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MECHANICAL PERFORMANCE AT ELEVATED TEMPERATURES OF NON-METALLIC DOWELS FOR MASS TIMBER STRUCTURES

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ABSTRACT: Connections between timber structural elements are normally accomplished using metallic bolts, pins, and rods whose high thermal conductivity typically generates undesirable in-depth heating and charring of timber in fire. Despite existing studies on the fire performance of non-metallic shear connections, knowledge of the isolated mechanical performance of non-metallic dowels at elevated temperatures is scarce. To address this knowledge gap, a bespoke experimental rig was developed to evaluate the performance of circular glass fibre reinforced polymer (GFRP) and oak dowels at elevated temperatures. A comparison between GFRP (E-glass with vinyl ester) and oak dowel strength and deformation with temperature is presented, with GFRP displaying superior performance given its higher strength at all temperatures considered. However, oak maintained its strength better than the E-glass vinyl ester dowels when normalised against ambient temperature capacity.

KEYWORDS: timber connections, elevated temperatures, non-metallic dowels, glass fibre reinforced polymer, oak.

1 INTRODUCTION

A major challenge in building taller and more complex mass timber buildings is the high-level consequences that may manifest in case of fire. In modern mass timber buildings, structural connections are commonly made using metallic plates and fasteners. However, this increases risks in fire due to the high thermal conductivity of metals, and in particular, steel.

If left unprotected in a building fire, steel connections will readily conduct heat into timber elements and may char the surrounding in-depth timber, possibly resulting in structural failure. Non-metallic connections may present possible solutions, due to the drastically lower thermal conductivity of some such fasteners. Despite limited existing research on the structural performance of non-metallic dowelled connections in timber, there is a paucity of literature on the performance of such connections at elevated temperatures. Additionally, there is a lack of data on the isolated mechanical performance of non-metallic shear fasteners at elevated temperatures. The project presented in this paper therefore investigated the mechanical performance (in shear) of non-metallic dowels, namely GFRP and oak, at elevated temperatures.

2 PREVIOUS RESEARCH

2.1 GFRP DOWELS

There is an existing body of literature on performance of non-metallic timber connections, which was pioneered by Drake and other colleagues [1]. Their aim was to show that non-metallic (GFRP) based timber connections can provide suitable alternatives to steel-based connections. Initial experimental programs conducted double-shear tests using GFRP and steel dowels embedded in a laminated veneer lumber (LVL) member [2]. Despite the GFRP dowel yielding at a lower load than its steel counterpart, it "absorbed at least two or three times more energy" [2]. This can typically be considered beneficial in the context of designing mechanical connections, as structural engineers tend to prefer connections that fail in a ductile manner. In addition, the high strength-to-weight ratio, compatible stiffness between GFRP and timber, and a relatively high resistance to corrosion make GFRP-based connections a compelling replacement to steel-based connections in timber structures [2].

GFRP also has a much lower thermal conductivity than steel, which is a key factor influencing the heat transfer and mechanical performance of a dowelled connection in a fire scenario.

Despite experiments and existing literature suggesting that GFRP can be a suitable alternative to steel mechanical fasteners, no design guidance for their application currently exists. Pedersen [3] proposed changes to timber connection design rules when using GFRP connectors, however Thomson et al. [4] argued that there is a discrepancy between Pedersen's proposed yield equations and the available experimental data.

Additionally, the behaviour of GFRP at elevated temperatures has been previously studied in the context of replacing steel bars in reinforced concrete. Despite having a low thermal conductivity compared to steel, most

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polymers burn readily [5] and lose their mechanical properties (i.e., strength, stiffness, and bond) at much lower temperatures than steel, with some GFRP materials softening at temperatures below 100 °C [6].

As the polymer matrix resin in a GFRP softens with an increase in temperature, loss of bond with surrounding materials is typically observed; this has potential consequences where bond integrity is important, as in applications of reinforcing concrete with GFRP bars [7].

