Toumpanaki, E., Ramage, M., Shah, D. U., Reynolds, T., Andrews, S., & Flipo, B. (2021). *INFLUENCE OF WELDING TIME ON MECHANICAL FRICTION WELDING OF BEECH*. Paper presented at World Conference on Timber Engineering (WCTE2021).

INFLUENCE OF WELDING TIME ON MECHANICAL FRICTION WELDING OF BEECH

Eleni Toumpanaki[1], Thomas Reynolds[2], Scott Andrews[3], Bertrand Flipo[3], Michael Ramage[4], Darshil Shah[4]

ABSTRACT: The optimum welding time for welded beech specimens is assessed with a compression shear test method and the softening of the wood polymers during friction welding is evaluated by dynamic mechanical analysis (DMA). A welding time of 2-3 sec yields the highest mechanical performance (13.6-14.7 MPa) that is equivalent to the shear strength of glued-laminated beech. A shear strength reduction of up to 56% is observed when specimens are loaded perpendicular to the grain, compared with parallel-to-grain loading. An increase in welding time to 5 and 7 secs resulted in a sudden drop in shear strength capacity and smooth failure interfaces within the weld-line. This is attributed to expelled cellulose fibres and thermal degradation of cellulose with increasing temperature at longer friction welding times. The softening of beech wood to form the weld-line is postulated to occur at temperatures greater than 65ºC due to intermolecular debonding and depolymerisation of low molecular weight lignin. Drops in storage modulus via DMA were also observed at 125 and 175ºC attributed to softening of lignin and hemicellulose.

KEYWORDS: wood welding, wood melting; connections and joints; friction welding

1 INTRODUCTION

Mechanical friction welding remains an unexploited wood connection technique that can provide environmental friendly engineered wood products, quick connectivity and a healthier built environment. Joining wood by friction welding has numerous advantages over conventional polymer adhesive bonding, including reducing processing times (vis. high curing times avoided during glue laminating procedures), elimination of adhesive-related VOCs, as well as re-opening avenues to recycling and end-of-life disposal (e.g. incineration with energy recovery) of the timber. It is also considered as a cost-effective solution compared with alternative gluing options [1].

The mechanical performance of the bond-line in friction wood welding depends on the wood species, the grain, fibre and growth ring orientation, and to a greater extent, the welding parameters (e.g. welding pressure, vibrational amplitude, frequency and time). Hardwoods exhibit higher mechanical joint performance than softwoods [2] and variations among hardwood species have been observed with oak being the least favourable so far tested [3]. End grain to end grain welded joints have yielded lower shear strength capacity than edge grain-to-edge grain joints in *Eucalyptus saligna* [4]. Face grain-to-face grain maple welded joints had 20% lower mechanical performance than the edge grain-to-edge grain alternative options in [5]. However, a negligible shear strength difference has been observed in beech specimens between end grain-to-end grain and face grain-to-face grain butt joints [6]. In the latter study the strength deviations due to the grain direction were more discernible in oak specimens. The fibre direction seems to play an important role in the tensile strength of welded end grain-to-end grain butt joints with the highest performance being recorded when the wood fibers are perpendicular to the weld interface (0°). However, Rhême et al. [7] claimed that the planing and fiber direction are not statistically significant for the strength determination of the welded joints based on tensile, shear and mixed mode test data in beech specimens.

To achieve welded joints that meet the minimum standard requirements for structural joints (e.g. equivalent of BS EN 386:2001 [8]) , an optimised design between welding pressure (WP), vibrational amplitude (WA), frequency (WF) and welding time (WT) is required. All these parameters are related to the thermal energy developed during frictional welding that is responsible for the morphological and chemical modifications of the weld-line and thus its mechanical performance [4].

