Study of Stress Capacity Improvement of L-type Joint by Chemical Modification of Wood

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Chemical modification of wood with the aim of improving its dimensional stability can also influence the mechanical behavior of the timber when assembled into a structure. Hence, in this study, the stress-carrying capacity of mitred and butted L-type joints constructed from furfurylated wood samples with two weight percentage gains (WPGs), *i.e.*, 20 and 60% (low and high levels, respectively), was investigated by subjecting the specimen to a diagonal tension load. Results indicated that the bending moment resistance of both L-type joints depends on the WPG. The L-type joints' bonded stress value with poly-vinyl acetate (PVAc) adhesive decreased with increasing WPGs. Likewise, in the case where epoxy adhesive was used for jointing, the stress capacity increased for both joints constructed with furfurylated wood. Values of tension stress in the butted joint were higher compared to the mitred one. Evaluation of shear stress parallel ($\tau_{\parallel}$) and perpendicular ($\tau_{\perp}$) to the grain of members jointed with PVAc adhesive demonstrated that the shear stress-carrying capacity decreases as furfurylation level increases. However, by applying epoxy adhesive for jointing, $\tau_{\parallel}$ and $\tau_{\perp}$ were increased by raising the furfurylation levels.

Keywords: Furfurylation; Stress capacity; Dowel; L-type joint

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INTRODUCTION

Wood's engineering properties have established its suitability as a structural material. Its strength properties and the natural durability of certain wood species have provided humans with a material that can perform many functions (Eaton and Hale 1993; Schniewind 1989). However, wood also has properties that, in relation to specific applications, can be regarded as disadvantages. In buildings and various other structures, the wood-moisture interaction almost always has a decisive effect on the behaviour of a timber component. As a result, the most significant problem for structural timber is its lack of dimensional stability (Rowell 1991). In this context, chemical modifications can overcome these drawbacks to the use of wood and transform it from an unpredictable material to high-value timber products with desirable and predictable engineering attributes.

Joint design in structures, buildings, and furniture is one of the most important steps in designing and manufacturing. Even though the individual members may be strong enough to carry the loads acting upon them, the structure may still fail if the joints are not properly designed. Structural failures occur in frames more often because of weak joints than from any other single cause. Among the various timber structural components, the joints are often one of the weakest points. Additionally, the joints are one of the most important parts because they bear the carrying capacity load of the structure (Stamm 1964).

It is therefore important that the joints used in the fabrication of such structures are scientifically designed so that they can safely carry the load imposed upon them and improve the reliability of such structures.

Many authors have reported on the mechanical and physical properties of thermally or chemically modified wood (Kumar 1994; Larsson 1998; Rowell 1984), and several studies have been conducted to improve the design and manufacture of various furniture items and wood structures. World-wide environmental concerns are motivating efforts for a development of new biobased material systems and products. Furfurylation systems are now in commercial operation. Furthermore, furfurylated wood as a new environmentally friendly water-repellent wood product is already being produced by impregnating wood for the use as both furniture and in outdoor building and joinery applications (Larsson *et al.* 2008).

This paper presents an experimental investigation of the stress-carrying capacity of L-type joints constructed with two types of adhesives and modified members with the aim of providing joints with better strength and durability. Furthermore, the effects of diagonal loading pattern and induced combined forces on L-type joints constructed using furfurylated wood were studied to understand the failure mode to establish a more durable and effective L-type joint than the one normally used by manufacturers under diagonal tension force.

EXPERIMENTAL

Materials

Furfurylated beech (*Fagus orientalis)* wood was selected as the material for the joints. Wood dowels were made out of beech wood, measured 10 mm x 30 mm (diameter x length), and were used as mechanical fasteners (Fig. 1).

Poly-vinyl acetate, PVAc (grade H1000, homopolymer) was purchased from Resin and Chasbeshomal Chemical Industries. The epoxy (JALAPOX 797C) was from Jalasanj company. The PVAc and epoxy were used as adhesive.

