Influence of embedded length on strength of BFRP rods bonded parallel to the grain in low grade timber by pullout-bending tests

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ABSTRACT: Bonded-in rod connections in timber possess many desirable attributes in terms of efficiency, manufacture, performance, aesthetics and cost. In recent years research has been conducted on such connections using fibre reinforced polymers (FRPs) as an alternative to steel. This research programme investigates the pull-out capacity of Basalt FRP rods bonded-in in low grade Irish Sitka Spruce. Embedded length is thought to be the most influential variable contributing to pull-out capacity of bonded-in rods after rod diameter. Previous work has established an optimum embedded length of 15 times the hole diameter. However, this work only considered the effects of axial stress on the bond using a pull-compression testing system which may have given an artificially high pull out capacity as bending effects were neglected. A hinge system was utilised that allows the effects of bending force to be taken in to consideration along with axial forces in a pull-out test. This paper describes an experimental programme where such pull-bending tests were carried out on samples constructed of 12mm diameter BFRP bars with a 2mm glueline thickness and embedded lengths between 80mm and 280mm bonded-in to low-grade timber with an epoxy resin. Nine repetitions of each were tested. A clear increase in pull-out strength was found with increasing embedded length.

KEY WORDS: Low-grade timber; Basalt FRP; Composites; Bonded-in rods; Pull-out capacity; Pullout-bending; Parallel-to-grain.

1 INTRODUCTION

Bonded-in rods present a sustainable, aesthetically pleasing alternative to the cumbersome conventional steel moment connections that are often encountered in timber construction. Not only do connections with bonded-in rods look better than conventional connections, they also have enhanced fire protection as the rods which transfer moment are embedded inside, and are therefore protected by, the timber.

Bonded-in rods have great potential in a wide range of both new build and restoration projects. Successful renovation has been carried out in roof and floor beams in buildings subject to decay [1], [2]. In new build, five areas were identified where bonded-in rods may be used for connections: frame corner, beam-post connection, beam-beam joint, supports and hinged joints [3].

Since the late 1980s there have been many research projects commissioned on the use of bonded-in rods in timber construction e.g. GIROD and LICONS [4], [5]. In spite of this, no universal standard exists for their design. There had been an informative annex in the pre-standard PrBS ENV 1995-2:1997 which provided limited coverage of the design of bonded-in rods using steel bars however this document was replaced by BS EN 1995-2:2004 and no guidance is included in this current document.

There are three key elements to be considered when designing bonded-in rod connections: the timber, the rod and the adhesive. The most significant challenge in the development of a standard design method is the many varying approaches to defining each of these joint properties.

2 THEORETICAL BACKGROUND

2.1 Materials

The majority of research done in this area to date comprises steel rods bonded-in to glued laminated (glulam) elements with lamellae of a high strength class timber. There has however been some degree of research on the behaviour of bonded-in rods in lower grade timber eg. glulam beams using laminations of low-grade Sitka Spruce [6] and Spruce of strength class C16 in its sawn form [7]. In tests of reinforcement of timber beams with carbon fibre reinforced polymer (CFRP) and basalt fibre reinforced polymer (BFRP) materials locally sourced Pine beams have been used [8], whilst the use of bonded-in rods in Beech laminated veneer lumber has been investigated also [9].

This research investigates the use of locally sourced Irish grown Sitka Spruce. Sitka Spruce grown in Ireland has a fast growth time of approximately 30 to 40 years [10], as a result of this high growth rate the cell structure of the wood is less dense and therefore the timber generally has relatively poor strength and is of a low classification, typically C16 [11]. However, low transportation costs relative to imported timber means that Irish Sitka Spruce can be a very cost-effective building material if its full potential is utilised.

As well as alternative timber types, rod materials other than steel are being investigated, namely Fibre Reinforced Polymers (FRPs). FRPs are composite materials made of a polymer matrix reinforced with different fibres. They are more corrosion-resistant than steel and so they will have a longer service life, with less maintenance and monitoring required. Even the weakest FRP is stronger in tension than steel and they are all much lighter, meaning that an equally strong joint can be formed with less material being required.

Earlier studies investigated the use of glass fibre reinforced polymer (GFRP) as an alternative to steel [12]–[14] while carbon fibre reinforced polymer (CFRP) has been used more recently [15]. Despite its significant cost effectiveness compared to CFRP and its greater tensile strength compared to GFRP, basalt fibre reinforced polymer (BFRP) has only been touched upon in the literature with regards to its use in bonded-in technology [16]. BFRP has a Young's modulus closer to timber than the more commonly used material, steel. It is also a much lower cost material compared to the other FRPs. These advantages resulted in BFRP being selected for use in this research.

