LATERAL LOAD RESISTANCE BEHAVIOR OF WOOD-PLASTIC-TO-METAL SINGLE-BOLT CONNECTIONS IN OUTDOOR FURNITURE

Fuchun Kuang

Lecturer
College of Art
Qingdao Technological University
Qingdao, China
and
Former PhD Student
College of Furniture and Industrial Design
Nanjing Forestry University
Nanjing, China
E-mail: kfc2307@163.com

Zhihui Wu

Professor
College of Furniture and Industrial Design
Nanjing Forestry University
Nanjing, China
E-mail: wzh550@sina.com

Frank Quin

Research Associate
E-mail: fq3@msstate.edu

*Jilei Zhang**†

Professor
Department of Sustainable Bioproducts
Mississippi State University
Mississippi State, MS 39762-9820
E-mail: jz27@msstate.edu

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Abstract. The lateral load resistance behavior of an unconstrained, two-member, single-bolt connection in outdoor furniture applications was investigated. The unconstrained connection consisted of a wood-plastic composite (WPC) main member fastened to a metal plate as a side member through a 6.35-mm-diameter bolt without a nut or washer used. Experimental results indicated that unconstrained WPC-to-metal single-bolt connections had a significantly higher lateral resistance load if the WPC main member is loaded in the direction perpendicular to the WPC material extrusion direction than the parallel direction. Tested connections failed with bolts having one plastic hinge bent, which occurred at the interface between the metal plate and WPC main member, accompanied by the WPC main members having a compressive yield fracture at their sides close to the metal plate, but no obvious compressive mark was observed at the opposite sides. Proposed linear and yield mechanical models were verified experimentally as a valid means for deriving estimation equations of lateral resistance loads of unconstrained WPC-to-metal single-bolt connections.

Keywords: Single-shear bolted connections, lateral load resistance, wood-plastic composites, bolt-bending moment, bolt-bearing strength, European Yield Model, yield theory.

* Corresponding author
† SWST member

INTRODUCTION

Wood-plastic composites (WPCs) are a mixture of wood (of any form) with thermosets or thermoplastics (Clemons 2002). Thermosets such as epoxy and phenolic materials are plastics that once cured, cannot be melted through heating. Thermoplastics such as high-density polyethylene (HDPE) and low-density polyethylene (LDPE) are plastics that can be repeatedly melted. In recent decades, wood-thermoplastic composites have had tremendous growth in outdoor material markets such as decking, fencing, landscape timbers, and especially in furniture applications. This is due to its unique feature of having few splits and cracks, good weather resistance, durability, resistance to insects and fungal infection, and also good work ability (Klyosov 2007).

A single-shear bolted WPC-to-metal connection is commonly used in jointing WPC structural components in outdoor furniture constructions such as park benches because it provides an effective and convenient method for furniture installation, dismantling, and repair. Knowing the lateral load resistance capacity of a single-shear bolted WPC-to-metal connection is therefore important for strength and safety design of outdoor furniture frames in WPCs. Limited studies were found which evaluated and modeled the lateral load resistance behavior of single shear WPC-to-metal bolted connections, especially with a bolt diameter equal to or less than 6.35 mm, which are the common sizes used in outdoor furniture construction.

Most previous studies (Wilkinson 1978; McLain and Thangjitham 1983; Pedersen 2002) focused on bolted connections used in timber construction. Current general equations specified in the National Design Specification for Wood Construction (AWC 2012) for bolted connections were derived based on the European Yield Model (EYM) using a mechanics-based approach with certain assumptions. Main factors considered regarding lateral resistance load capacities of a single shear one-bolt connection included bolt-hole to edge and end distances, member shear and tensile strengths, bolt-bearing strengths in member materials, bolt-bending strengths, etc.

Balma (1999) studied the lateral load resistance behavior of double-shear bolted connections constrained and unconstrained in two formulations of extruded WPCs (50 wood fibers: 50 LDPE and 70 wood fibers: 30 HDPE). Bolts used had a nominal diameter of 12.7 mm. Results indicated that the EYM-predicted yield loads of connections with an aspect ratio (main member thickness to bolt diameter) of 3 with a maximum error of 4%, but yield loads of connections with an aspect ratio of 6 were overpredicted by 15-20% because of the localized deformations at the member interfaces caused by stress concentrations.

Parsons and Bender (2004) developed a rational method with six controlling yield modes to predict the lateral load behavior of the hollow WPC sections based on the virtual displacement method. The models were validated with double-shear bolted connection tests using two WPC formulations, three wall thicknesses (10.16, 7.62, and 5.08 mm), and three dowel diameters (9.525, 6.350, and 4.763 mm). The results show that the yield model performed well with an average difference of 5.7% between theoretical and tested maximum loads.