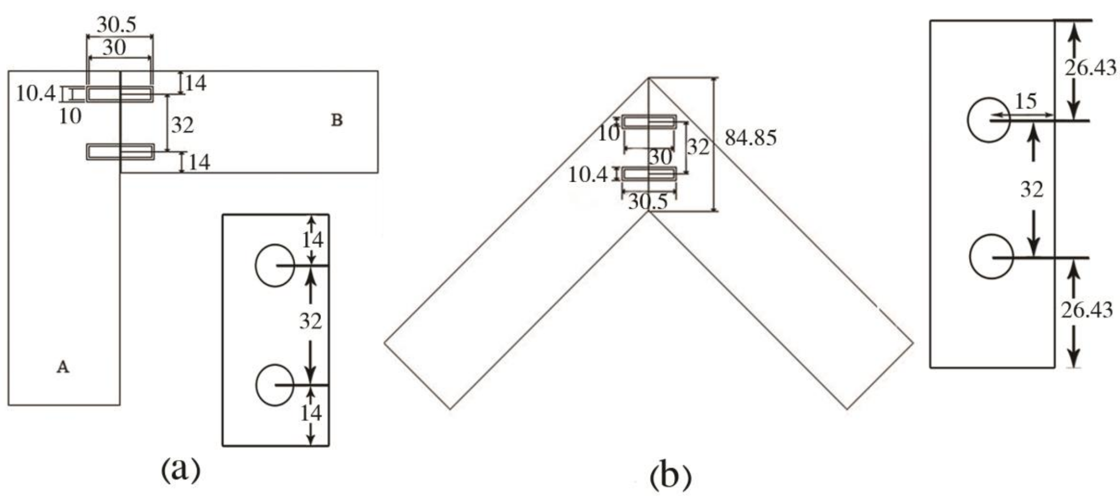

Fig. 1. The dowel position and its dimension (in mm) in the (a) butted joint and (b) mitred joint

Methods

Furfurylation

Defect-free, straight-grain beech samples 60 mm × 30 mm in cross section and 160 mm in length were treated using a full-cell impregnation process in a lab-scale impregnating vessel. Impregnation solutions were prepared with two different furfuryl alcohol (FA): ethanol volume ratios of 70:30 and 30:70 to achieve high and low levels of WPGs, respectively. Specimens were impregnated with FA (98%, Merck) and 1.5% citric acid (98%, Merck) as a catalyst using the following procedure: (1) Pre-drying: Samples were dried at 60 ºC for 24 h and then weighed; (2) Impregnation: Samples were placed in a cylinder filled with FA solution, and a vacuum (0.10 bar) was applied for 45 min followed by a pressure of 6 bar for 2 h using compressed air. After removal from the cylinder, excess liquid was wiped from the samples; (3) Curing: Treated specimens were wrapped in aluminium foil and subjected to a temperature of 103 ºC for 16 h to cure; and (4) Drying: The foil was removed, and the samples were kiln-dried for 168 h at 40 ºC, and the samples weighed before conditioning at 20 ± 1 ºC and 65 ± 3% RH. The weight percentage gain (WPG) was determined as an average of 20 and 60%, ranked as low and high levels of furfurylation, respectively. Six samples were taken for determination of each level WPGs. Standard deviations were calculated as 3.48 and 7.52 for low and high levels respectively.

Scanning electron microscopy (SEM)

The samples of furfurylated wood with dimensions of 10 mm × 10 mm × 5 mm were cut. The surface of samples were then smoothed with the sliding blade of a microtome and sputter-coated with gold to avoid charging. The sections were analyzed using a VEGA II SEM (TESCAN, Czech Republic) operating at an accelerating voltage of 7 kV.