Kumahara et al. [8] and Hajiloo et al. [7] tested vinyl ester GFRP rods in tension at elevated temperature. Kumahara et al [8] tested GFRP rods in tension at 240 °C and 400 °C and reported losses of 40% and 60% of tensile strength, respectively. Hajiloo et al. [7] also observed a loss of 25% tensile strength at a temperature of about 150°C. In both cases, the loss in tensile strength was observed at temperatures near the glass transition temperature of the polymer matrix, which for vinyl esters is typically between 55 °C-145 °C [9]. Glass transition temperature may be highly variable within any class of polymers and corresponds to the temperature at which the polymer matrix enters a soft rubbery state and the stiffness and strength rapidly decrease [10].

Brandon [11] tested GFRP bars in torsion to measure shear properties at different temperatures; he observed a decrease in shear strength and modulus of specific GFRP bars with temperature. However, in full-scale testing of dowelled connections under a transient thermal regime, the time to failure of dowelled double shear timber connections was shorter for metallic connections as compared with non-metallic connections [11].

Another important factor to consider for GFRP dowel behaviour at elevated temperatures is creep, which can be expected to accelerate at elevated temperatures.

2.2 TIMBER DOWELS

Given its comparatively poor shear strength relative to either steel or GFRP, softwood timber has not been widely considered as a potential alternative mechanical fastener. Additionally, like GFRP, timber also loses its mechanical properties at relatively low temperatures in comparison to steel; this is potentially important in the context of fire performance. Given its limited shear strength, timber dowelling has mainly been used in furniture applications – with much lower loads than structural applications – and in mortice and tenon joints – which rely on a large section of timber to transfer loads.

Despite existing guidance on timber's thermomechanical properties in the Structural Eurocodes, the existing literature on such matters is comparatively scarce and inconsistent [12-14]. BS EN 1995-1, the Eurocode for Timber Structures, suggests a 60% loss of transverse shear strength at 100 °C.

Despite comparatively poor thermomechanical performance, the experimental program included mechanical tests on oak dowels in addition to GFRP dowels. This is in the interest of advancing understanding of the mechanical behaviour of fully timber connections at elevated temperature.

3 MATERIAL CHARACTERISTATION

Thermogravimetric analysis (TGA), Dynamic mechanical analysis (DMA) and moisture content tests were performed to assess the fundamental properties of the dowels, including the glass transition temperature, T_g, of the GFRP. The results from those characterisation tests were used to decide the testing temperatures in the double-shear tests.

3.1 MATERIAL PROPERTIES

The GFRP rods were manufactured by pultrusion from unidirectional E-glass fibres in a vinyl-ester polymer matrix. The diameter of the rods was 12 mm, so as to be representative of dowel sizes likely to be used in practice. The GFRP rods had a nominal tensile strength of 1000 MPa and a nominal fibre content of 80% by mass.

The timber dowels were made of hardwood oak, chosen for its increased strength, stiffness, and durability compared to typical softwoods [2]. Oak dowel rods were sourced from a local commercial supplier with a nominal diameter of 12 mm; no technical information could be obtained from the supplier on their mechanical properties.

3.2 THERMOGRAVIMETRIC ANALYSIS

Thermogravimetric analysis (TGA) was performed on the GFRP dowels to validate the fibre mass fraction provided by the manufacturer, and to determine the decomposition temperature, T_d, of the polymer matrix. The TGA tests were performed using a Mettler-Toledo TGA/DSC1. Two samples were tested in an oxidative (air) atmosphere, and two in an inert (nitrogen) atmosphere to assess the potential role of oxidation in accelerating decomposition. A temperature range between 25 °C and 800 °C, with a heating rate of 10 °C/min, was used for all samples in accordance with BS EN ISO 11358-1 [15].

The average fibre mass content, determined from a mass loss curve, from the 4 tests, was 79.4% which is in accordance with the value provided by the manufacturer (80%). The mass derivative (MLR) curves for all four samples are presented in Figure 1. These data suggest that no significant decomposition of the GFRP bars occurs below about 225 °C, as should be expected for a glass/vinyl ester polymer composite product. In addition, the mass derivative curves indicate decomposition temperatures of 371 °C and 386 °C in oxidative and inert atmospheres, respectively.