A series of studies were performed at the Department of Sustainable Bioproducts, Mississippi State University, to investigate major factors such as bolt-hole to edge and end distances, WPC shear and tensile strengths, WPC bolt-bearing strengths, and the effect of constrained and unconstrained bolts on the lateral load resistance behavior of single shear WPC-to-metal one-bolt connections in outdoor sitting furniture applications. This paper reported results from the investigation of single shear unconstrained WPC-to-metal connections with yielding failure modes developed during connection testing. Therefore, specific objectives of this study were to 1) evaluate effects of wood fiber orientation in WPCs on bolt-bearing strength properties; 2) characterize the lateral load-deformation behavior of a single shear unconstrained WPC-to-metal one-bolt connection; 3) propose mechanical models for describing the internal force distribution in the connection at different loading stages such as the proportional limit, yield, and ultimate loads; and 4) derive equations based on proposed mechanical models for estimating lateral resistance loads at different loading stages of a single shear unconstrained one-bolt WPC-to-metal connection.

MATERIALS AND METHODS

Materials

In this study, full-sized WPC lumbers provided by Advanced Environmental Recycling Technologies, Inc., Arkansas, measured 4876.8 mm long × 137.16 mm wide × 25.4 mm thick were used. The product is a mixture of wood fiber (45-60% by weight), carbon black (less than 1% by weight), and zinc borate (1-2% by weight) in a thermoplastic matrix of polyethylene (40-50% by weight). Both from the Hillman Group (Cincinnati, OH) 6.35 mm × 69.85 mm (bolt-bearing and connection tests), and 6.35 mm × 152.4 mm (for bolt-bending test), zinc-plated standard (Society of Automotive Engineers) hex bolts purchased from a location hardware store were used in the experiment. The metal plate material was multipurpose Aluminum 6061.

Experimental Design

The general configuration of an unconstrained two-member WPC-to-metal single-bolt connection in this study is shown in Fig 1a. The unconstrained connection consisted of a WPC main member attached to a metal side member through a single bolt without a nut and washer used. The metal side member measured 223 mm long × 51.8 mm wide × 8 mm thick (Fig 1b). The effect of WPC extrusion direction on the lateral resistance load of an unconstrained WPC-to-metal connection was investigated through loading WPC members in the directions parallel and perpendicular to their material extrusion direction. Figure 2 shows the detailed configurations and dimensions of WPC members used for two evaluated directions. The diameter of a bolt connecting hole in a WPC member was 0.8 mm larger than the bolt diameter. For each of two loading directions, 30 WPC replicates were tested. Lateral load testing was performed according to ASTM (2013a).

Figure 3 shows general configurations of half-hole specimens used for evaluating the bolt-bearing strength of WPCs used in this study. For each of two orientations, parallel and perpendicular to WPC extrusion direction, 36 specimens were tested according to ASTM (2013b). The diameter of a half-hole was 7.2 mm, which was 0.8 mm larger than the bolt diameter. Bending properties of 20 randomly selected bolts were tested according to ASTM (2013c).

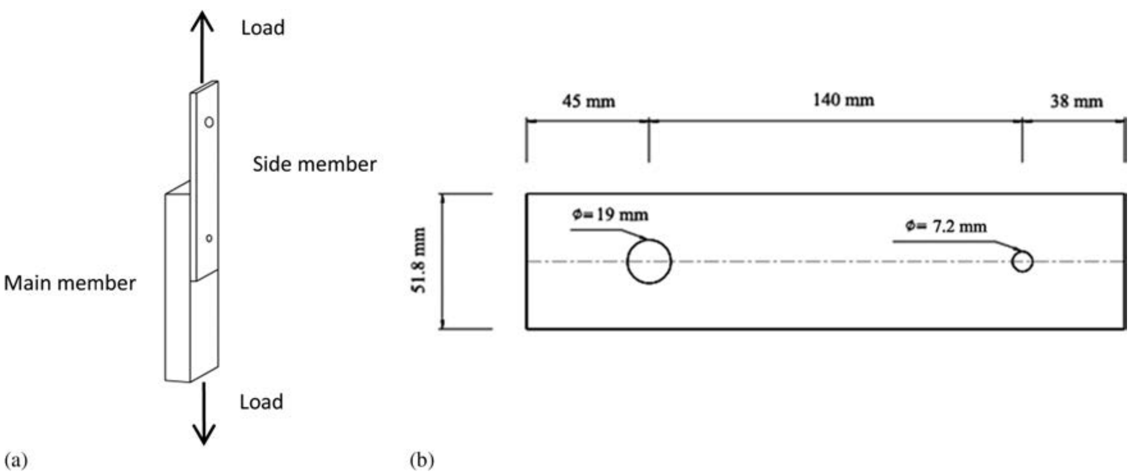


Figure 1. The general configuration of (a) an unconstrained two-member WPC-to-metal single-bolt connection and (b) detailed dimensions of a metal plate side member.

