Prediction of L-type Mitered Joint Behavior with Linear Elastic Fracture Mechanics: Experimental and Numerical Modeling

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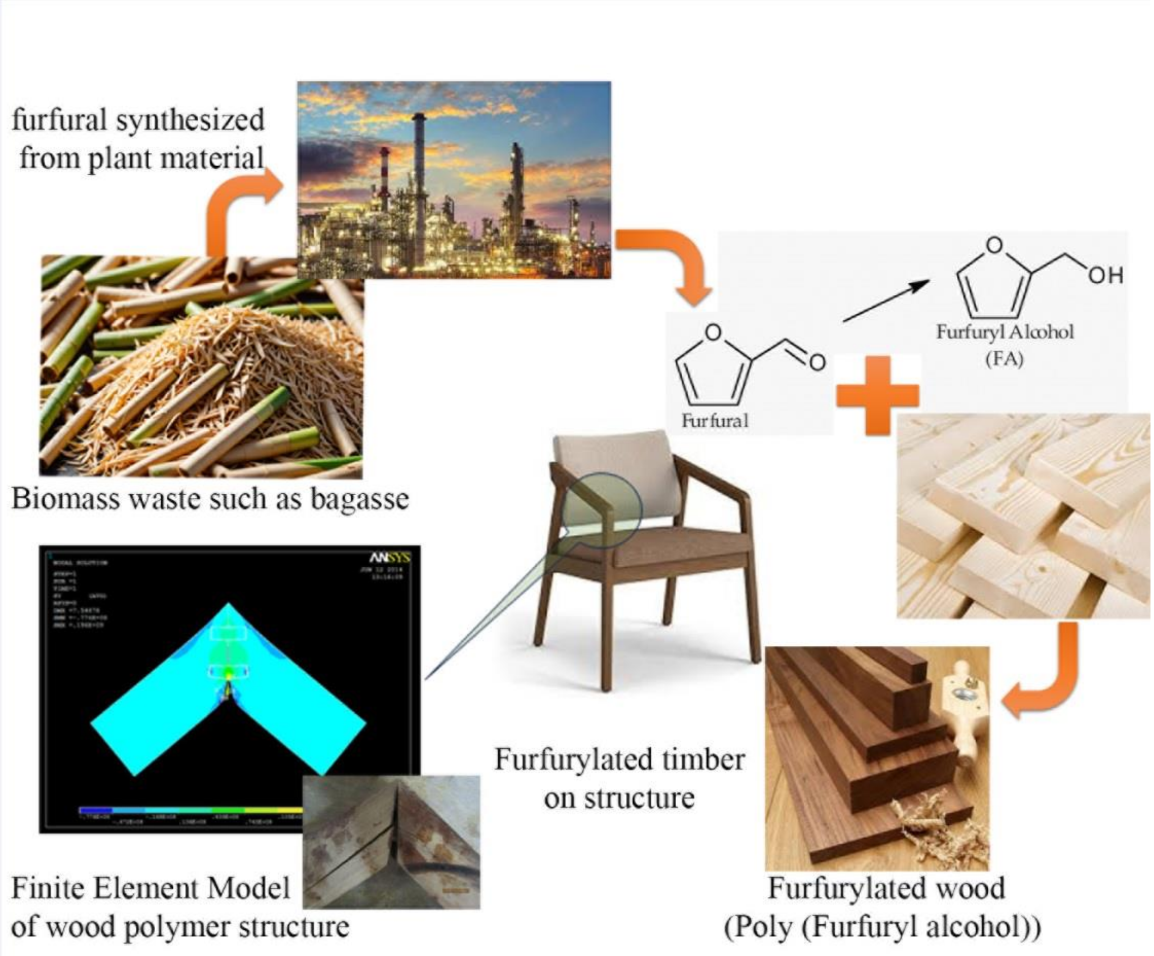
GRAPHICAL ABSTRACT



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Numerical modeling was used for mitered joints prepared with wood-based composite members (poly(furfuryl alcohol)) using Linear Elastic Fracture Mechanics (LEFM). The aim was to understand the joint performance under outdoor conditions. Analysis of fracture mechanics properties of wood-based composite is necessary to obtain a good understanding of joint behavior and to predict the reasons for its fracture. The fracture stiffness of furfurylated wood under mixed mode (I/II) was investigated. In both crack systems, the distribution trends of K_{IC}/K_{IIC} with furfurylation changed. The results of corner mitered joints showed that the mixed mode I/II was the effective fracture mode under diagonal compression (DC) and tension (DT) load. Based on the results obtained from fracture mechanics, the structural performance of mitered joints increased with increasing furfurylation level. The model results confirmed the experimental results.