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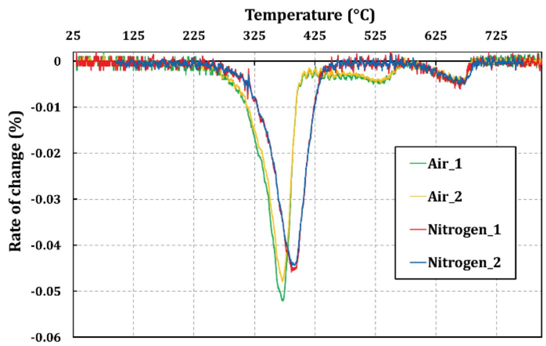

Figure 1: *Differential Thermogravimetry (DTG) results from TGA tests on GFRP dowels.*

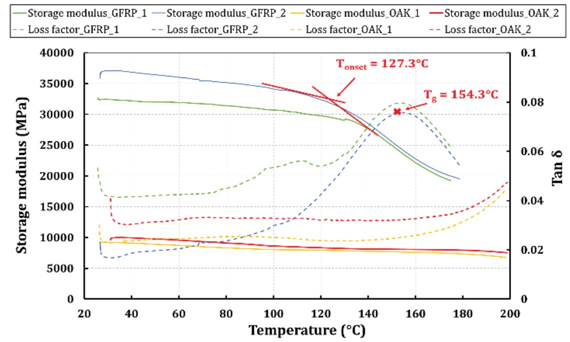

Figure 2: *Storage modulus and loss factor of GFRP and oak dowel materials.*

3.3 DYNAMIC MECHANICAL ANALYSIS

Dynamic mechanical analysis (DMA) was used to define the glass transition temperature T_g of the polymer matrix and to characterise the elastic and viscous behaviour of the GFRP bars. Even though DMA is generally used to characterise polymers, analysis of oak from the timber dowels used in this study can also indicate changes in the behaviour of this material as temperature increases. The DMA tests were performed using a DMA850 testing device manufactured by TA Instruments. Samples of dimensions 50 mm x 12 mm x 2 mm were tested in three point bending mode and were subject to sinusoidal loading at 1 Hz. They were heated from 25 °C to 180 °C or 200 °C, for the GFRP and oak, respectively; at a heating rate of 3 °C/min.

The results from the DMA were analysed according to BS ISO 6721-11 [16] (see Figure 2). The glass transition temperature of the GFRP was obtained from the peak in the loss factor. From two tests, the T_g of the GFRP was determined to be 154 °C. In addition, the onset temperature, T_{onset}, was graphically determined from tangents to the storage modulus curve as can be seen in Figure 2. The mean onset temperature of the three tests was 130 °C. These TGA data suggest that considerable reductions in polymer matrix dominated mechanical properties (including shear strength and stiffness) can be expected in the temperature range of 130-154 °C.

The DMA results for the oak were not taken to a high enough temperature to determine a classical T_g value, but suggest that oak is less sensitive to elevated temperatures than GFRP (in terms of reductions in elastic modulus under cyclic flexural loading). This is shown in Figure 2, where the modulus values for oak decrease only mildly at temperatures below 180 °C. These TGA data suggest only minor reductions in flexural stiffness of oak at temperatures as high as 200 °C.

3.4 OAK MOISTURE CONTENT

Two 60 mm long oak samples were each enclosed in a metal container and dried in an oven at 60 °C for 48 hours. Their mass was measured every 24 hours using a high precision balance, until the change in weight measured was less than 5%. From the two samples, the moisture content of the oak was determined as about 9.0%.

4 MATERIALS AND METHOD

4.1 RIG DESIGN AND FABRICATION

The aim of the rig in this experiment was to load the dowel in shear, up until failure, whilst simulating the embedment of the dowel in timber (Figure 3). The rig was made from steel, due to its superior thermo-mechanical properties in comparison to timber and GFRP and loaded the dowels in double shear. The steel rig provides an embedding constraint and forces the dowel to fail at each of two interfaces [2].

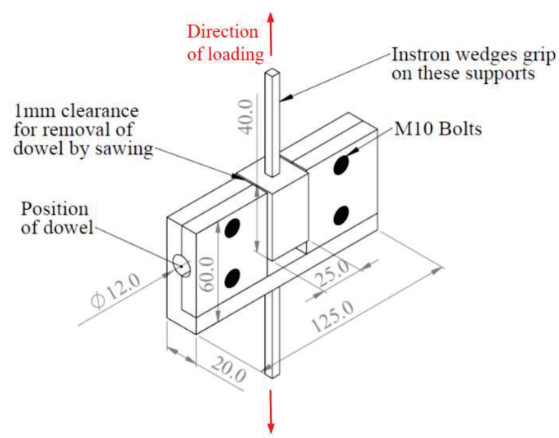

Figure 3: *Isometric view of the double shear steel rig. All dimensions are in millimetres.*

The rig was loaded in tension to help with alignment of the steel elements and dowels during loading. The hole in which the dowels placed was made 12 mm in diameter (later enlarged to fit the timber dowels), for a tight fit around the GFRP dowels.