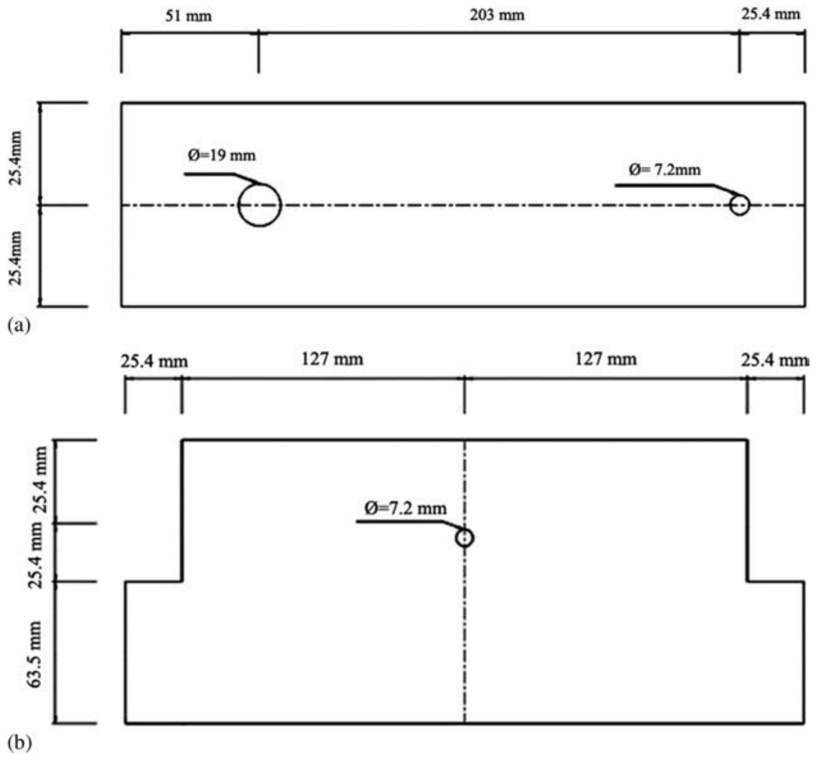


Figure 2. Basic configurations of wood-plastic composite (WPC) main members for evaluating lateral resistance loads of unconstrained WPC-to-metal single-bolt connections: (a) parallel and (b) perpendicular to WPC extrusion direction.

Specimen Preparation and Testing

All specimens for evaluating WPC mechanical properties were cut from the center piece of full-size WPC lumber as shown in Fig 4a and b, respectively. All connection specimens were cut from two end pieces as shown in Figs 4a, c, and d. Prior to testing, all specimens were conditioned in a humidity chamber controlled at 20°C ± 2°C and 50% ± 5% RH for 40 h in reference to ASTM (2010). Density and density profiles of WPC specimens cut off from connection main members were measured using Density

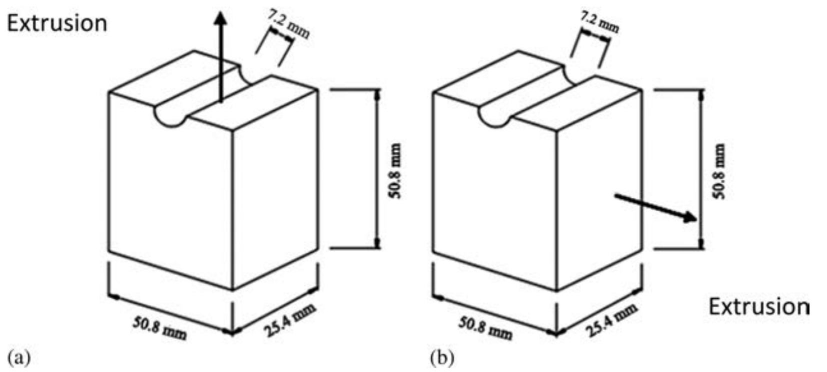


Figure 3. General configurations of half-hole specimens used for evaluating the bolt-bearing strength of wood-plastic composites (WPCs) (a) parallel and (b) perpendicular to WPC extrusion direction.