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Keywords: Finite element method; Corner joint; Fracture mechanics; Poly (Furfuryl alcohol); Wood-based composites

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INTRODUCTION

Joints are one of the most important and controversial parts in any wood structure because joints transfer forces between structural members and maintain the integrity of structures. Most collapses occurring under loads are due to inappropriate joints. Further, stability and durability of structures are mainly supplied by joints (Abdolzadeh *et al.* 2014). Wood frames in different structures, such as furniture, are affected by axial, shear, bending, and even torsional loads, and in some cases by a combination of different loads (Golabchi 2008). Weakness of wood timber is maximized when exposed to tension perpendicular to the grain stress ($T_{\perp}$) and shear parallel to the grain ($S_{\parallel}$). This weakness in structures with light frames needs special attention. Each of these stresses can reduce structural strength; however, if they are applied simultaneously, their destructive effects on wooden structures will be greater. Combined stress and wood defect in $T_{\perp}$ and $S_{\parallel}$, make designers reinforce wood members under combined load using different methods while increasing the stress capacity of joint and wood members with different techniques.

Wood is a natural biopolymer composite (Jiang and Singamaneni 2017; Chen *et al.* 2020). Many wood modification methods have been developed (Beck *et al.* 2017; Tu *et al.* 2018; Shen *et al.* 2021). Many bio-renewable and ecofriendly wood modifiers have received attention, as they reduce the negative environmental effects of chemicals. Furfuryl alcohol is a renewable chemical because it is derived from furfural, which can be produced from hydrolyzed biomass waste, such as corncobs, bagasse rice hulls, and others (Machado *et al.* 2016). The properties of furfurylated wood depend on the retention of polymerized furfuryl alcohol (PFA) in the wood (Lande *et al.* 2010; Yao *et al.* 2017; Kong *et al.* 2018). Ecotoxicity tests studies showed low release of non-reacted furfuryl alcohol in the final products (Lande *et al.* 2004). The researchers reported that furfurylation affected the plasticization and compression capability of wood, and the durability of low-density biomass increased based on the furfurylation level (Buchelt *et al.* 2012; Szymona *et al.* 2014).

In recent decades, wood-based composites have been used for optimization of wood applications and to improve physical and mechanical properties of wood to develop its outdoor service application and construction usage. Wood-based composites are the main material that affect stress capacity in members under load. Thus far, several researchers have paid special attention to wood-based composites prepared by furfurylation as new products for the manufacture of wood products, doors and windows, flooring, wainscotting, and furniture (Dong *et al.* 2014, 2015). Moreover, research conducted on modification of wood only includes some studies on chemical, physical, and mechanical properties of such products (Jia and Fiedler 2018; Hadi *et al.* 2022). Despite some structural applications, none of these results address a practical discussion on wood-based composites or an investigation of their reaction under various loads in the structure. Meanwhile, an examination of corner joint constructed with wood-based composites members without considering its fracture mechanics cannot provide a good understanding of joint performance.

Using FEM for simulation of failure behaviour of structure with furfurylated members is one of the best ways for determining properties of wood-based composite and its behaviour. Jensen (2005) studied the quasi-non-linear fracture mechanics model, as compared with other models. Tests were conducted to reveal the influence of the geometrical properties of the DCB specimen. Moura and Dourado (2018) studied the mode I fracture characterization of wood using the Tapered Double Cantilever Beam test (TDCB). All the results confirmed the appropriateness of the TDCB test with linear tapering. Nakagawa *et al.* (2024) investigated the effect of thermal modification of western hemlock on the flexural properties, transverse fracture energy, and hardness. Further research by Warguła *et al.* (2021) determined the material properties necessary to develop the model used in FEM. The main purpose of the developed model will be to determine the maximum stress value necessary to estimate the destructive force for the tested wood sample.

The objective of this study was to compare the results of numerical and experimental studies of structural performance of a joint under combined stress with wood-based composites members. The influence of furfurylation and its weight percentage gain (WPGs) on shear strength can affect fracture behaviors. Therefore, a numerical model was developed for prediction of brittle behavior of timber and wood-polymer members of joints under linear elastic conditions. In addition, an appropriate geometric design for joints with furfurylated wood members was presented. Although the influence of modification effect on some wood strength and physical properties had been studied, numerical analysis of wood-based composites used constructions have never been reported. Therefore, the aim of this study was to investigate the furfurylation and its WPGs effect on the LEFM behavior of such wood-based composites and its modeling. This method allows the development of the results obtained from experimental tests with new geometric parameters or different joint designs.