4.2 TESTING PROCEDURE

The shear tests were performed using an Instron 600LX loading frame with a capacity of 600 kN (Figure 4 a.). The loading frame measures the crosshead displacement of the rig as opposed to the absolute displacement of the dowel. However, given a minimal stress is applied to the steel elements compared to the yield strength of the steel, the deformation of the steel rig and testing frame are assumed to be negligible (aside from seating effects). All results in this paper are presented in terms of displacement measured by crosshead stroke of the testing machine.

GFRP and oak rods were cut into 130 mm long dowels to fit within the rig with their ends protruding to allow observations during testing. All dowels tested at elevated temperature had a 3 mm diameter hole drilled 50 mm into them centroidally along their length so as to fit a T-type thermocouple to measure the dowel internal temperature. For ambient and steady-state tests, a vertical crosshead displacement rate of 2 mm/min was used based on similar experimental programs available within the literature [7,17].

For transient temperature tests, a heating rate of 5 °C/min was used; this facilitated comparatively homogeneous heating of the samples without leading to very long exposure times which may overestimate strength degradation [17]. Two temperatures were recorded (Figure 4 b.) during each test: first, a thermocouple was placed inside the oven to measure air temperature, while a second thermocouple measured the temperature inside the dowel adjacent to the shear failure plane. The second measurement was used to assess critical temperatures for the dowels themselves.

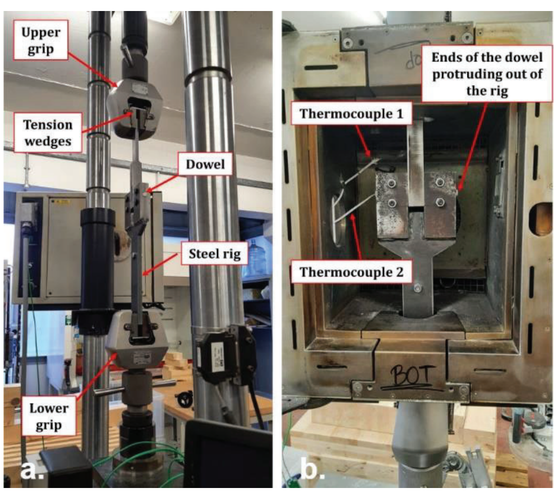

Figure 4: *Experimental set-up: a. rig in Instron frame without oven, b. close-up of the oven.*

4.2.1 Steady state tests

Steady state tests heated the sample to a target temperature before loading it to failure at constant temperature. Four steady state temperatures were selected for each material. For the GFRP, the aim was to study the behaviour of the dowel around the glass transition temperature, since there is a significant drop in mechanical properties around that temperature. A range of temperatures was chosen to observe how this physical change in the material could be correlated to a change in its shear properties at elevated temperatures. A temperature of 120 °C was selected to assess the behaviour just prior to the onset temperature, and a temperature of 140 °C was selected to assess the behaviour just prior to the glass transition temperature. Temperatures of 100 °C and 200 °C were selected since they were respectively well below and well above the glass transition temperature.

For the oak, the aim was to explore the behaviour of the dowel as it loses its moisture content, near to 100 °C. Thus, temperatures of 90 °C and 110 °C were selected. An additional two temperatures, at 140 °C and 200 °C were (semi-arbitrarily) selected to allow comparison between the oak and the GFRP.

4.2.2 Transient state tests

The transient tests loaded the specimens to a target sustained level, and then heated them up while the load remained constant. The critical temperature at failure, under sustained load, was recorded by a thermocouple inside the dowel (as already discussed).