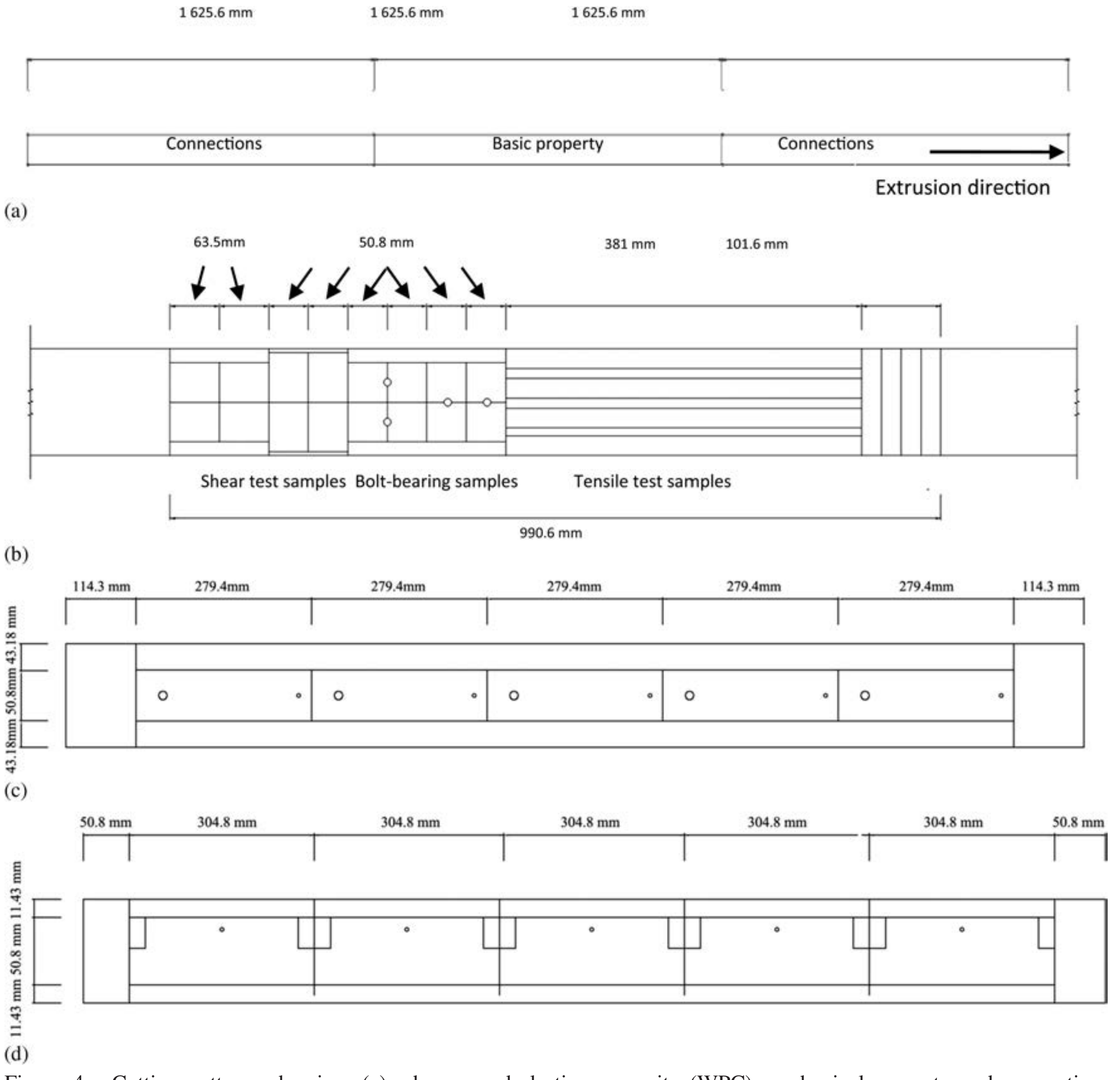
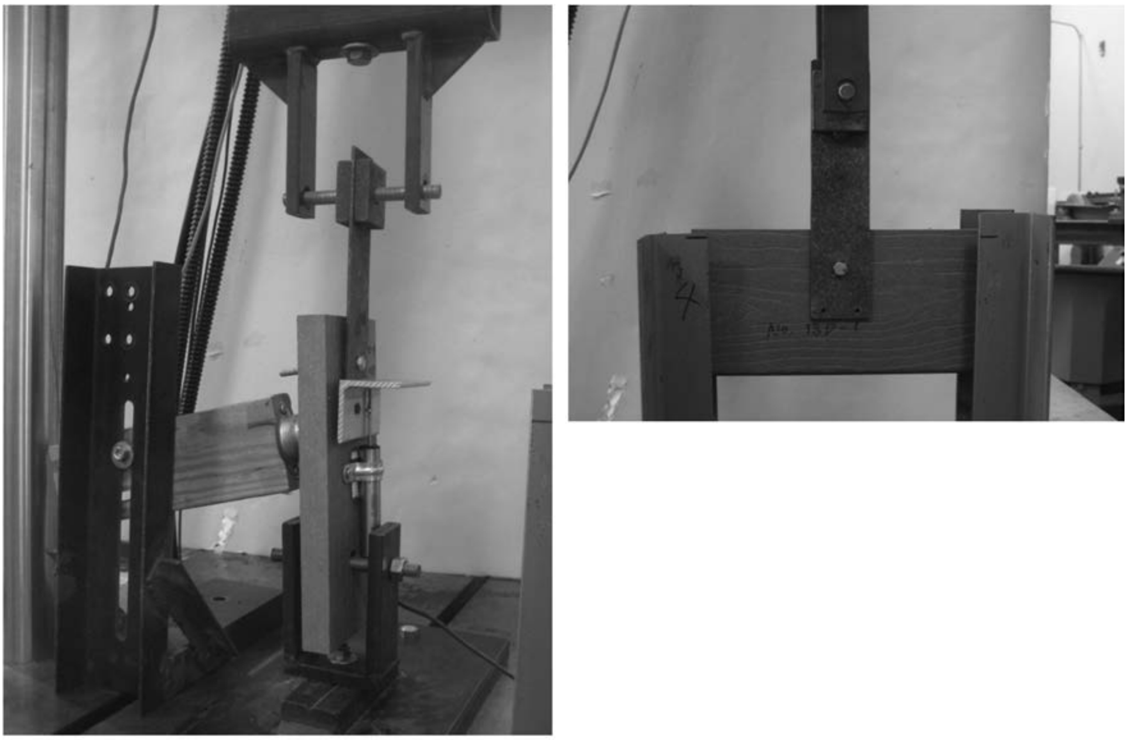


Figure 4. Cutting patterns showing: (a) where wood-plastic composite (WPC) mechanical property and connection specimens were cut from full-size WPC lumbers, (b) how WPC mechanical property specimens were cut, and how connection specimens (c) parallel and (d) perpendicular to extrusion direction were cut.

