforced beam and the use of more expensive epoxy adhesives at the FRP–wood bond interface is avoided.

1. General introduction

With increasing focus on the development of sustainable construction systems, the use of wood in the built environment is at present receiving much attention [1]. This is because wood is a recyclable material and is a natural resource. Wood is also cost competitive, has good mechanical properties and is architecturally attractive [2]. The use of advanced fibre reinforced polymer (FRP) materials is also becoming more widespread in the civil engineering industry, particularly for reinforcement and rehabilitation applications in concrete and masonry [3,4]. While, the primary focus of studies to date relate to the use of FRP materials for the reinforcement of concrete, several research studies have also examined the use of FRP materials for the strengthening of timber elements. FRP materials have excellent mechanical properties and exhibit very good characteristics in relation to durability [5]. The use of faster grown wood species which produce lower grade timber for the construction industry can particularly benefit from the addition of FRP reinforcement. The effects from strength reducing

* Corresponding author. Tel.: +64 9 923 8536.
E-mail address: G.Raftery@auckland.ac.nz (G.M. Raftery).

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defects which are a regular characteristic of such low-grade timber can be decreased considerably from the process of glued lamination. Furthermore, FRP plate material can be incorporated without difficulty in the higher stressed tension zone of such glued laminated timber. At present, epoxy adhesives which are more expensive than conventional wood laminating adhesives are widely regarded as the first choice of adhesive at the FRP–wood interface. However, the development of such a reinforced engineered wood product becomes significantly more cost-effective if the one adhesive is used throughout the depth of the section. This paper reports on investigations that examine the structural performance of FRP plate reinforced low-grade glued laminated timber where the same adhesive is used throughout the depth of the section in order to increase cost competitiveness.

1.1. FRP–wood bonded joints

The quality of the joint in any composite system involving dissimilar materials is of critical importance. This issue is of particularly high relevance when undertaking hybrid product development with wood as it is a natural material whose physical dimensions can change with alterations in the temperature and humidity of the surrounding environment. When joined with a dissimilar material that may not swell and shrink to the same magnitude, increased stress is placed at the interface between the two materials. Structural epoxy adhesives in industry are the generally accepted class of adhesives that are used to bond FRP materials to wood [6]. In comparison to other common wood laminating adhesives, epoxy adhesives have the advantages that they require low clamping pressures and are gap filling. However, several research programmes have highlighted concerns. A conclusion from an early research programme investigating commercial epoxy adhesives for timber applications was that starved joints were the principal cause for low bond quality [7]. In another early study which examined the bonding of wood with epoxy adhesive, it was reported that the bond strength formed in the joint failed to reach the strength of the timber and it was considered that an inadequate bond was formed [8]. Durability of the bond has been reported as a concern when no coupling agent has been applied to the wood surface [9–11]. In another test programme which used thick epoxy bond lines at the wood–wood interface, only two epoxy adhesives out of ten achieved shear strengths equal to or greater than solid wood specimens [12]. It was seen that water soaking weakened epoxy bonded wood specimens considerably and poor wood failures were obtained which was in contrast to the performance of dry non-durability tested specimens which exceeded the strength of the wood itself [13]. Bulk cohesive and interfacial failure of the epoxy were reported after investigating epoxy bonded specimens subjected to a cyclic water soak, heat-drying procedure [14]. In a more recent study that examined the bond quality at the FRP wood bond interface when using thin bondlines, only specific epoxies formed strong durable bonds [15]. It is noted that the use of plate reinforcement incorporated into the glued laminated timber procedure does not essentially require a gap filling adhesive if a durable bond can be formed. Therefore, results from a recent test study demonstrated that certain conventional wood laminating adhesives such as phenol resorcinol formaldehydes were successful in resisting severe hygrothermal stresses at the FRP–wood interface when using low quality wood [16].

1.2. FRP plate strengthened timber

Only a limited number of studies are available in the literature on the reinforcement of low-grade glued laminated timber. A research programme assessed the reinforcing effect of epoxy bonded recyclable FRP plates which included unidirectionally aligned glass fibres with such timber when the FRP reinforcement was strategically located in the tension zone [17,18]. Further investigations examined the effect of bonded-in glass fibre reinforced rods on the mechanical performance of low-grade glued laminated timber which included an examination of the groove geometry [19] and reinforcement and repair of low-grade timber with basalt fibre rods [20]. An early review was undertaken which assessed several investigations that examined the reinforcement of timber but it was concluded that such a product had not been commercialised because of the additional steps that needed to be incorporated during production [21]. Considerable increases in the stiffness and ultimate bending moment were reported when glass fibre reinforced polyester profiles were included in timber sections [22]. However, problems were reported in the bond quality between the FRP material and the timber. CFRP plate reinforcement was used to reinforce glulam beams where the expected mechanical improvements were obtained but it was believed that the gains in strength over that of unreinforced beams would not be economically viable because of the cost of the CFRP reinforcement [23]. Carbon fabric in an epoxy matrix was deemed to be effective for the flexural reinforcement of old wood beams [24] and fir and chestnut beams were successfully reinforced with epoxy bonded FRP profiles [25]. Old wooden beams were reinforced with CFRP strips using a number of configurations and it was concluded that the effectiveness of the reinforcement significantly depended on the quality of the wood–CFRP strip bond [26]. Another study used a finite element model to predict the behaviour of reinforced solid timber beams [27]. It was reported that the bond shear-slip between the FRP and timber had little effect on the stiffness and ultimate load capacity. In North America and Europe, attempts to commercialise FRP reinforced glulam have achieved some success [28]. Steel plate reinforcement has also been examined but this has involved the use of epoxy adhesives [29].

1.3. Objectives of the present study

The objective of this research is to examine the reinforcement of low-grade glued laminated timber beams using pultruded glass fibre reinforced polymer plates. The use of the conventional wood laminating adhesive, phenol resorcinol formaldehyde is examined for all bonding applications in the beams which makes the hybrid section more cost effective. The mechanical performance of the reinforced beams is compared with that of unreinforced glulam beams in relation to load–deflection behaviour, failure mode, enhancements in both stiffness and ultimate moment capacity as well as the changes in strain profile distribution. A nonlinear finite element model is developed and predictions are compared with the experimental results.

2. Experimentation

2.1. Materials

2.1.1. Wood species

The species used in the experimental testing was Irish grown Sitka spruce. This species is characterised by its large ring widths and short crop rotation time of approximately 35 years. In order to reduce variability from contrasting growth conditions, all the timber in the study was sourced from the same sawmill. The timber was plain sawn, kiln dried to approximately 18% moisture content and was mechanically graded to C16 grade [30]. The boards had cross-sectional dimensions of 96 × 44 mm and were 4200 mm in length. After delivery the timber was conditioned in a chamber to an environment of 65 ± 5% relative humidity and 20 ± 2 °C temperature for a minimum period of three months. After the conditioning period, the mean equilibrium moisture content was determined as 11.8% and the mean board density was determined as 380 kg/m^3.