The transient loads were taken (again, semi-arbitrarily) as 20% and 50% of the dowel capacity at ambient temperature. The lower load value was selected from literature as the suggested value to avoid creep-rupture failure in GFRP [18]. The higher loading value was set to allow for meaningful comparisons of the effects of applied stress at credible upper limit in-service levels. From the results presented in the next section, these loads translated to 9.6 kN and 23.9 kN for the GFRP, and 2.2 kN and 5.6 kN for the oak dowels, respectively.

Table 1: *Summary of testing programme.*

		Number of tests	
		Oak	**GFRP**
Ancillary tests	**TGA (air/nitrogen)**	-	2/2
	DMA	3	4
	Moisture Content	2	-
Ambient tests	**25°C**	2	2
Steady state tests	**90°C**	2	-
	100°C	-	2
	110°C	2	-
	120°C	-	2
	140°C	2	2
	200°C	2	2
Transient state tests	**20%**	2	2
	50%	2	2

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5 RESULTS

5.1 AMBIENT TESTS

Tests were performed at ambient temperature (i.e. approximately 20 °C) to establish a comparison baseline for the mechanical properties and behaviour of the dowels within the loading rig used in this study. Tensile load versus crosshead displacement curves are presented in Figures 5 and 6. The **GFRP dowels** (see Figure 5) exhibited a comparatively higher initial stiffness. A first drop load was observed at a crosshead displacement of around 5 mm, followed by a second shorter drop at around 9.5 mm. These drops, as suggested in previous experiments [19], can be attributed to sequential failures of shear planes within the GFRP material. The mean maximum load reached for the GFRP samples was 48.9 kN. To find the average shear strength of the dowel (within this loading rig), the maximum load was divided by two and then by the cross-sectional area of the dowel; this gave a mean shear strength of 219.6 MPa. Despite loading the dowels in shear, in the next section it is explained that that the calculated strength does not actually correspond to pure shear.

The **oak dowels** (see Figure 6) were much less stiff and much weaker and exhibited a more ductile failure. In both tests, the dowels failed at around 8 mm of crosshead stroke, as indicated by the sharp decrease in load. Compared to GFRP dowels, the oak dowels were much weaker. The mean peak load of oak dowels was 11.15 kN which represents only 23% of the peak shear load carried by the GFRP dowels of similar diameters.

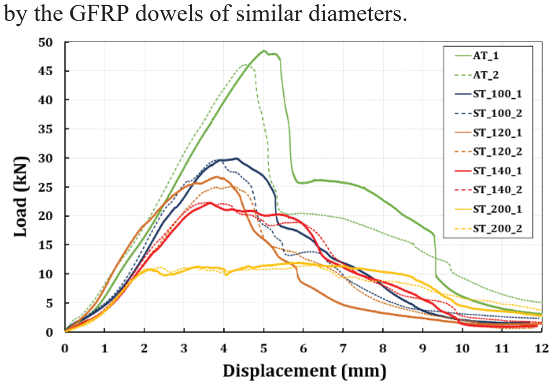

Figure 5*: GFRP load-displacement curves for steady state tests.*

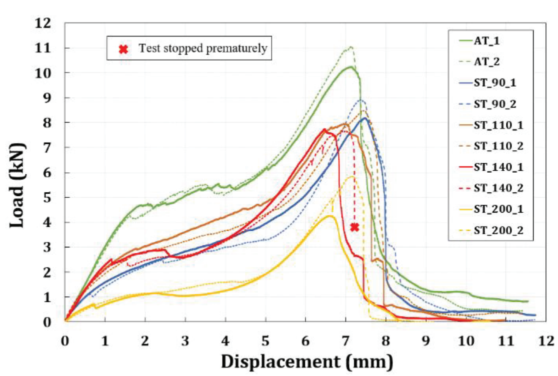

Figure 6: *Oak load-displacement curves for steady state tests.*

5.2 STEADY STATE TESTS

Figure 5 shows the load versus crosshead displacement curves for GFRP dowels at different steady state temperatures. The reproducibility of the tests was generally reasonable, hence only 2 tests were performed under each condition. Up until 120 °C, and hence before entering the glass transition, the GFRP dowels showed an essentially elastic behaviour until failure, similar to their behaviour at ambient temperature. Furthermore, it can be seen from the slope of the load displacement curves, that the initial stiffness of the dowels remained relatively constant. At 140 °C and 200 °C, the dowels' stiffness drops and the ductility of the response increases. The GFRP dowels change from a comparatively high strength, high stiffness material at ambient temperatures to a lower strength, more ductile material at elevated temperatures.