Profiler Model QDP-01X (Quintek Measurement Systems, Knoxville, TN).

All bolt-bearing, bolt-bending, and connection tests were performed on a hydraulic SATEC (Norwood, MA) universal testing machine. Figure 5 shows the setups for evaluating lateral resistance loads of unconstrained WPC-to-metal single-bolt connections. The loading speed was 1 mm/min (ASTM 2013a). One linear variable differential transformer was attached to each WPC main member by a bracket to measure connection deformation during lateral loading test. All connections were tested to failure within a 10- to 20-min range.

Figure 6 shows the setup for evaluating half-hole bolt-bearing strength properties in WPCs. The bolt was compressed into a half-hole WPC specimen with a constant rate of 1 mm/min



(a) (b)

Figure 5. Setups for evaluating lateral resistance loads of unconstrained single-bolt connections in wood-plastic composite (WPCs) (a) parallel and (b) perpendicular to machine extrusion direction.

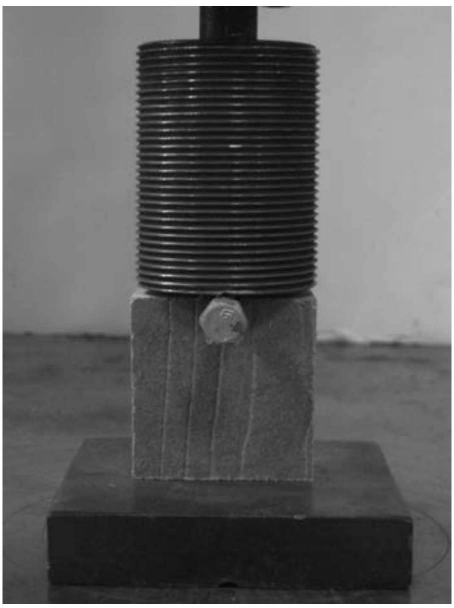


Figure 6. Setup for evaluating half-hole bolt-bearing strength in wood-plastic composites.

(ASTM 2013b). The bolt-bearing strength in WPCs can be calculated using $F_{em} = P/Dt$ (MPa), where P is the compressive load (N), D is the bolt diameter (mm), and t is the thickness of a WPC specimen (mm).

Figure 7 shows the setup for testing the bending properties of bolts used in this experiment. The center-loading bending test at a constant displacement rate of 6.35 mm/min was implemented with a span of 76.2 mm. The critical bending moments of M_{pl} at proportional limit, M_y at yield point, and M_{ult} at ultimate point were calculated using $M = P_b S_{bp}/4$ (N·mm), where P_b is the test bending load at each critical point as determined from load-deformation curves (N); S_{bp} is the span between two supports (ASTM 2013c) (mm); D is the bolt diameter (mm).

Load-deformation curves and failure modes of all tested specimens mentioned previously were recorded. The yield load of a tested

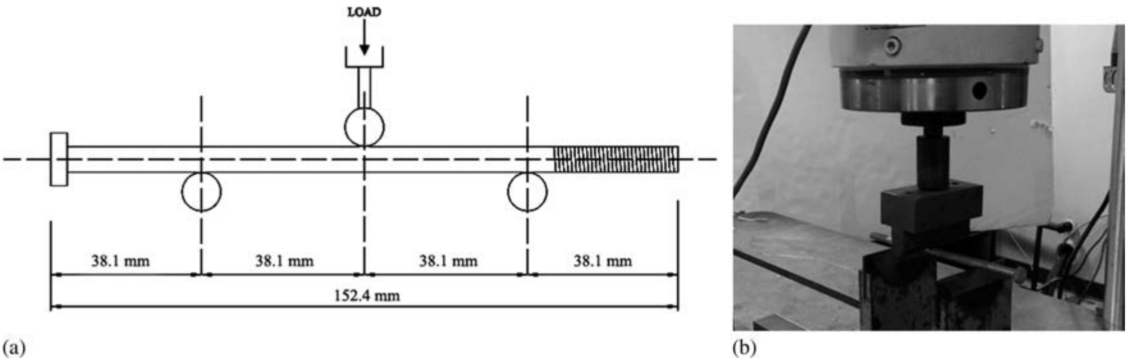


Figure 7. Setup for evaluating bending strength properties of bolts used in this study: (a) detailed dimensions and (b) actual setup.

specimen is determined through fitting a straight line to the initial linear portion of the load-deformation curve recorded, offsetting this line by a deformation equal to 5% of the bolt diameter.