Experimental specimens and design

A double-spread method was applied, where adhesive was applied to both the dowel hole and the surface of the dowels. After this, L-shaped test specimens were assembled as butted and mitred corner joints. The assembled test joints were clamped for 24 h to allow the adhesive to cure. In butted joints, member A had dimensions of 160 mm × 60 mm × 30 mm, and member B had dimensions of 100 mm × 60 mm × 30 mm. However, in the mitred joints, both members had the same dimensions, 160 mm × 60 mm × 30 mm. Both type of joints were constructed in four replicates. Table 1 summarizes the experimental design.

Table 1. The Experimental Design

Type of Joints	Type of Adhesive	Furfurylation level	Abbreviation of treatments
Mitered	PVAc	Control	MPC
		Low	MPL
		High	MPH
	Epoxy	Control	MEC
		Low	MEL
		High	MHL
Butted	PVAc	Control	BPC
		Low	BPL
		High	BPH
	Epoxy	Control	BEC
		Low	BEL
		High	BEH

Testing procedure

As shown in Fig. 2, in a conventional testing method the L-type test specimens (including butted and mitred joints concerning α angle variations) are subjected to a tension force that causes the joint to open. In the case of the tension test, each member is placed on rollers so that the joint is forced to open. This action tends to enlarge the angle formed by parts joined together. In the tension test setup case, legs are positioned horizontally on rollers on the bed of the testing machine so that the 2 joint members are free to move sideways when the joint was loaded. Steel bars are used to distribute the load uniformly along the length of the specimens (Zhang and Eckelman 1993; Tankut and Tankut 2004).

Mechanical properties of untreated and furfurylated beech wood including tension perpendicular to the grain, compression perpendicular to the grain and shear parallel to the grain were determined according to ASTM D-143 using an Instron 4486 device.

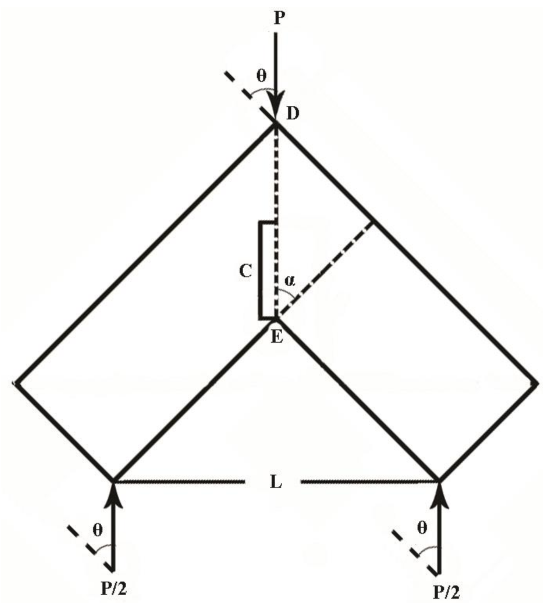

Fig. 2. Schematic design of corner butted joint and mitred joint showing the applied force and support reaction forces. *P* is loading at yield point, *θ* is angle between member and loading direction, *α* is an angle which specifies the type of joint (*α*=0° for butted joint and *α*=45° for mitered joint), D and E are the points in outer and inner corners respectively, *L* is the distance between supports and C is the centroid.

Stress capacity

The stress-carrying capacity induced across the joint surface by various bending and axial forces *i.e.*, the combined stresses, were calculated as follows.

The failure load, *P*, of each specimen type was measured. The stress value, σ_a, of the two joint corners (at points D and E) and shear stress, τ, (parallel and perpendicular to the grain) were calculated by substituting the values of α and θ. At the butted joint, $\theta = 45^o$ and $\alpha = 0^o$, and the stress value, σ_a, is given by Eqs. 1 and 2.

$$\sigma_{a)_D} = -0.707\frac{P}{tb} - 1.5\frac{PL}{tb^2} \qquad (1)$$

$$\sigma_{a)_E} = -0.707\frac{P}{tb} + 1.5\frac{PL}{tb^2} \qquad (2)$$

At the mitred joint, θ = 45º and α = 45º, and the stress value is given by Eqs. 3 and 4.