EXPERIMENTAL

Numerical Model

Mitered joints with two dowel connections in wood and PFA are illustrated in Fig. 1. Wood is often assumed to be homogeneous for purposes of numerical modeling. The capacity of joints was defined by brittle failure modes. Therefore, wood and wood-based composites are assumed as linear elastic and orthotropic (Table 1). The elastic modulus of axial compression in the longitudinal direction was experimentally determined (ASTM 143 1994) using an Instron 4486 device with 5 replications and other values with the relations E_{L}: G_{LR} ≈14:1, G_{LR}: G_{LT}: G_{RT} ≈ 10: 9.4: 1, as calculated from Bodig and Jayne (1982) and Obara (2018).

A 3D FE model of the tested joint was built. The commercial FE code, ANSYS was used. Beech wood, LPFA (Low Polymerized Furfuryl Alcohol with 20% WPG) and HPFA (High Polymerized Furfuryl Alcohol with 60% WPG) were modelled by brick 20-node elements (SOLID186), which is well suited to modeling irregular meshes. An element with an aspect ratio close to 2.0 was used. The contact elements, such as CONTA174 and TARGE170, were used for modeling adhesive line of contact between the dowel and members and jointing two members (Fig. 1) (McKenzie and Karpovich 1968; Tannert 2009; Tannert *et al.* 2011).

Table 1. Modulus of Elasticity for Axial Compression of Solid Wood and Furfurylated Wood

Specimens	E_X	E_Y	E_Z	G_{xy}	G_{yz}	G_{xz}	v_{YZ}	v_{XZ}	v_{XY}
Control	3666	293.28	183.3	261.86	26.186	246.15	0.37	0.50	0.67
LPFA	5369	429.52	268.45	383.5	38.35	360.49	0.37	0.50	0.67
HPFA	6375	510	318.75	455.36	45.54	428.03	0.37	0.50	0.67

Units of modulus of elasticity (*E*) is MPa; Units of modulus of rigidity or shear modulus (*G*) is MPa; LPFA: Low Polymerized Furfuryl Alcohol (20% WPG); HPFA: High Polymerized Furfuryl Alcohol (60% WPG); ν is Poisson's ratio

The model proposed is only intended for simulation of the joint elastic stiffness, which can be compared with the available experimental results allowing the calibration of the model. Contact stiffness (FKP), penetration tolerance (FTOL), friction coefficient (μ), and the initial connection gap between the connecting members affect result accuracy and convergence. FKP and FTOL are parameters that describe the relative contact stiffness and the allowable penetration, respectively. Based on preliminary investigations (Tannert 2009; Tannert *et al*. 2011), FKP was set to 0.02, a value that allowed convergence, and FTOL to 0.5, a value that allowed realistic interpenetration of the surfaces.

The contact performance is strongly influenced by the gap between dowel and hole. Researchers suggested that good agreement between analytical and experimental load response curves can be achieved by modeling a gap of 0.1 to 0.5 mm (Tannert 2009; Dos Santos *et al*. 2009; Tannert *et al*. 2011). The friction coefficient μ was set to 0.3, which is similar to previous research (McKenzie and Karpovich 1968).

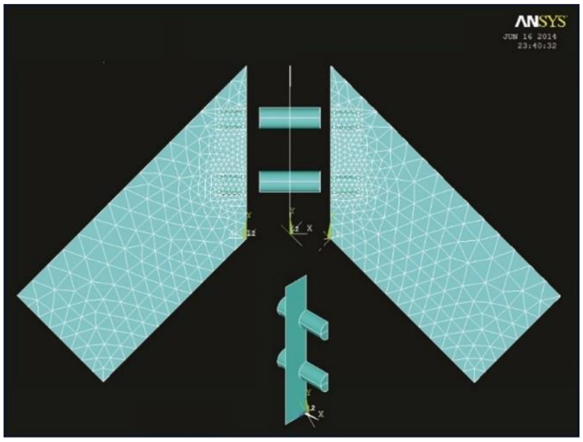


Fig. 1. A complete numerical model along with mesh structure of joints, contact elements for adhesive line of joint