[1] Eleni Toumpanaki, University of Bristol, Department of Civil Engineering, Queen's Building, University Walk, BS8 1TR, UK, e-mail: eleni.toumpanaki@bristol.ac.uk
[2] Thomas Reynolds, University of Edinburgh, School of Engineering, UK, T.Reynolds@ed.ac.uk
[3] Scott Andrews, TWI, UK, scott.andrews@twi.co.uk
Bertrand Flipo, TWI, UK, bertrand.flipo@twi.co.uk
[4] Darshil Shah, University of Cambridge, Department of Architecture, UK, dus20@cam.ac.uk
Michael Ramage, University of Cambridge, Department of Architecture, UK, mhr29@cam.ac.uk

Some researchers have applied different parameters at different stages of the wood welding manufacturing process- preheating, welding and cooling (holding) phase- and the cooling phase has been considered a significant part for the structural integrity of the joint. An increase in the holding time at the cooling stage can benefit significantly the mechanical performance of the welded joint [2, 4]. The weld-line is a mix of unevenly distributed fibres within a matrix of molten wood cellular components and therefore it exhibits transversely isotropic properties [7]. Considering that failure lies in the bond interface, the strength properties of the welded wood joint should be independent of the fiber orientation. A short welding time and amplitude is associated with a lower amount of expelled fibres from the welded interface edge and less char formation (black layer) at the weld-line [9]. The excess of fibres at the edges of the welded wood joint indicates less fibre reinforcement in the interfacial weld composite and the char layer is linked with increased porosity discounting the mechanical performance [9, 10].

During friction wood welding a non-uniform temperature profile is developed along the length of the specimen and peak temperatures up to 284°C [5] for maple at WT=4 sec and 380°C for beech at WT=3sec [11] have been recorded. This results in softening of wood (usually > 180 °C [12]) and thermal degradation of wood constituents (e.g. hemicellulose and lignin) can take place at much higher temperatures (> 180-250 °C [13]). To avoid severe thermal wood degradation, a maximum welding time of 2.5 sec and 8 sec has been recommended for beech and spruce respectively at a welding frequency of 100 Hz, welding pressure of 1.5 MPa and welding amplitude of 2.8-3.0 mm [11]. The differences among wood species are attributed to the faster heating rate recorded in beech. The mechanical strength of the weld-line has been primarily attributed to the higher densification of the cellular structure combined with a mix of molten lignin and hemicellulose and wood cell entanglement. Secondary effects of higher lignin crosslinking due to an increase in heat energy input during friction welding [2] and polymerization reactions of carbohydrates with themselves and the lignin [11] have also been proposed. The latter is the result of acetic acid formation from hemicellulose deacetylation at high temperatures leading to carbohydrates' depolymerisation. Lignin condensation is related to a stiff but brittle welded wood joint [11].

Existing data on welded wood joints focuses on the shear strength properties (tensile shear or compression shear according to the relevant test method), but their mechanical performance is inferior under pure tension. Rhême et al. [7] reported an average tensile strength of 2.3 MPa for welded beech specimens equivalent to 33% of the respective shear strength (7 MPa). The introduction of tension resulted in a sudden drop in the fracture energy and a mixed mode fracture envelop was determined with the Arcan test method. However, negligible differences between tensile and shear strength were observed in [6] for the same wood species. The observed deviations among studies are attributed to the different test methods and welding manufacturing regimes. A higher welding pressure and amplitude and a lower frequency were applied in [7].

The inherent moisture content of wood is expected not to play an important role in the performance of the welded joint due to moisture evaporation during the friction welding. However, Hahn et al. [14] contented that the moisture evaporation and the volatiles from the thermally decomposed wood result in an internal gas pressure that is more dominant in the centre of a welded joint. The gas pressure decreases the friction between the wood interfaces during friction welding and the moisture evaporation reduces the developed heat energy. Therefore, the mechanical performance of the joint is discounted. The combination of moisture and high temperature during friction welding may result in early depolymerization of cell wall and should also be considered. A parametric study on welded spruce joints [15] showed that dry specimens yield 44% higher shear strength and lower standard deviation compared with specimens with a moisture content, MC=12%. However, welding of dry wood samples can result in crack formation along the bondline due to the developed residual stresses from the swelling and shrinkage effects under humidity variations. Wood welding is considered suitable only for interior applications due to the inferior durability performance in high humidity environments. A 63% and 53% reduction in tensile strength and mode I fracture energy respectively were reported in [16] in welded beech joints due to a 10% increase in moisture content (MC=12% is the reference point). Several methods are being investigated to improve the durability of welded wood joints ranging from thermal modification of the wood [17] to extractives impregnation (e.g. rovin) [18] to meet the minimum standard requirements for structural joints..