$$\sigma_{a)_D} = -0.353\frac{P}{tb} - 0.75\frac{PL}{tb^2} \qquad (3)$$

$$\sigma_{a)_E} = -0.353\frac{P}{tb} + 0.75\frac{PL}{tb^2} \qquad (4)$$

The shear stress parallel, $\tau_{||}$, and perpendicular, $\tau_{\perp}$, to the grain in the mitred joint is given by following two equations, respectively,

$$\tau_{||} = 0.25\frac{P}{tb} \qquad (5)$$

$$\tau_{\perp} = 0.35\frac{P}{tb} \qquad (6)$$

where t and b are the thickness and width of section respectively.

RESULTS AND DISCUSSION

Stress Capacity of L-type Joint based on Points D and E under Diagonal Tension Force

It can be seen from Fig. 3 that the stress-carrying capacity of L-type joints with PVAc adhesive decreased with increasing furfurylation level.

The obtained results were similar to those described by others (Abdolzadeh *et al.* 2011; Rowell 2006; Rowell *et al.* 1989). The reason for this behaviour is attributed to the weak adhesion between the furfurylated members and wooden dowels and decreased surface wetting by the resin. The cell wall can be bulked with bonded chemicals like furfuryl alcohol (FA). Therefore, resins that are water-soluble and depend on a hydrophilic adherent for penetration like PVAc will be less efficient due to the decreased hydrophilic nature of the cell wall resulting from modification.

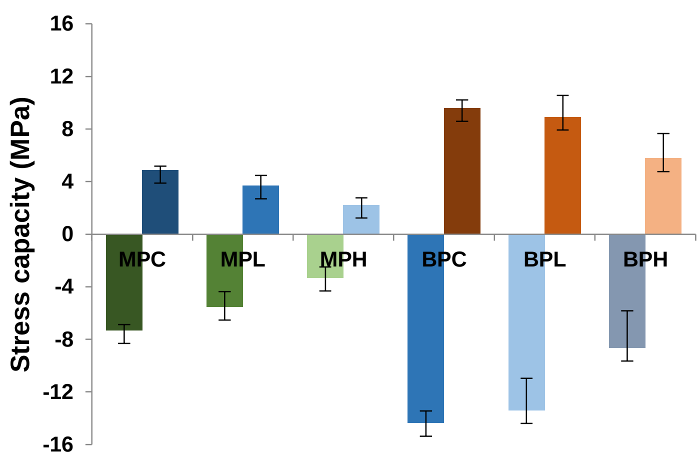

Fig. 3. The effect of furfurylation level on stress capacity of L-type joint with PVAc adhesive; negative and positive values indicate σ_a at points D and E, respectively.

Micro cracks at the middle lamella of furfurylated members developed with increasing levels of furfurylation (Fig. 4). At the microscopic scale, three types of failure can be distinguished: intercell, intra wall, and transwall. Intercell failure (IC) occurs at the middle lamella and represents the separation of cells (Smith *et al.* 2003). Despite the increasing toughness of wood through furfurylation, the increase in the number and size of micro-cracks at the middle lamella would increase failure under tension loading perpendicular to the grain.