Many investigations have been undertaken to determine which adhesive type is best suited to glued-in rod applications. The adhesive must have good gap-filling properties to ensure a good bond along the entire length of rod, good adhesion to both the rod material and the timber and higher shear strength and stiffness than the timber being used. In a number of studies it was determined that epoxy adhesives had higher strength than phenol resorcinol and polyurethane alternatives and that epoxies are most suitable for glued-in rod applications [17], [18]. A two-part thixotropic gap filling epoxy was used. This adhesive only flows under shear so is ideal for applications such as overhead beam repair and jointing overhead.

In order to create a strong connection, a large surface area of the glue around each rod must be in contact with the timber. Variables that can be altered to increase this surface area include: thickness of the glue-line, length of rod glued (embedded length), number of rods used and rod diameter. Edge distance between the centre of the rod and the edge of the sample must also be considered to ensure the connection does not split prematurely.

2.2 Pull-out test methods

There are several test configurations seen in the literature that can be used to assess pull-out capacity of a rod bonded-in to timber. The five most common are pull-pull, pull-push, pull-pile foundation, pull-beam and pull-bending. Each test method has its own merits and demerits but pull-pull was identified as the more representative, producing relatively higher pull-out strengths [19]. However in a moment resisting timber connection, such as a knee joint in a portal frame structure, it is highly likely that some bending forces would be acting on the glued-in rod rather than axial-only as in the pull-pull set-up. In order to include these bending effects a hinge system, based on the concrete beam test proposed by RILEM 1982 [20] will be used. This type of pull-out test is known as a pull-bending test.

The pull-bending set-up allows the effects of bending forces to be taken in to consideration along with axial forces in what is essentially a pull-pull type test. The system allows bending strength of the bonded-in rod connection to be evaluated by removing the timber in the section being loaded so that the only resistance is from the BFRP bars bonded-in to the timber.

This type of pull-out test has been used successfully in investigating the bond behaviour between glulam elements and GFRP [21], [22]. It is this system that will be used in this research to establish pull-out capacity.

2.3 Embedded Length, l_b

Embedded length is thought to be the most influential variable contributing to pull-out capacity after diameter of the rods used [23], [12]. Following a series of pull-out testing of BFRP rods bonded in to glulam elements with an epoxy resin, it was found that the ultimate pull-out capacity would be reached at a rod embedment length of 15*d* i.e. 15 times the rod diameter [24]. However, the pull-out testing set-up used to determine this only considered the effects of axial stress using a push-pull testing system which may have given an artificially high pull out capacity as bending effects were neglected.

2.4 Edge Distance, a

A minimum edge distance, i.e. the cross-sectional distance between the centre of the bar and the edge of the timber, must be prescribed in order to prevent the timber from splitting prematurely. As well as this it has been stated that small edge distances can result in a lesser bond strength and a decrease in average pull-out capacity [25]. Most of the latest design approaches use an edge distance of *2.5d* [26]; [27]. However, there has not been a significant amount of research in this area to date.

2.5 Glueline Thickness, t

In an experimental study on load capacity of bonded-in rods it was found that a larger glue-line thicknesses resulted in an increase in ultimate load [28]. Pull-out capacity of the joint was also found to increase with increasing glue-line thickness beyond a minimum thickness of 2mm [12]. This is a result of a larger shear area with the increased thickness of glueline and hence an increase in capacity. However this advantage must be weighed against the disadvantage of an increase in cost when more glue is required as well as the possibility of an increase in void formation and micro-cavities with increased glueline thickness.

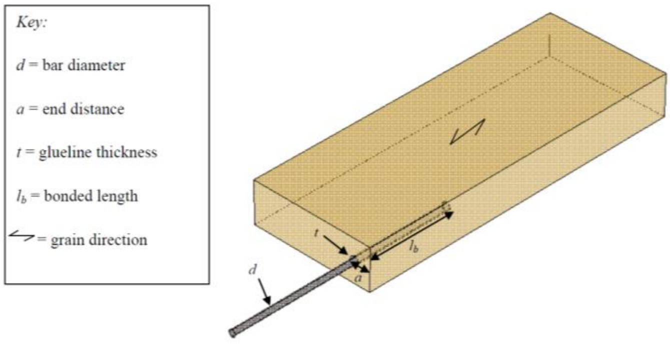

Figure 1: Specimen Geometric Variables

Table 1: Specimen Variables

Embedded length, l_b (mm)	Rod Diameter, *d* (mm)	Edge Distance, *a* (mm)	Glueline Thickness, *t* (mm)	Direction to grain	Moisture Content	No. Repetitions
80	12	30	2	Parallel	9-11%	9
130	12	30	2	Parallel	9-11%	9
180	12	30	2	Parallel	9-11%	9
230	12	30	2	Parallel	9-11%	9
280	12	30	2	Parallel	9-11%	9
330	12	30	2	Parallel	9-11%	9
380	12	30	2	Parallel	9-11%	9
600	12	30	2	Parallel	9-11%	9

3 TESTING

3.1 Timber

Class C16 Irish Sitka Spruce (Picea sitchensis), sourced from Balcas Sawmill, Co. Fermanagh, with a size of 75mm x 225mm sawn section was used. The C16 classification shows that the timber has a 5th percentile bending strength of 16N/mm^2 and a density of 370kg/m^3. Material testing will establish these strengths.