Research so far in the field of wood welding has focused on optimising welding parameters to increase the mechanical joint performance. Yet, there is limited understanding in the correlation of the welding time and shear strength capacity with the physical transformation changes taking place at the bond-line. This study aims to shed light on this area and it is part of a wider investigation on the mechanical performance of weld laminated beech specimens at elevated temperatures. Delamination of lamellae of engineered wood products in fire accelerates the degradation of their strength and adds to the fuel load they present [19]. The high-temperature behaviour of the weld line is, therefore, an important parameter for consideration of the safety of these elements in fire.

2 EXPERIMENTAL PROCECURE

The aim of the experimental programme is to investigate the physical characteristics and shear strength capacity of weld laminated beech specimens having the welding time as the main variable. Adhesive bonded beech specimens, as found in literature, are used as a benchmark to compare the mechanical performance of linear friction welding.

2.1 MATERIALS

The specimens consist of two steamed beech laminates with density 682 ± 8 kg/m^3 and nominal dimensions of 100 x 100 x 33 mm. The laminates and the final welded specimens were conditioned at 23.9 ± 0.4 °C and *RH*= 55.0 ± 1.0 % before friction welding and testing respectively.
Beech blocks of 50 x 50 x 50 mm were used to mechanically characterise the material in shear and relate the bond-line properties to the beech shear strength.

2.2 MATERIAL MECHANICAL CHARACTERISATION

Beech specimens were tested according to BS 373:1957 [20] and the shear strength parallel and perpendicular to the growth rings was measured.

2.3 FRICTION MECHANICAL WELDING

The specimens were welded with an E20 Linear Friction Welding Machine (Kuka model) along the face grain at a frequency of 75 Hz, vibrational amplitude of 1 mm and under applied pressure of 6 MPa. Different welding times of 2, 3, 5 and 7 sec were adopted.

2.4 WELD-LINE SHEAR STRENGTH

The shear strength of the welded beech specimens was determined according to BS EN 392:1995 [21]. The nominal dimensions of the welded beech samples for the determination of the shear strength were 50 x 50 x 50 mm. The samples were prepared using an electrical mitre saw (Festool KS 120 EB). The true dimensions of the weld-line interface were measured with a caliper and used to calculate the interfacial shear area. In total 37 welded beech specimens were tested.

2.5 OPTICAL MICROSCOPY

The effective thickness, the ultrastructure of the weld-line and the failure surface were qualitatively observed for each welding time with a Kranich 1000x USB microscope.

2.6 DYNAMIC MECHANICAL ANALYSIS (DMA)

The softening behaviour and the physical transformation changes in beech with increasing temperature were determined with DMA testing (nominal dimensions of 45mm x 10mm x 5mm). A three-point bending mode was adopted. Thermal scans were carried out from 30 °C to 220 °C at a heating rate of 3 °C/min, displacement amplitude of 20 μm, and frequency of 1 Hz.

3 RESULTS

3.1 WELD-LINE SHEAR STRENGTH

The shear strength values of the weld laminated beech specimens as a function of welding time are depicted in Figure 1. The benchmark values of the shear capacity of the solid beech specimens at 2.54 mm displacement and after 300 sec of testing are shown with lines in Figure 1. Most specimens did not delaminate after 420 sec of testing parallel to growth rings. This is based on test recommendations in BS EN 373:1957 for the maximum duration of the experiments. Therefore, the solid steamed beech shear strength is expected to be higher than these values. For example, an average shear strength of 21.43 MPa has been reported in [19] for beech (*Fagus sylvatica*) based on the Arcan test method. The moisture content of the welded and solid beech specimens was 9.3 % and 8% respectively as measured according to BS 373:1957 [20].

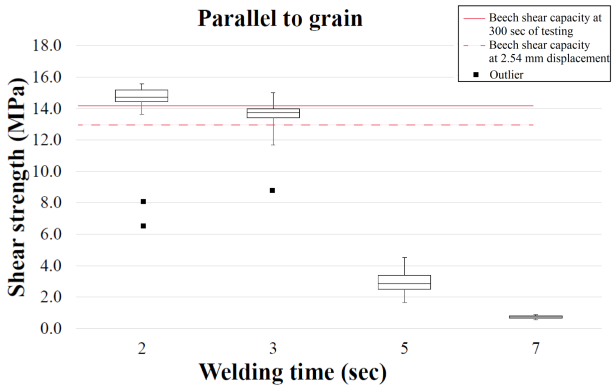

Figure 1: *Shear strength of weld-line in beech specimens as a function of welding time-Parallel to grain -Experimental.*