Joints Preparation for DT and DC Tests

Beech wood (*Fagus orientalis*) and its furfurylated members connected with two solid beech dowels using PVAc adhesive were tested under DT and DC. The members dimensions were 160 × 60 × 30 mm^3. These members were cut as a mitered joint by 45˚ at D point. Two different levels of furfurylation consisting of LPFA and HPFA were compared to the control specimen by the Thygesen *et al.* (2010) method. Wood members were treated by a full-cell impregnation process in a lab-scale impregnating vessel. Two different furfuryl alcohol (FA) concentrations were used: 70 and 30%. Ethanol (95%) concentrations of 30 and 70% for high and low levels, respectively, were used for dilution of the samples. 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 aluminum foil and subjected to a temperature of 103 °C for 16 h to cure; and (4) Drying-The foil was removed, the samples were kiln-dried for 168 h at 40 °C, and the samples weighed before conditioning at 20 ± 1 °C and 65 ± 3% RH. The WPG was determined as an average of 20 and 60%, ranked as low and high levels of furfurylation, respectively. These treatments were compared to beech wood as a control specimen.

Fracture Mechanic Test

Single edge notched tensile (SENT) specimen

Finding a load configuration with which the mode mixed is the main problem in mixed mode fracture testing. The configuration of specimens for evaluating the stress intensity factors should be simple (Jernkvist 2001).

The SENT specimens were fabricated with the tailoring of a crack in RL (Radial-Longitudinal direction) and TL (Tangential-Longitudinal direction) systems (Fig. 2). The dimensions were 60 × 30 × 20 mm^3. The stress intensity factors were determined from the Eqs. 1 and 2,

$$K_I = \sigma\sqrt{\pi a} f_I(\varphi) \tag{1}$$

$$K_{II} = \sigma\sqrt{\pi a} f_{II}(\varphi), \quad (2)$$

Where φ is the angle (0° and 45°) of the initial crack created to the line of symmetry, σ is the normal stress, a is crack length, and the functions f_I and f_{II} depend on the specimen geometry and the elastic anisotropy of the material (Jernkvist 2001). These functions were determined by use of plane strain finite element analyses.

$$f_I(\varphi) = 3.028 - 3.22 \times 10^{-3}\varphi + 3.73 \times 10^{-4}\varphi^2 - 9.14 \times 10^{-6}\varphi^3 \quad (3)$$

$$f_{II}(\varphi) = \sin(2\varphi)(0.644 + 4.89 \times 10^{-3}\varphi) \quad (4)$$

In Eqs. 3 and 4 φ is given in degrees (°), where W and L are width and length of specimens, respectively.