3.2 Rod

12mm diameter Basalt Fibre Reinforced Polymer (BFRP) rods were used in this experimental programme. These rods were found to have a tensile strength of 920 N/mm^2 under a low loading rate of 0.2kN/s [29]. Unlike steel or some other FRPs, no extensive cleaning of the rods was required prior to bonding as they are sand-coated which provides a good surface for adhesion.

3.3 Adhesive

A two-part thixotropic gap filling epoxy was used. This adhesive only flows under shear so is ideal for applications such as overhead beam repair, jointing overhead and such.

3.4 Sample fabrication

Samples were prepared as per the specification given in Table 1.

Moisture content of each sample was recorded during sample preparation and before testing using a handheld moisture meter. Moisture content was found to range from 9% to 11%, which corresponds to Service Class 1 (EC5, Part 1-1).

An auger drill bit was used to drill holes of 16mm diameter, thus producing a glueline thickness of 2mm all around the 12mm diameter rods. Guide blocks were used to ensure the holes were drilled accurately. Drilled lengths varied from a minimum of 80mm in steps to a maximum of 600mm, as shown in Table 1. The holes were drilled 30mm in from the specimen edge; this corresponds to an edge distance, *a =2.5d* where *d* is rod diameter.

The surface of the specimen around the drilled hole was sealed with candlewax to ensure that any glue overspill would not penetrate the sample and result in a false increase in strength around the hole.

The holes were 2/3rds filled with glue using a hose cut to the length of the drilled hole on the end of the nozzle of the glue cartridge to ensure that the glue filled all voids from the very bottom of the hole to the top.

Rods were twisted into place to allow any trapped air to be expelled and for the glue to fully coat the surface of the rods.

A device was used to hold the sample in place and ensure the 2mm bondline was maintained whilst drying. When the glue had hardened the steel hinges and strain gauges were fitted. The samples were then left until the glue had a minimum of 7 days to cure fully before testing.

3.5 Testing Set-up

The pull-bending test set-up was used as it more closely imitates the forces which a bonded-in rod connection would be under in a real application. This test requires a hinge system to be developed that can transfer load through the sample such that the bonded-in rod is under bending forces as well as axial forces. Figure 2 below shows this pull-bending test set-up.

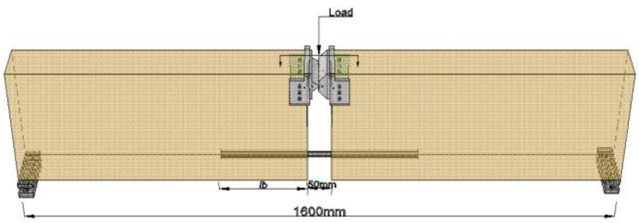

Figure 2: Pull-Bending Test Set-up

A strain gauge was placed on the BFRP rod at mid-span on each sample to monitor the stress-strain in the rod as the sample is loaded.

Samples were loaded in 0.5kN increments to failure using the accurately calibrated 600kN capacity hydraulic actuator.

Deflection at mid-span and net horizontal movement of the bar as the sample was loaded was recorded with data acquisition connected to the transducer, as shown in Figure 3.

Failure load was recorded when the sample could not take any additional load. The mode of failure was recorded also –

percentage failure mode was then calculated for each bonded length.

As per Table 1, each test was repeated multiple times due to the high variability of the timber used.

Figure 3: Transducer Set-up Used to Monitor Movement

4 RESULTS

4.1 General

Table 2 below details the failure modes observed within each sample set. The observed failure modes are illustrated in Figure 4. All specimens failed in a sudden, brittle manner.