The general trends for the load versus crosshead displacement curves for oak dowels did not significantly change with increasing temperature (Figure 6). Increases in temperature result in decreases of initial stiffness of the dowels. Failure displacements of the samples however remained unchanged, at around 8 mm at all temperatures.

The loss of strength for both GFRP and oak dowels is presented in Figure 7. Despite the smaller percentage loss of strength of oak dowels at elevated temperatures, comparison of absolute strengths shows that the oak dowels remained considerably weaker than the GFRP dowels for all steady state temperature conditions.

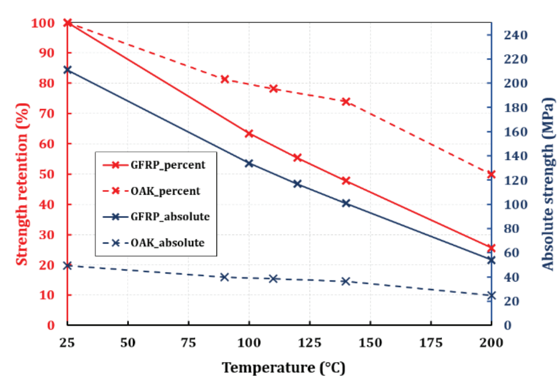

Figure 7*: Absolute and relative strength of GFRP and oak dowels.*

5.3 TRANSIENT STATE TESTS

For each loading case, Figure 8 shows that the failure temperature was similar between the oak and GFRP dowels. Thus, dowels loaded at 20% of ambient peak strength failed on average at 224 °C. Dowels loaded at 50% failed on average at 105 °C. Despite this similarity, the temperature at failure of oak dowels was on average 14 °C higher than for GFRP dowels. This seems to corroborate findings from the steady state tests, which showed that oak dowels were better at retaining their strength at elevated temperature.

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In the 20% loading case, the displacement rate of GFRP dowels increases from 0.13 mm/10°C, until 170 °C, to 1.28 mm/10°C in the rubbery phase of the material, after its glass transition. The oak dowels exhibit a relatively constant increase in displacement until failure, however, they both experience a jump in displacement at 100 °C, which is presumed to reflect the loss of moisture at these temperatures.

In the 50% loading case, the displacement rate of the GFRP dowels is maintained relatively constant until a sudden failure around 100 °C. The oak dowels exhibit a more progressive behaviour to failure. Indeed, between 30 °C and the failure temperature, the oak dowels show a crosshead displacement of 4.4 mm; this is versus a 2 mm displacement for the GFRP dowels.

In addition, between 30 °C and 80 °C, all dowels have similar displacement versus temperature traces, except the oak dowels in the 50% loading case which showed significantly higher deflections at temperatures well below 100 °C.

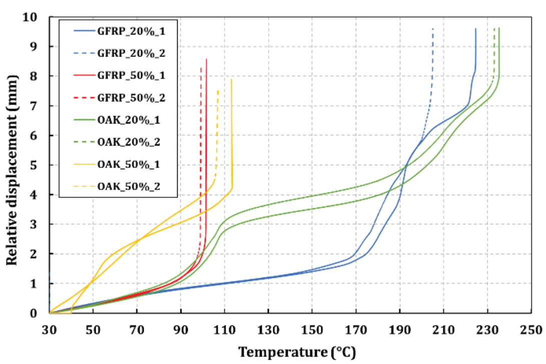

Figure 8: *Transient state analysis for oak and GFRP dowels.*

5.4 SAMPLE OBSERVATION

The GFRP and oak dowels tested in steady state conditions at 140 °C, are presented in Figure 9. The GFRP dowels exhibited signs of delamination at their edges, which is attributed to interlaminar shear failure. On the failure planes, on each side element, it can be seen that the fibres on the top half of the dowel were severed in the transverse axis, whilst the fibres in the bottom half were bent upwards. This behaviour suggests that, during loading, the dowels experienced both transverse shear and bending. Since GFRP is weaker in shear than in tension, it can be assumed that the top fibres in the dowel failed in shear, whilst the bottom fibres, loaded in tension, continued to carry some of the load until fibre failure. This test setup therefore fails to capture "pure" shear, and the true loading condition of the dowels is much more complex as the crosshead displacements grow.