Attempts to make samples at 1 sec weld times were unsuccessful, suggesting this is not long enough to generate the temperatures necessary to soften wood constituent polymers to form a weld. A welding time of 2 sec results in the highest mean mechanical performance of the weld-line, but notably 2 out of 8 specimens exhibited half the mean values. This was attributed to unwelded contact faces as visually observed at the failure interface. This might be the result of a lower temperature developed at the ends of the specimen during friction welding leading to a much thinner weld line as also reported in [4]. Similar results with a non-uniform distribution of a perfectly composite weld interface have been reported in [14] attributed to scale effects (for welded areas greater than 30000 mm^2) combined with high internal gas pressure. A welding time of 3 sec provides a high shear strength capacity up to 13.6 MPa and it is preferred due to a more uniform weld-line from the increase in the heat energy input as observed with optical microscopy. Higher welding times (5 and 7 sec) result in much lower capacity in the range of 0.7-3.0 MPa. The failure interface of these specimens exhibited a much smoother profile than specimens welded at 2 and 3 sec (see later discussion of Figure 5). This can be the result of fibres expelled at the edges during the frictional welding and thermal degradation of cellulose from the developed high temperatures (>225°C [22]). Increased porosity due to char formation might be limited due to the high applied pressure. The shear strength capacity of the weld-line in beech laminated specimens tested perpendicular to the fibre direction was in the range of 38-56% of the equivalent performance parallel to the grain (see Figure 2). This suggests that the loading direction plays a significant role in the mechanical performance of the weld-line. The higher compliance of the material perpendicular to the fibre direction should also be considered.

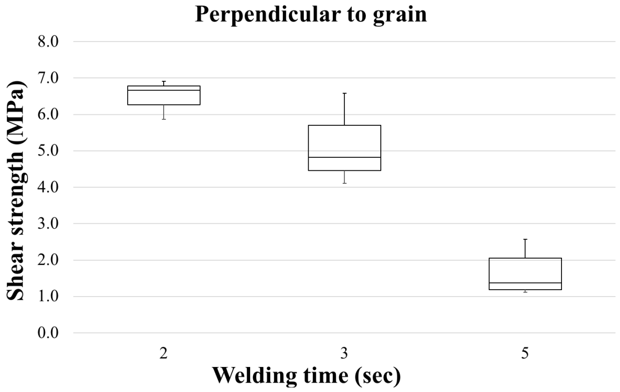

Figure 2: *Shear strength of weld-line in beech specimens as a function of welding time - Perpendicular to grain - Experimental.*

A summary of all the bond shear strength values for welded beech joints as found in literature and including the experimental data presented here is depicted in Figure 3. It should be noted that variations in the welding regime and test method exist among studies. The experimental results are derived from a tensile shear test [2, 3, 6, 22], according to BS EN 205[23], or the Arcan test method [7, 24]. Here a compression shear test method according to BS EN 392:1995 [21] was adopted to enable a direct comparison with adhesively bonded beech specimens [25, 26]. The experimental data is differentiated according to the welding frequency and welding amplitude. In most studies found in literature the welding pressure was 1.3-1.5 MPa, except in Omrani et al. [6] where WP=0.75 MPa, and small deviations existed in the holding pressure and time. Investigations that adopted a WF=150 Hz and WA=2 mm have empty markers and those that applied a WF=100 Hz and WA=3 mm have filled markers in Figure 3. It is observed that a good weld-line shear strength is achieved at WT=2-4.5 sec where the shear strength is above 6 MPa regardless the welding regime. The shear strength values reported here for WT=2 and 3 sec are within the strength range of adhesively bonded beech specimens. A shear strength of 13.5-14.0 MPa [25, 26] and 14.9 MPa [26] has been recorded in glue laminated beech with melamine formaldehyde (MUF) and polyurethane (PU) respectively. Yet, the minimum shear strength requirements for glue laminated timber are related to specific wood failure percentages (WFP) and pure failure in the bondline is not recommended [8]. Most values reported in [25, 26] refer to WFP >70% and a minimum WFP=45% is preferable [8]. In this study all failures lied in the weld-line with WFP<15%, as observed in Figure 5. The highest shear strength values above 13 MPa have been found in Omrani et al. [6] and in Gineste et al. [24] for a mixed mode of compression and shear loading (not included in Figure 3). Therefore, it seems that the test method and the resulting stress transfer mechanism play a significant role in the interpretation of the results and further investigation is needed towards standardisation. In Ganne-Chedeville et al. [22] the highest bond strength was derived after 4.5 sec. The temperature of 225°C was reached at 4 sec and high bond was maintained until 6 sec. Here, the temperature profile might be different due to the higher welding pressure resulting in an earlier cellulose degradation and lower strength at WT> 5 sec.