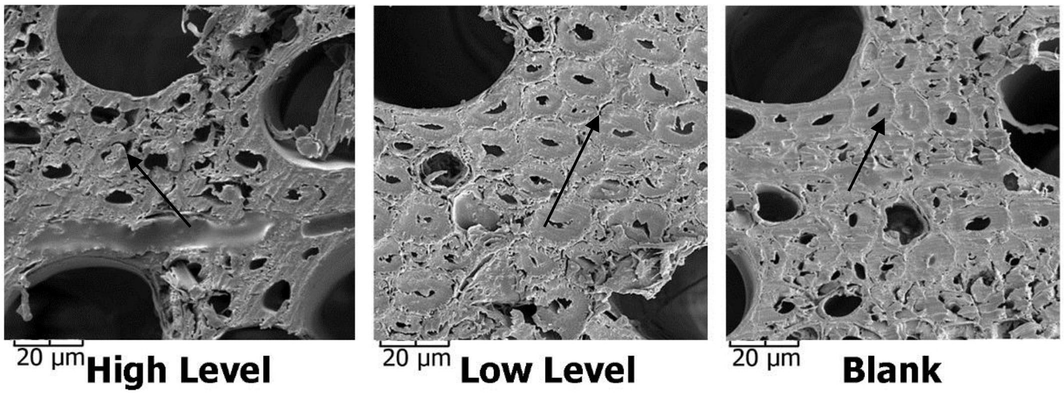

Fig. 4. Microscopic effects of furfurylation and micro crack effects (arrows) on intercell failure

Resins that are water-soluble and depend on a hydrophilic adherend for penetration, like PVAc, will be less efficient due to the decreased hydrophilic nature of the cell wall resulting from modification.

Vick *et al.* investigated adhesion properties such as polyvinyl acetate (PVAc) in laminates of two modified softwoods. They found that acetylated laminates with PVAc resisted delamination as long as individual lamellae had equal acetyl content, but the unmodified lamellae performed better (Vick and Christiansen 1993; Vick *et al.* 1993; Vick 1995;). All other wood adhesives bond more poorly to chemically modified wood than to untreated wood (Marra 1992; Davis 1997; Vick 1999; Custodio *et al.* 2009).

The results in Fig. 5 indicate that the stress-carrying capacity of butted joints is higher than mitred joints, regardless of the applied adhesive type. The connections are the critical locations of timber structures, and about 80% of timber structural failures are due to connections (Itany and Faherty 1984). During tension strength tests performed on the mitred joints, the adhesive line, connections, and joint itself directly carry the stress. However, in the case of the butted joint, the wood member primarily carries the stress and transfers stress to the adhesive line and connections, resulting in higher loading endurance in butted joints. Stress capacity in joints not only is affected by applied load, but also is influenced by other parameters such as joint geometry. Applying Eqs. 1 through 4 to calculate σ_a results in a higher value for butted joints than for mitred joints at the same load.

The stress-carrying capacity of L-type joints with epoxy adhesive as the bond line were improved by increasing the furfurylation level. The experimental results also demonstrated that applying epoxy adhesive can enhance the bond line of both L-type joints. Studies have shown that, despite the negative effects that chemical preservatives bring to the adhesion, many types of preservative-treated timber can still successfully bond with specially formulated adhesives (Tascioglu *et al.* 2003).

In both L-type joints under diagonal tension load, the joint strength and stress-carrying capacity of the joint are affected by tension and compression perpendicular to the grain and shear parallel to the grain of the members, which are strongly influenced by furfurylation. Therefore, furfurylation contributes to the compression perpendicular to the grain of wood and thus leads to an improvement of the joint tension performance. The mechanical properties are summarised in Table 2.

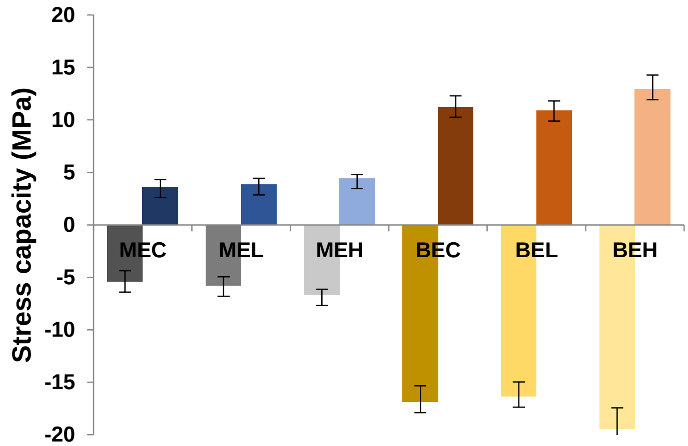

Fig. 5. The effect of furfurylation level on stress capacity of L-type joints with epoxy adhesive; negative and positive values indicate σ_a at points D and E, respectively.