The oak dowels also exhibited signs of a shear/bending behaviour: curvature of the central element, cracks in the bottom part of the side element, cracking of the top fibres and compression of the bottom fibres in the central element. In addition, oak dowels showed strong discolouring at 200 °C, possibly indicating the onset of pyrolysis reactions (Figure 9), as should be expected at these temperatures.

Figure 9: *Failed samples, from top to bottom: GFRP in steady state at 140 °C, oak in steady state at 140 °C, oak in steady state at 200 °C.*

6 DISCUSSION

6.1 INCREASE IN DUCTILITY AT ELEVATED TEMPERATURES

The steady state and transient results show a ductile failure mode at elevated temperatures for both the GFRP and oak dowels. For the GFRP dowels, this represents a net change of behaviour from ambient conditions, characterised by a high stiffness. Indeed, at 200 °C, the dowels maintained their peak load capacity until a crosshead displacement of 9 mm, which represents 3/4 of their nominal diameter. Ambient shear tests from the literature [20], report a maximum test load carried between a fibre displacement of 1/4 and 1/3 of the rebar diameter for GFRP dowels. This difference in deformations is evidence of the increased ductility (and reduced stiffness) of the GFRP at elevated temperatures.

Furthermore, due to the polymeric nature of the GFRP's matrix, the mechanical behaviour of the dowel is greatly influenced by its glass transition. However, the comparison of DMA and steady state results, suggests that the onset temperature is a better indicator of behaviour change than the glass transition temperature determined via peak loss factor. Figure 5 shows that, at 140 °C, the GFRP dowels had already transitioned to a more ductile failure mode at temperatures 14 °C below the glass transition temperature.

The oak dowels exhibited no significant change in their behavioural trends between 25 °C and 200 °C. However, the peak shear strength is notably reduced at 200 °C. In addition, at 200 °C, the oak dowels experienced a sharp increase in loss factor (see Figure 2). Further research is required to fully understand and explain the changes in properties of oak dowels at 200 °C.

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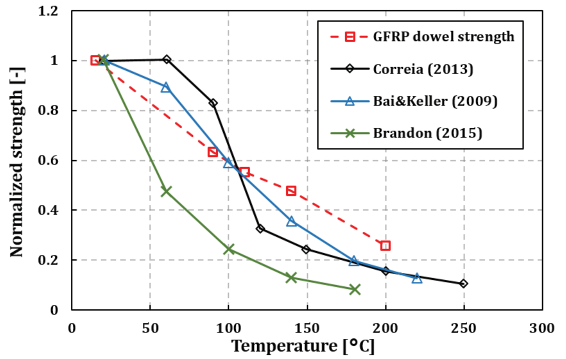

Figure 10: *GFRP dowel strength against literature values of interlaminar shear strength with temperature [17,21,11].*

6.2 SIGNIFICANCE OF BENDING IN DOWEL FAILURE

The study of the failed dowels, for both GFRP and oak, highlighted the significance of bending in their failure. In particular, curving of the fibres in the central oak element, and delamination of the top layers of the GFRP dowel are signs of a combined shear and bending mechanism. As such, results from this study are not in complete agreement with findings from the literature which test dowels in pure shear or pure bending.

From Figure 10, at higher temperatures, the GFRP dowels used in the current study appear to retain more of their strength at higher temperatures than values of interlaminar shear strength obtained for GFRP in studies found in the literature. It is considered likely that, upon loading at elevated temperatures, the dowels – both GFRP *and* oak – first failed essentially in shear, with fibres in the bottom part of the dowel on the tension side continuing to carry the load at larger crosshead displacements up until failure (i.e., a combined shear and flexural mechanism). The choice of testing rig is hence a determining parameter as it influences the amplitude of bending experienced by the fastener. Further, embedding tests of the dowel in a timber element are necessary to assess the degree of bending which non-metallic dowels are able to achieve. Indeed, the current study has not addressed whatsoever the interactions between dowels and timber elements that would undoubtedly be relevant in the elevated temperature performance of a dowelled timber connection (involving the use of any type of dowel, whether oak, GFRP, or indeed steel). Additional research is required to study such issues before GFRP dowels can be confidently applied in connections in timber structures requiring fire resistance.