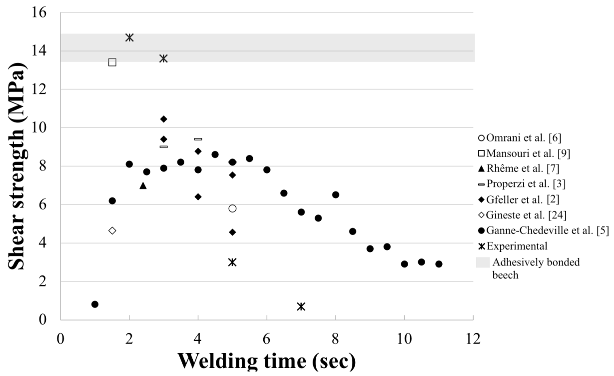

Figure 3: *Shear strength of weld-line in beech specimens as a function of welding time – comparison with literature.*

3.2 OPTICAL MICROSCOPY

The weld-line of indicative specimens welded at WT=2,3,5 and 7 sec is depicted in Figure 4. It is observed that a char layer starts to form at low welding time (2 sec). This is the result of the high welding pressure applied here (WP=6 MPa) that leads to a steeper increase in temperature during frictional welding combined with the lack of oxygen availability enhancing pyrolysis reactions. Char layer formation at a low welding time (WT=2.4 sec) and lower welding pressure (WP=1.5 MPa) has also been observed in [7]. An increase in char thickness and heat affected zones with increasing welding time (WT> 5 sec) can be discerned. Similar findings have been detected in [22]. It is argued that charcoal formation starts at 300ºC [22]. This might change depending on the wood species and moisture content.

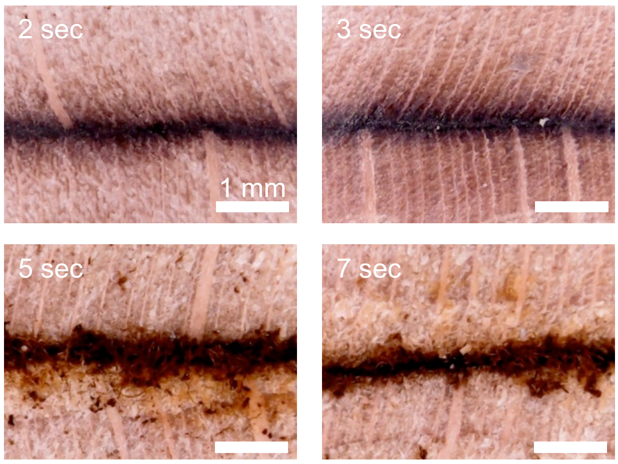

Figure 4: *Shear strength of weld-line in beech specimens as a function of welding time – Summary.*

Figure 5 shows the failure interface of welded beech samples at WT=2,3 and 7 sec and of solid beech samples (Figure 5a) for ease of comparison. It is observed that the failure interface lies within the weld-line and it exhibits a rougher surface at low welding times (2-3 sec). This is the result of more wood fibres remaining in the weld line and lower thermal wood decomposition at lower welding times. Therefore, the bond performance is higher due to a higher mechanical interlocking effect and greater chemical adhesion between wood polymer components. A small percentage of wood fibres is detected at low welding times (2-3 sec) indicating the high mechanical performance of the weld-line. A smooth and uniform failure interface is observed at a welding time of 7 sec and this is also reflected in the shear strength capacity of the specific welded beech specimens.