Table 2: Failure Modes Experienced

	Percentage of Failure Mode Observed					
Embedded Length, l_b	Shear failure in Timber	Timber Splitting	Rod/Adhesive failure	Shear failure within adhesive	Tensile failure of Rod	Coating of bar failure
80	83	0	17	0	0	0
130	78	22	0	0	0	0
180	67	11	22	0	0	0
230	56	11	33	0	0	0
280	56	11	33	0	0	0
330	67	22	11	0	0	0
380	78	11	0	0	0	11
600*	22	22	0	0	0	0

*crushing of timber experienced in 67% of 600mm long samples

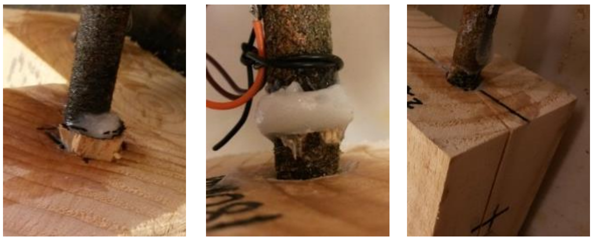

Figure 4: Failure modes observed: a) Shear in timber; b) Rod/Adhesive Failure; c) Timber Splitting

The most prevalent failure mode was a failure in shear of the timber with a total of 64% of all samples failing in this manner. This was as expected due to the timber being the weakest element in the bond. When splitting of the timber occurred the length of the split was often equal to the embedded length of rod. Tensile failure of the rod never occurred as the load required for the rupture of the rod was never reached.

4.2 Influence of increasing embedded length on pull-out capacity

A clear increase in pull-out strength was observed with an increase in embedded length. Figure 5 shows this relationship.

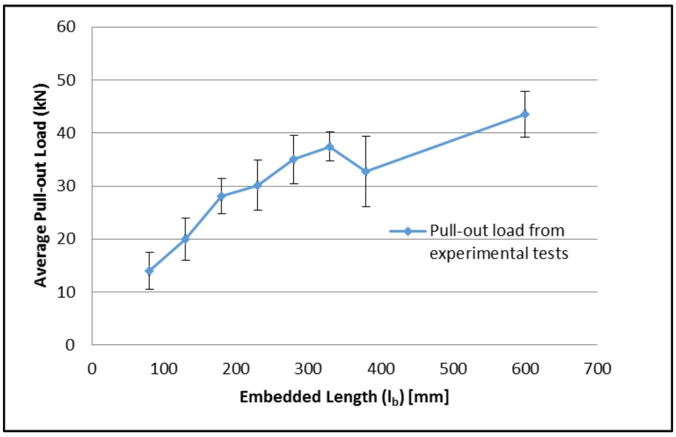

Figure 5: Average Failure Load vs Embedded Length

An increase in pull-out capacity of 168% was observed between the shortest embedded length of 80mm and the longest length of 330mm. The overall relationship between embedded length and pull-out capacity was almost linear.

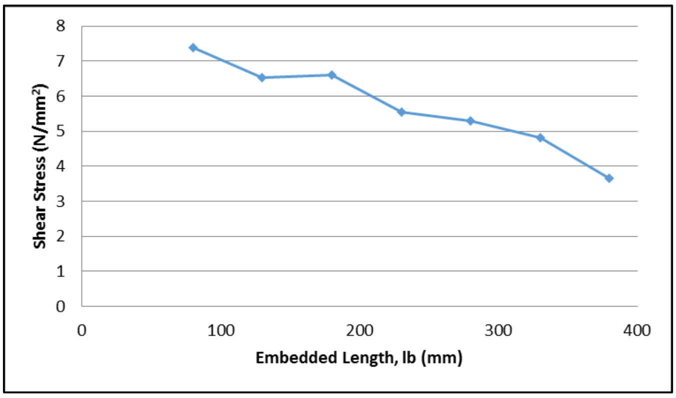

Figure 6: Peak Shear Stress at Timber/Adhesive Interface

Failure mode noticeably shifted from mainly failing in timber shear in the shortest embedded length to other failure modes in the longest embedded length. This is supported by the way in which shear stress at the timber/adhesive bond decreases with increasing embedded length, as detailed in Figure 6. Shear stress at the timber/adhesive bond decreased steadily with increasing embedded length with the exception of Sample B-Sample C where a slight increase was observed.

The applied load at which the samples failed at is presented in the figures below however the geometry of the test rig can be used to evaluate the equivalent axial stress and thus the data obtained can be compared with established design models for axial-only loading.

5 CONCLUSIONS

A clear increase in pull-out capacity with increased embedded length of the bonded-in BFRP rods was seen, which is reaching a plateau as failure is occurring in the timber as opposed to in the bond.

Material testing will be carried out to determine the properties of the timber, adhesive and rod. This will allow comparisons to be made between the achieved results and predictions from models developed by other researchers. Thus, the significance of the induced bending forces can be determined.

It is planned that additional longer embedded lengths will be investigated to determine at what point the additional length becomes inactive. It is suggested also that an investigation is undertaken where edge distance is increased to determine if failure due to splitting of timber can be avoided.

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