6.3 COMPARISON OF METALLIC AND NON-METALLIC DOWELS

Figures 7 shows that both types of dowels experienced a loss of strength at elevated temperatures. At 200 °C, the GFRP and oak dowels retain 25% and 50% of their ambient strength, respectively. In comparison, steel shows no reduction of its effective yield strength until about 400 °C, according to EN 1991-1-5 [22]. However, the increased ductility of non-metallic fasteners, which leads to the more progressive failure of the dowel, may present significant advantages in timber connections.
In addition, at elevated temperature steel fasteners, which have a comparatively high thermal conductivity as compared with either oak or GFRP, will conduct heat into a connection and may lead to a loss in strength due to accelerated in depth heating and/or charring of the surrounding timber.

In a ductile failure, the fastener externalises strain energy by means of cracking or displacement, and transfers the energy to the surrounding timber. Since the stiffness of the non-metallic dowel is more compatible with timber than steel [2], the surrounding timber can absorb the energy released by the fastener and experience ductile deformations. Since the stiffness mismatch is reduced between the fastener and the timber, the likelihood of a brittle failure of the connection is thus reduced. It can thus be suggested that, with non-metallic dowels, the failure of the connection at elevated temperatures is a combined failure of the fastener and embedding timber instead of an inefficient and ultimately disadvantageous use of the strength of the metallic fastener.

6.4 DESIGN CONSIDERATIONS

Current timber fire protection strategies typically rely on encapsulation [23]; this aims to protect a connection by ensuring that heat does not reach the fasteners too quickly. However, this strategy leads to an increase in material and weight of the connection, as well as being aesthetically undesirable in many cases. Non-metallic connections, due to the low thermal conductivity of the fasteners, are less susceptible to elevated temperatures. By quantifying the performance of non-metallic dowels at elevated temperatures, design of connections using non-metallic dowels can become a more realistic option.

For GFRP dowels, if adequate protection is provided to the connection to minimise heat exposure of the fastener and ensure that the temperature in the dowel remains below the glass transition temperature of the material, conventional elastic design can perhaps be used, taking the strength of the dowel obtained at 120 °C, or before the onset of glass transition. This strength value represents 55% of the strength of the dowel at ambient temperature.

6.5 FUTURE WORK

The aim of the research presented in this paper was to study the shear behaviour of oak and GFRP dowels. However, in this process, the influence of the embedding timber on the failure of the connection was removed. Further embedding tests, including a direct measurement of the strain of the fastener within embedding timber should be conducted to assess the behaviour of full dowelled connections.

The steady state study should be complemented with more temperatures, especially between 150 °C and 180 °C for the GFRP, to observe the behaviour of the dowel just after its glass transition. In addition, different loading and heating rates should be explored. Finally, extensive modelling research is required to translate the behavioural observations presented in this thesis, into adequate design rules to improve the fire performance of non-metallic dowelled connections in timber structures.

7 CONCLUSION

This paper has explored the behaviour of GFRP and oak dowels at elevated temperatures to initially assess their potential as a replacement for steel in timber connections. The dowels were tested in a steel rig which was designed to simulate the behaviour of a connection. Through a series of steady state and transient state elevated temperature tests, the following preliminary conclusions were obtained:

- The failure of both oak and GFRP dowels was by a combination of bending and shear failure at elevated temperatures. This led to the loss of interlaminar shear strength for GFRP dowels, and failure of fibres in tension for oak dowels.
- At 200 °C, GFRP dowels retained only 25% of their ambient temperature shear strength, whereas oak dowels retained 50%. Despite this less severe loss in strength, oak dowels were significantly weaker than GFRP for all tested temperatures.
- Even though GFRP and oak dowels are significantly weaker than steel dowels, their progressive failure at elevated temperatures – as well as their lower stiffness even at ambient temperatures – increases their compatibility with embedding timber; this may lead to a beneficial more ductile failure of non-metallic dowelled connections.

The non-metallic dowels tested in this study appear to represent feasible alternatives to metallic dowels for some timber connections, and in particular appear to provide compelling advantages for architecturally expressed connections in mass timber structures (subject to considerable additional research).

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