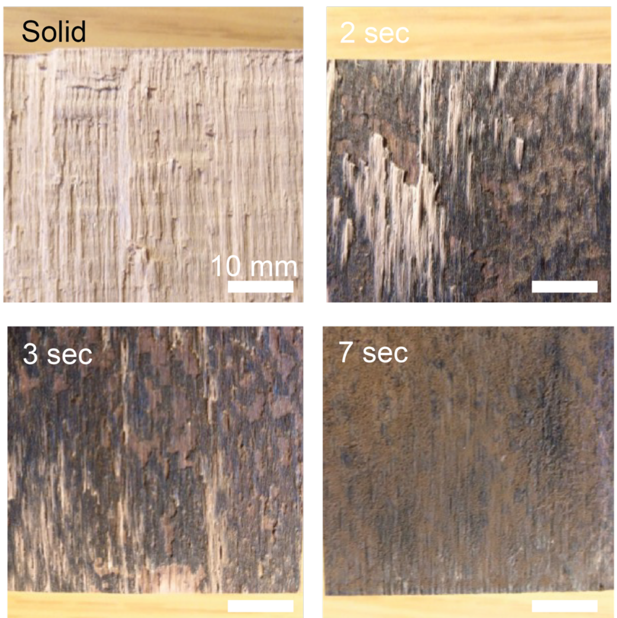

Figure 5: *Failure surfaces of sheared beech specimens as a function of welding time.*

3.3 DYNAMIC MECHANICAL ANALYSIS (DMA)

The normalised storage modulus and tanδ values with respect to temperature for a typical DMA steamed beech sample are depicted in Figure 6. There are three distinctive peaks in the tanδ plot corresponding to glass transition temperatures of $T_{g\text{-}tan\delta}$= 90, 140 and 190ºC. The glass transition temperature values associated with a drop in storage modulus and softening behaviour are $T_{g\text{-}onset}$= 65, 125 and 175ºC. It should be noted that the third drop in storage modulus cannot be clearly defined. The $T_{g\text{-}tan\delta}$ definition is related to mechanical damping or internal friction in a viscoelastic material and the $T_{g\text{-}onset}$ is related to melting of wood polymers.

Although different test methods result in different glass transition temperatures [27], Goring [28] reported softening temperatures of 127-193ºC and 167-181ºC for lignin and hemicellulose accordingly by observation of the thermally induced collapse of a column of wood polymer powder under constant load. The wide temperature range is attributed to differences among softwood and hardwood species. A drop of approximately 50ºC in the softening temperatures was observed with a 12% increase in moisture content. Chow and Pickles [12] measured a softening temperature of 180ºC in dry red alder samples using the same test method. Although a decrease of 20ºC was reported with a moisture content of 10%, the plots showed a less discernible softening region around 90-100ºC.

Wood softening is affected primarily by the chemical interaction and molecular arrangement of the wood polymers and secondarily by the softening of the wood constituents[12]. In our study the moisture content of the steamed beech samples is in the range of 8-9% and the first drop in the storage modulus is assumed to be associated with slippage of the intermolecular bonds as a result of increased motion from the heat energy input. Lignin forms with low molecular weight may also be related to the lowest T_g value. The higher recorded glass transition temperatures are attributed to lignin and hemicellulose softening. Cellulose softens at around 240ºC and seems not be affected by moisture due to its high crystalline structure [28]. A drop in the storage modulus of birch xylan was observed at 60ºC and *RH*=20% (equivalent of approximately 5% MC) in [31] with DMA under humidity scans from 1-90% *RH*. The glass transition of hemicellulose is related to the degree of polymerisation and crystallinity and the molecular weight of the polymer and differences are expected between alkali extracted and native hemicelluloses.

Any thermal degradation of the beech samples due to the steaming treatment should also be considered in the interpretation of the results. Small reductions in compressive strength (up to 13.2%) and in the hemicellulose content were reported in [29] by steam heating beech at 80ºC for 100hrs. Placet et al. [30] reported $T_{g\text{-}tan\delta}$ values in the range of 90-95ºC by testing wet beech samples at a frequency of 1Hz and up to 95ºC. It seems that softening and chemical bonding during frictional welding can be initiated at temperatures around 65ºC in lab conditioned steamed beech. A fair agreement between bonding and softening temperature was observed in [28] although deviations in the moisture content of the specimens in the relevant test procedures existed. Moisture evaporation taking place during friction welding is expected to increase the true softening/glass transition temperature of beech wood.