RESULTS AND DISCUSSION

Bolt-bearing and Bending Properties

WPC density averaged 999 kg/m^3 (with a specific gravity of 1.00) with its coefficient of variation (COV) at 1.1% across its thickness. Figure 8 indicated that the wood fibers in WPCs evaluated in this study were oriented in the extrusion direction, ie along the WPC lumber length direction. The bolt-bending moment at proportional limit, M_{pl}, averaged 29.8 N·mm with its COV at 1.3%. The bolt yield bending moment averaged 32.6 N·mm with its COV value at 1.1%. The bolt ultimate bending moment averaged 41.5 N·mm with its COV value at 1.6%.

Table 1 summarizes mean values of bolt-bearing strength in WPCs, including the values at proportional limit, $F_{em,\ pl}$; at yield point, $F_{em,\ y}$; and at ultimate point, $F_{em,\ ult}$, respectively. The ultimate bolt-bearing strength in WPC parallel to the extraction direction was 43.33 MPa, which is similar to the magnitude of 43.09 MPa for 6.35-mm bolt bearing in wood (with a specific gravity of 0.56) parallel to grain listed in AWC

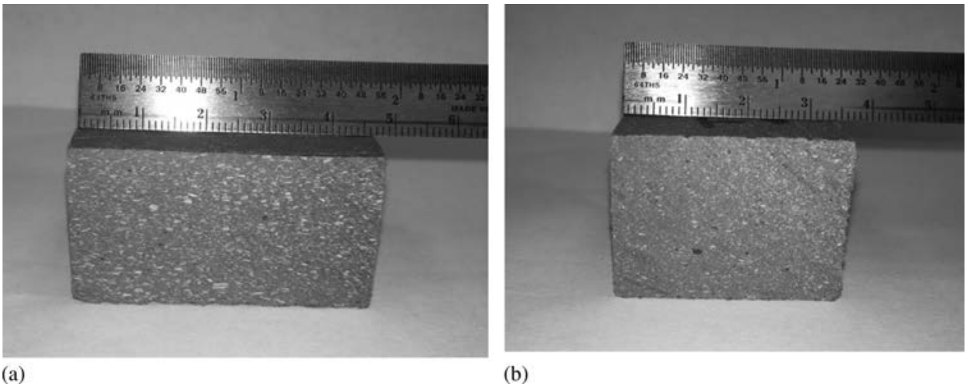


Figure 8. Cross sections of wood-plastic composite (WPC): (a) material cut parallel to extraction direction showing wood fibers parallel to extrusion direction and (b) material cut perpendicular to extrusion direction showing perpendicular to extrusion direction.

Table 1. Mean values of bolt-bearing strength properties in wood-plastic composites.[a]

Loading direction	Proportional limit, $F_{em, pl}$	Yield, $F_{em, y}$	Ultimate, $F_{em, ult}$
	MPa		
Parallel	27.36 (5.5) B	34.25 (5.3) B	43.33 (6.1) B
Perpendicular	29.41 (6.5) A	36.52 (4.1) A	54.69 (8.3) A

[a] Means in each column not followed by a common letter are significantly different from one another at the 5% significance level. Values in parentheses are coefficients of variation in percentage.

(2012). The ultimate bolt-bearing strength in WPC perpendicular to the extraction direction was 54.69 MPa, which is higher than the highest listed value of 53.43 MPa for 6.35-mm bolt bearing in wood (with a specific gravity of 0.73) perpendicular to grain in AWC (2012).

Mean comparisons between two values within each strength value column were performed at the 5% significance level. Mean comparison results indicated that in general, bolt-bearing strengths in the direction perpendicular to the WPC extrusion direction were significantly higher than those in the parallel direction. This observation is different from the general trend observed in bolt bearing in wood (AWC 2012), ie in general, the bolt-bearing strength in wood parallel to grain orientation is higher the perpendicular one.

Figure 9 is a typical load-deformation curve of bolt-bending strength tests. Figure 10 is a typical load-deformation curve of bolt-bearing strength tests in WPCs. Figure 11 shows typical failure modes observed in bolt-bearing tests. In general, a typical compressive fracture mode occurred in both WPC specimens loaded in the directions parallel and perpendicular to the extrusion direction.