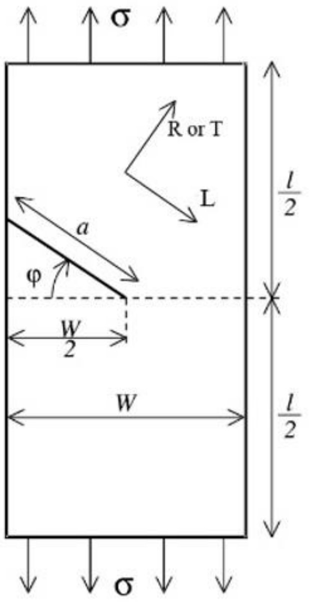


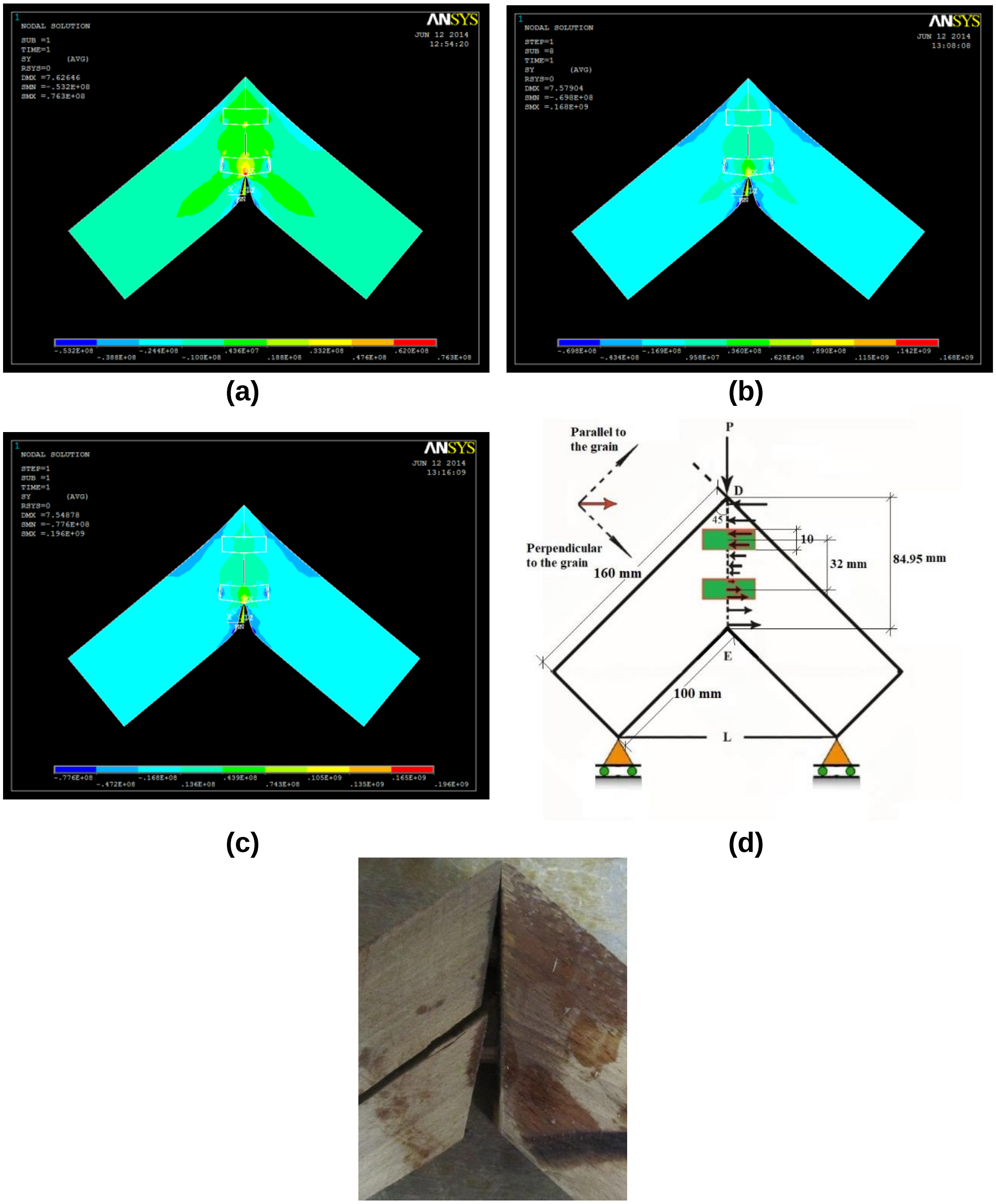
Fig. 2. SENT specimen in LR and TL crack system

RESULTS AND DISCUSSION

Joint Under DT

The connection close to point E is under tension (Fig. 3d). The green area that illustrates the fracture area in control specimens becomes clearly smaller under stress in HPFA specimens. Through reinforcing the adhesive line and increasing its strength against opening, the fracture is transferred to members. Because the fracture of mitered members occurs under mixed-mode, with the increase in furfurylation level, the joint strength under DT loading increases.

The coordinate axes rotation at the mitered surface and transformation of tension stress at the inner edge of the joint to the shearing stress and the normal stress caused mixed-mode fracture in the members. The principal planes of stress became smaller due to furfurylation and increased its level. Fracture mechanics tests conducted on LPFA and HPFA specimens under mixed-mode indicated that furfurylation changed the solid wood, leading to an increase in its stiffness. Because beech wood is sensitive to drying processes, the possibility of microcracks in wood during the construction of wood-based composites with a heating catalyst seems inevitable. These cracks come together during loading accelerating fracture, thereby reducing K_{IC} in this system in wood-based composites specimens. In contrast, using a polymer in a wood structure increases plasticity of wood. Moreover, in the HPFA specimen, increasing the plasticity of wood overcomes the negative effects of temperature during polymerization and lower equilibrium moisture content of the product.



(a) (b) (c) (d) (e)

Fig. 3. a) Von Mises stress in blank, b) LPFA, c) HPFA, d) Joint preparation with two dowels as connections under DT, and e) a close up of experimental result (Stress unit is Pa)

The furfuryl alcohol complexes were predominantly deposited in the wood cavities and cell walls. Polymerization took place in microscopic cell cavities. Recent nanoindentation studies have indicated that increases in indentation modulus and hardness of furfurylated wood cells are manifested indirectly (Li *et al.* 2016). Another perception is that furfurylation leads to a permanent "bulking" of the cell wall, meaning that the cells are swollen in a permanent way. One possible explanation is that the furfuryl alcohol polymer inside the cell wall occupies some of the space that is normally filled with water molecules when wood swell in humid conditions (Lande *et al.* 2008). Various scientists consider wood furfurylation as an impregnation modification process, in which the properties of the furfurylated material appear more like those of a polymer-filled cell wall rather than a reacted cell wall (Rowell 2012).