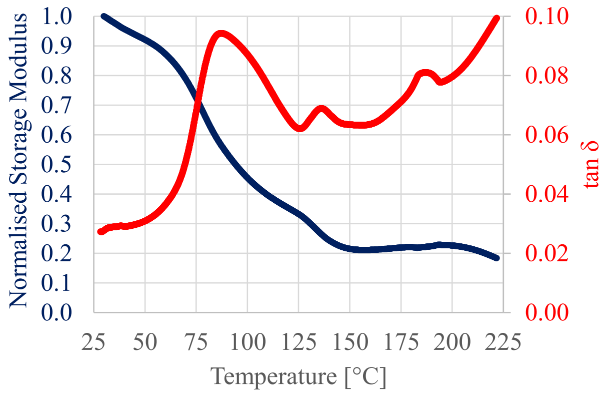

Figure 6: *Evolution of normalised storage modulus and damping ratio tan δ with temperature.*

4 CONCLUSIONS

The friction wood welding technique is promising for joining steamed beech laminates resulting in shear strength capacity equivalent to glue laminated products. However, the loading direction can significantly affect the mechanical performance of the beech welded specimens. The optimum welding time at a welding pressure of 6 MPa, welding amplitude of 1 mm and welding frequency of 75 Hz is 2-3 sec. Higher welding times lead to expelled fibres, more extensive thermal degradation of cellulose and a smooth failure interface within the weld-line. It is postulated that the temperature profile is more uniform at higher welding times and values greater than 240ºC are attained at greater welded surface. An increase in the char layer structure was also observed with increasing welding time. The formation of the weld-line is postulated to take place at temperatures above 65ºC where softening of beech was observed based on DMA tests. This is associated with intermolecular bond slippage and intramolecular motion of lignin with a low molecular weight.

ACKNOWLEDGEMENT

The authors are grateful to the Leverhulme Trust and the Centre for Digital Built Britain (part of the Construction Innovation Hub funded by UK Research and Innovation through the Industrial Strategy Challenge Fund) for financial support. The authors would also like to thank Paul Clark from TWI who was involved in the wood welding manufacturing process.

REFERENCES

[1] Zhang H, Pizzi A, Xiaoning L.: Palmyra palm bonding by vibrational welding. European Journal of Wood and Wood Products, 72: 693–695, 2014.

[2] Gfeller B., Zanetti M., Properzi M., Pizzi A., Pichelin F., Lehmann M., Delmotte L.: Wood bonding by vibrational welding. Journal of Adhesion Science and Technology, 17(11): 1573-1589, 2003.

[3] Properzi M., Leban J.M., Pizzi, A., Wieland S., Pichelin F. and Lehmann M..: Influence of grain direction in vibrational wood welding. Holzforschung, 59(1): 23-27, 2005.

[4] Belleville B., Amirou S., Pizzi A., Ozarska B.: Optimisation of wood welding parameters for Australian Hardwood species. Bioresources, 12(1): 1007-1014, 2017.

[5] Ganne-Chedeville C., Properzi M., Pizzi A., Leban J.M., Pichelin F.: Parameters of wood welding: A study with infrared thermography. Holzforschung, 60(4): 434-438, 2006.

[6] Omrani P., Mansouri H.R., Pizzi A.: Influence of wood grain direction on linear welding. Journal of Adhesion Science and Technology, 23: 2047-2055, 2009.

[7] Rhême M., Botsis J., Cugnoni J., Navi P.: Mixed mode fracture behavior of welded wood joints investigated with the Arcan test. Wood Science Technology, 50: 53-69, 2016.

[8] BS EN 386:2001: Glued laminated timber. Performance requirements and minimum production requirements.

[9] Mansouri H.R., Omrani P., Pizzi A.: Improving the Water Resistance of Linear Vibration - Welded Wood Joints. Journal of Adhesion Science and Technology, 23: 63-70, 2009.

[10] Gfeller B., Pizzi A., Zanetti M., Properzi M., Pichelin F., Lehmann M., Delmotte L.: Solid wood joints by in situ welding of structural wood constituents. Holzforschung, 58(1): 45–52, 2004.