Bolted Connections

Figure 12 shows a typical load-deformation curve of an unconstrained WPC-to-metal single-bolt connection. A linear region is clearly observed before the 5% bolt diameter offset yielding point, and there is a yield region before the lateral load reaches its ultimate value. Figure 13 shows typical failure modes of tested connections observed when the lateral load passed its ultimate value point. In general, all connections failed with WPC material beneath the bolt compressively fractured at the main member side close to the metal plate (Fig 13a) and barely compressed at the opposite side (Fig 13b), accompanied with a bent bolt (Fig 13c), ie one plastic hinge was developed at the interface between the metal plate and WPC main member. The failure modes of compressive fracture of the WPC main member and the bent bolt implied that the bolt and main member have yielded completely. In addition, if the applied testing load passed its ultimate

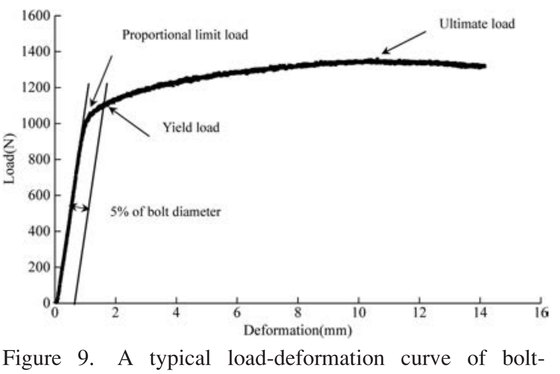


Figure 9. A typical load-deformation curve of bolt-bending tests.

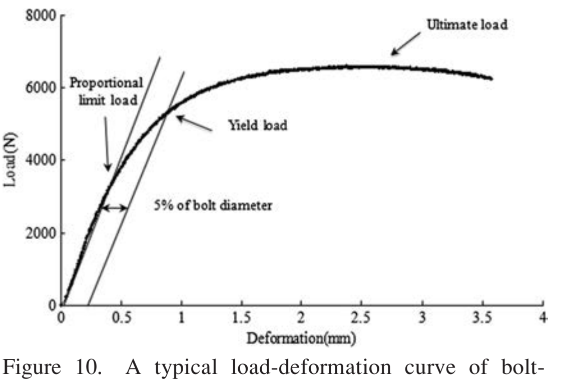
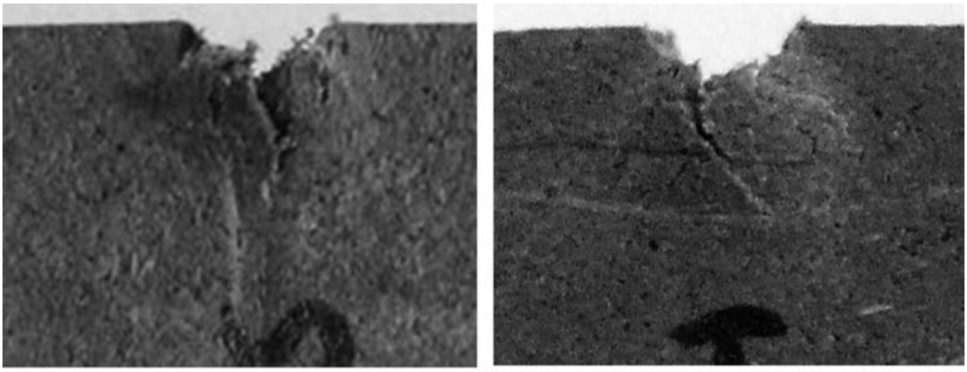


Figure 10. A typical load-deformation curve of bolt-bearing tests.



(a) (b)

Figure 11. Typical failure modes observed in bolt-bearing tests in wood-plastic composite (WPCs): bearing load (a) parallel and (b) perpendicular to WPC extrusion direction.

value for an extensive time, some degree of compressive fracture can be observed at the opposite side. The failure mode observed at the opposite side indicated that the material that was compressed beneath the bolt could still be in the elastic range and with its limit reaching to the material yield point. This failure mode observation can govern our assumption on internal force distribution at the region close to the opposite side, ie the internal force distribution assumed at the region in compression was still in its elastic range instead of full plastic yield assumed in EYM (AWC 2012) calculations.

Table 2 summarizes mean lateral resistance load values of unconstrained WPC-to-metal single-bolt connections at proportional limit, yield, and ultimate points. Mean comparisons performed at the 5% significance level indicated that in general

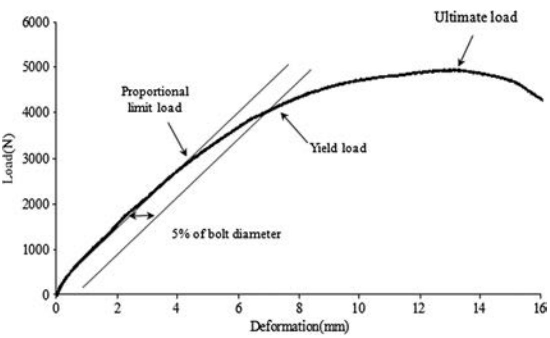


Figure 12. A typical load-deformation curve of bolted connections.

unconstrained WPC-to-metal single-bolt connections evaluated in this study had significantly higher lateral resistance loads if the WPC main members were loaded in the direction perpendicular to the WPC extrusion direction than the parallel ones. The average lateral resistance loads perpendicular to the extrusion direction at proportional limit, yield, and ultimate points were 6.71%, 4.65%, and 15.83% higher than their corresponding loads parallel to extrusion, respectively.