When using a mitered joint and transformation of tension stress as weakness of L-type joint to the shearing ($S_{\|}$) and the normal stress ($C_{\perp}$), it is possible to control fracture of modified members of joint by increasing some mechanical properties such as $S_{\|}$ and $C_{\perp}$ (Abdolzadeh 2014). Therefore, when carrying out furfurylation and increasing its level, it is important to pay attention to the position of members under load and type of joint.

Figure 4 illustrates a comparison of mixed-mode fracture of wood, LPFA, and HPFA in the two different systems. Fracture toughness is one property of the physical nature of materials. Through examining the distributions of K_{Ic} and K_{IIc} values obtained from mixed-mode, results regarding properties of the material were achieved.

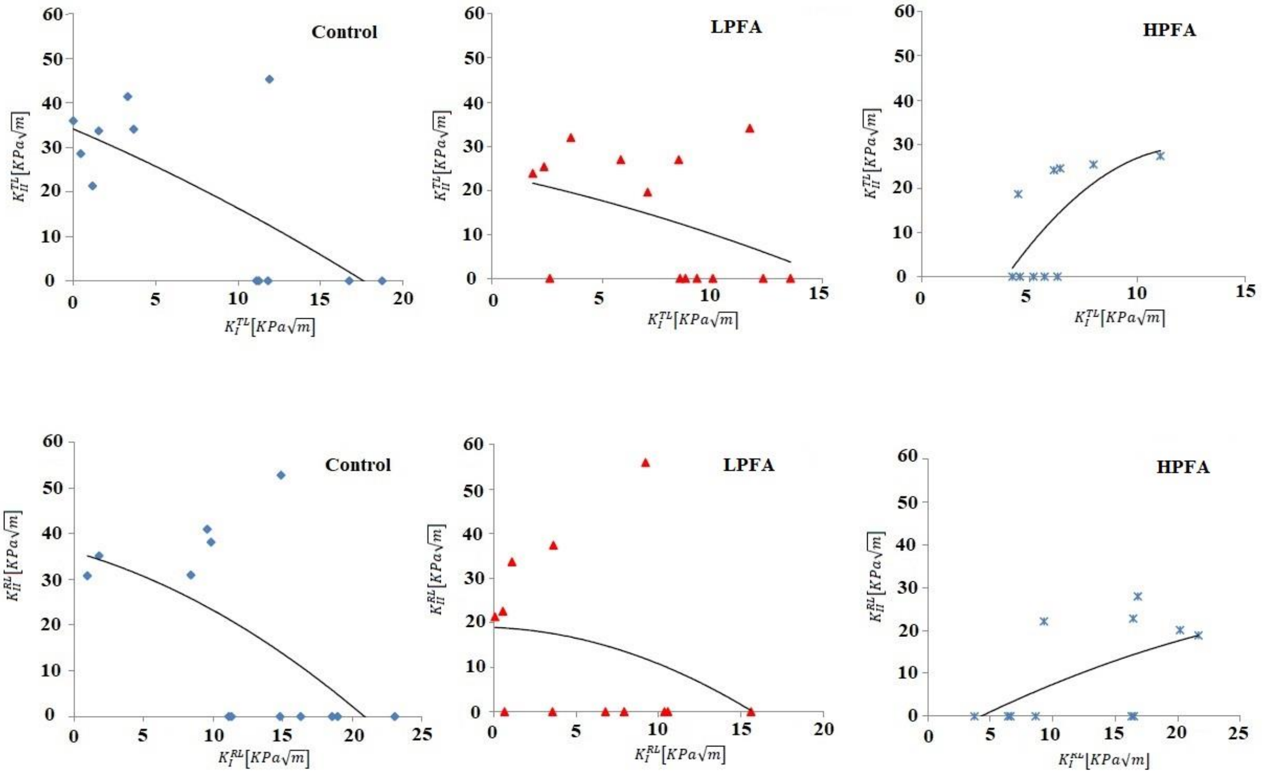
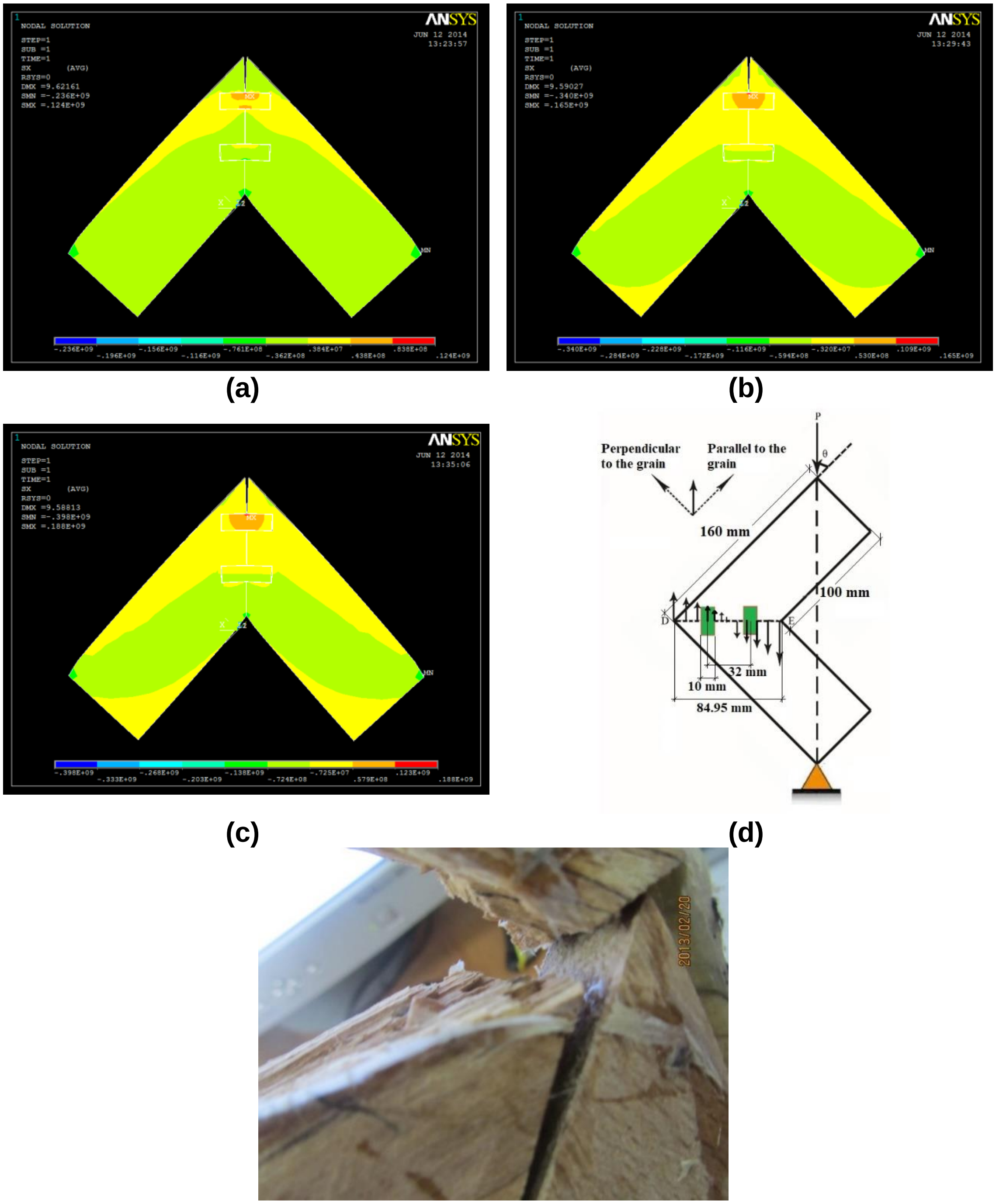


Fig. 4. Fracture level of mixed-mode of beech wood, LPFA, and HPFA on TL (First row) and RL (second row) systems

Distribution of the stress intensity factors in the control specimen is almost the same as results obtained by other researchers (Valentin and Adjanohoun 1992; Jernkvist 2001). This distribution changed in the LPFA; however, trend lines followed an almost similar trend as the control specimens. As furfurylation level increased, this trend changed completely in HPFA specimens. The main reason for value difference can be attributed to determination of the critical load at fracture.



(a) (b)

(c) (d)

(e)

Fig. 5. a) Von Mises stress in blank, b) LPFA, c) HPFA, d) Joint preparation with two dowels as connections under DC, and e) the close up of experimental results (Stress unit is Pa)

Joint Preparation Under DC

The connection close to point D (Fig. 5d) is under tension. Therefore, stress concentration is expected to be higher in this area, and $T_{\perp}$ and $S_{\parallel}$ occur in this area.