[11] Peña M.I.P., Deutschle, A.L., Saake, B., Pizzi, A., Pichelin, F.: Study of the solubility and composition of welded wood material at progressive welding times. European Journal of Wood and Wood Products, 74: 191-201, 2016.

[12] Chow S.Z., Pickles K.J.: Thermal softening and degradation of wood and bark. Wood and Fiber, 3(3): 166-178, 1971.

[13] Lowden L.A., Hull, T.R.: Flammability behaviour of wood and a review of the methods for its reduction. Fire Science Reviews, 2(1), 2-19,2013.

[14] Hahn B., Stamm B., Weinand Y.: Linear friction welding of spruce boards: experimental investigations on scale effects due to humidity evaporation. Wood Science Technology,48: 855-871, 2014.

[15] Stamm B., Weinand Y., Hahn B., Rossmair G. Influence of the moisture content on the shear strength of welded wood-to-wood connections. COST Action FP0904 Thermo-hydro-mechanical wood behaviour and processing, book of abstracts 131–133, 2011.

[16] Rhême M., Botsis J., Cugnoni J., Navi P.: Influence of moisture content on the fracture characteristics of welded wood joint. Part 1: Mode I fracture. Holzforschung, 67(7): 747-754, 2013.

[17] Ruponen J., Čermák P., Rhême M., Rautkari L.: Reducing the moisture sensitivity of linear friction welded birch (*Betula pendula* L.) wood through thermal modification. Journal of Adhesion Science and Technology, 29(22): 2461-2474, 2015.

[18] Pizzi A., Mansouri H., Leban J., Delmotte L., Pichelin F.: Enhancing the exterior performance of wood joined by linear and rotational welding. Journal of Adhesion Science and Technology, 25:

2717-2730, 2011.
[19] Emberley R., Inghelbrecht A., Yu Z., Torero J.L.: Self-extinction of timber. Proceedings of the Combustion Institute, 36(2): 3055–3062, 2017.
[20] BS 373:1957. Methods of testing small clear specimens of timber.
[21] BS EN 392:1995: Glued laminated timber: Shear tests of glue lines.
[22] Ganne-Chédeville C., Properzi M., Leban J.M., Pizzi A., Pichelin F.: Wood Welding: Chemical and Physical Changes According to the Welding Time. Journal of Adhesion Science and Technology, 22(7):761-73, 2008.
[23] BS EN 205:2016: Adhesives. Wood adhesives for non-structural applications. Determination of tensile shear strength of lap joints.
[24] Gineste B., Cognard J.Y., Pizzi A.: Analysis of the Mechanical Behavior of Wood and Welded Wood under Tensile–Shear Loads Using a Modified Arcan Device. Journal of Adhesion Science and Technology, 26(10-11):1717-31, 2012.
[25] Aicher S., Reinhardt, H.W.: Delaminierungseigen-schaften und Scherfestigkeiten von verklebten rotkernigenBuchenholzlamellen. Holz als Roh- und Werkstoff, 65: 125-136, 2007.
[26] Aicher S., Ohnesorge D.: Shear strength of glued laminated timber made from European beech timber. European Journal of Wood and Wood Products, 69: 143-154, 2011.
[27] Toumpanaki E., Lees J.M., Barbezat M., Terrasi G.P.: Effect of internal moisture content and dynamic mechanical analysis testing conditions on the Tg values of CFRP tendons. Construction and Building Materials, 227:116771, 2019.
[28] Goring D.A.I.: Thermal softening, adhesive properties and glass transitions in lignin, hemicellulose and cellulose. In Consolidation of the Paper Web, Trans of the IIIrd Fund Res Symp Cambridge, 1965.
[29] Yilgor N., Unsal O., Kartal S.N. Physical, mechanical and chemical properties of steamed beech wood. Forest Products Journal, 51:89-93, 2001.
[30] Placet V., Passard J., Perré P.: WAVET*, A CUSTOM DEVICE ABLE TO MEASURE VISCOELASTIC PROPERTIES OF WOOD UNDER WATER-SATURATED CONDITIONS (* WAVET : Environmental Vibration Analyser for Wood). Maderas Ciencia y tecnología, 10(1):45-60, 2008.
[31] Olsson A., Salmén L. The Softening Behavior of Hemicelluloses Related to Moisture. In ACS Symposium Series 864:184-197,2004.