Table 2. Mechanical Properties of Beech Wood and Furfurylated Wood

Test materials		Tension perpendicular to grain (MPa)	Compression perpendicular to grain (MPa)	Shear parallel to grain (MPa)
Beech wood	Control	4.62 (1.44)	9.5 (5.28)	17.43 (3.49)
Furfurylated wood	Low	3.36 (1.03)	11.84 (1.88)	27.85 (0.81)
	High	2.23 (0.69)	14.54 (2.33)	32.43 (1.14)
Values in parentheses are standard deviation				

Shear Stress Parallel ($\tau_{//}$) and Perpendicular ($\tau_{\perp}$) to the Grain of L-type Joints

Based on the experimental results, shear stress capacity parallel to the grain ($\tau_{\shortparallel}$) and perpendicular to the grain ($\tau_{\perp}$) are shown in Fig. 6. The shear stress-carrying capacity of joints using epoxy adhesive as the bond line increased with increasing furfurylation level. The shear stress-carrying capacity also increased due to the enhanced tension performance of the joint.

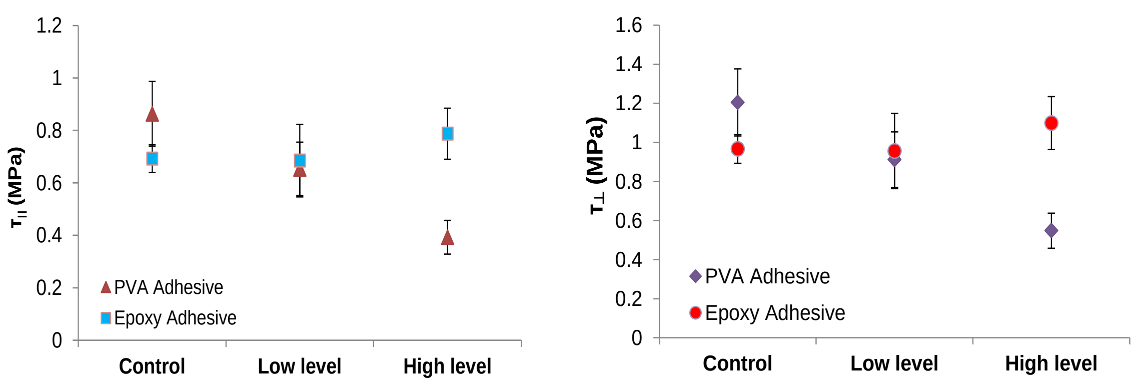

Fig. 6. The effect of furfurylation level and adhesive type on shear stress parallel and perpendicular to the grain of mitred joints

According to results presented in Table 2, the determined mechanical properties of furfurylated wood increased except tension perpendicular to grain. Shear strength parallel to grain increased about 59% and 86% in low and high levels of furfurylation, respectively. Also according to our observations, joints with furfurylated members bonded by PVAc adhesive easily failed at the bond line under diagonal tension force. The PVAc is a water-soluble adhesive and depends on a hydrophilic adherent for penetration, but the same joints bonded with epoxy adhesive are resistant in bond line and fracture that occur in the joint members. Therefore, the diagonal tension performance of joints was decreased in joining by PVAc adhesive and increased by furfurylation and application of epoxy adhesive. Since application of epoxy adhesive enhanced the tension performance of the joint, the shear stress carrying capacity increased as expected.

CONCLUSIONS

1. Furfurylated wood does not always result in decreased stress-carrying capacity in joints. By applying proper adhesive to the joints, both the stress-carrying capacity and dimensional stability can be improved.
2. Epoxy adhesive reinforces the bond line and thus improves the stress transfer to the members and joints. This further improves wood's ability to withstand tension load until failure occurs.
3. Furfurylation caused the development of micro cracks at the middle lamella, which influenced negatively the stress-carrying capacity of the joints.

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