The yellow area (Figs. 5a-c) illustrates the area of tension stress. Fracture of mitered joint specimens under DC occurs in this area.

Although the members in this joint are under mixed-mode of fracture, angular position of the dowel close to the external edge relative to grain direction creates a special fracture in this area. At HPAF, the area under compression in the internal edge (*E* point) becomes smaller. This is due to the increase in $C_{\perp}$ and $C_{\parallel}$ of wood-based composites and improving the mechanical properties of composites (*e.g.*, Young's modulus increases). These results are similar to those of Jia and Fiendler (2018) and Hadi *et al*. (2022). Due to the decrease in wood toughness under mode-I, a similar trend occurs in the second dowel with an increase in furfurylation level and the resulted tension stress on top of the second dowel also accelerated the fracture. In general, in LPAF specimens, hardness is increased and K_{IC} is decreased, and this result was in line with Dong *et al*. (2015), who reported that furfurylated wood had improved hardness.

By using a stronger adhesive line, the possibility of member displacement under load decreases a little and postponing tension stress on top of the dowel close to the external edge causes an increase in joint strength under loading. Using furfurylated members and reducing the possibility of members crushing at an internal edge, the joint strength will experience a greater increase.

Model Validation

Validation of experimental results was done by simulating the amount of force proportional limit to DT and DC tests and their load-displacement curves that were recorded (Sangree and Schafer 2009). The model with high accuracy demonstrates the stress distribution of different tests and predicts the mode of fracture in wood and furfurylated members.

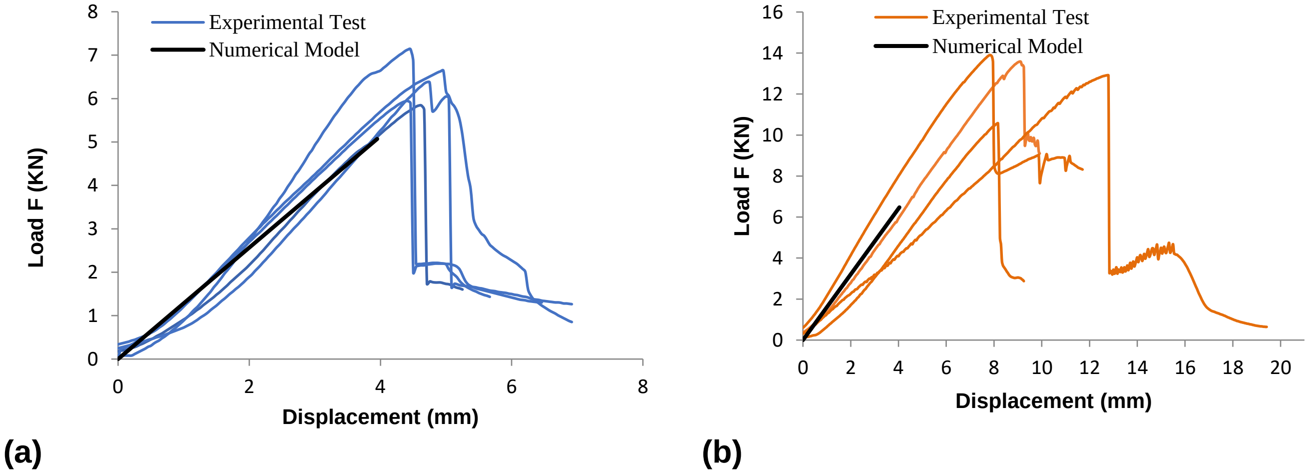


Fig. 6. Comparison of the numerical solution to the recorded experimental load deflection curve (Under DT (a), DC (b))

CONCLUSIONS

1. When chemical modification in structural applications is used, close attention to the position of members under load is important.
2. In furfurylated members, one should avoid application of tension stress perpendicular to grain as much as possible.
3. The shear strength parallel to grain of wood-based composites has a positive effect on corner joints performance under combined loading.
4. Fracture mechanics tests were used for understanding the behavior of corner joints. Moreover, they contribute to investigation of joint member fracture of beech wood and wood-based composites. The results revealed that fracture under mode I is accelerated by furfurylation.
5. Reasonable agreement under linear elastic fracture mechanics (LEFM) was obtained between experimental results and the finite element method (FEM), thereby contributing to understanding the fracture behavior and prediction of fracture mode of members under combined loading.

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