Lateral Resistance Load Estimation Equations

Linear model. Figure 14a shows the linear mechanical model proposed in this study to derive equations for prediction of the lateral resistance load of unconstrained WPC-to-metal single-bolt connections at proportional limit, including a free-body diagram of the portion of a bolt in the main member (Fig 14b). The assumptions are that 1) WPC material in compression beneath the bolt is in its elastic range since no obvious nonrecoverable deformation was observed at this stage during connection testing; 2) the compression end close to the metal plate, point A, just reaches its bolt-bearing strength at proportional limit, $F_{em,\ pl}$, ie the unit proportional limit bolt-bearing load at point A, $q_{m,\ A,\ pl} = F_{em,\ pl}\ D$ (N/mm); and 3) the bolt bends in its elastic range, just reaches its bending moment, M_{pl} (N·mm), at proportional limit, and remains in static equilibrium. Based on the geometric relationship, the bearing unit load at point B, $q_{m,\,B}$ (N/mm), can be derived as follows:

$$\frac{q_{m,\,B}}{q_{m,\,A,\,pl}} = \frac{a}{l-a}$$

$$q_{m,\,B} = \frac{q_{m,\,A,\,pl}a}{l-a}$$

where l is the thickness (mm) of the WPC main member and a is the length (mm) of the compressed portion beneath the bolt which is close to end B of the WPC member.

Summarizing all forces (Fig 14b) in the vertical direction, F_V, to zero yields the following equation for calculation of the proportional limit shear force, V_{pl} (N), at point A of the bolt:

$$\sum F_V = 0$$
$$V = \frac{q_{m,\,A,\,pl}(l-a)}{2} - \frac{q_{m,\,A,\,pl}a^2}{2(l-a)} \quad (1)$$

Summarizing all moments (Fig 14b), M, to zero at pivot point A yields the following equation:

$$\sum M = 0$$
$$M_{pl} = \frac{q_{m,\,A,\,pl}a^2}{6} - \frac{q_{m,\,A,\,pl}al - \frac{1}{3}q_{m,\,A,\,pl}a^2}{2(l-a)} - \frac{q_{m,\,A,\,pl}al}{3} + \frac{q_{m,\,A,\,pl}l^2}{6}$$
$$-q_{m,\,A,\,pl}a^3 + 3q_{m,\,A,\,pl}a^2l + q_{m,\,A,\,pl}a^2 - 3q_{m,\,A,\,pl}al^2 - 3q_{m,\,A,\,pl}al + 6M_{pl}a + q_{m,\,A,\,pl}l^3 - 6M_{pl}l = 0$$
$$k_1a^3 - k_6a^2 + k_7a - k_5 = 0 \quad (2)$$

where $k_1 = q_{m,\,A,\,pl}$; $k_2 = 3q_{m,\,A,\,pl}$; $k_3 = 3q_{m,\,A,\,pl}l^2$; $k_4 = 6M_{pl}$; $k_5 = (q_{m,\,A,\,pl}l^3 - 6M_{pl}l)$; $k_6 = k_1 + k_2$; $k_7 = k_2 + k_3 - k_4$.

Solving Eq 2 yields the solution for a value:

$$a = \frac{k_6 - \sqrt[3]{X_1} - \sqrt[3]{X_2}}{3k_1}$$

where $X_{1,2} = -k_6A + 3k_1\left(\frac{-B \pm \sqrt{B^2 - 4AC}}{2}\right)$; $A = k_6^2 - 3k_1k_7$; $B = 9k_1k_5 - k_6k_7$; $C = k_7^2 + 3k_5k_6$; $k_6 = (k_1 + k_2)$; $k_7 = (k_2 + k_3 - k_4)$

Substituting a into Eq 1 yields the following equation for calculating the lateral resistance load of unconstrained WPC-to-metal single-bolt connections at proportional limit:

$$V_{pl} = \frac{q_{m,\,A,\,pl}\left(l - \frac{k_6 - \sqrt[3]{X_1} - \sqrt[3]{X_2}}{3k_1}\right)}{2} - \frac{q_{m,\,A,\,pl}\left(\frac{k_6 - \sqrt[3]{X_1} - \sqrt[3]{X_2}}{3k_1}\right)^2}{2\left(l - \frac{k_6 - \sqrt[3]{X_1} - \sqrt[3]{X_2}}{3k_1}\right)} \quad (3)$$

Table 2 shows predicted lateral resistance loads at proportional limit using Eq 3 and ratios of predicted lateral loads to their corresponding tested values. Ratio values that range from 1.06 to 1.07 indicate that the prediction Eq 3 derived from the linear mechanical model reasonably estimates the lateral resistance load of unconstrained WPC-to-metal connections, but tends to overestimate lateral resistance loads. This would be because the bolt-bending moment used in the equation, M_{pl}, was higher than the actual value of the bending moment existing at point A when the lateral resistance load of unconstrained connections reached its proportional limit value. Predicted lateral resistance loads were calculated with Eq 3 using reduced moment values in terms of different percentage

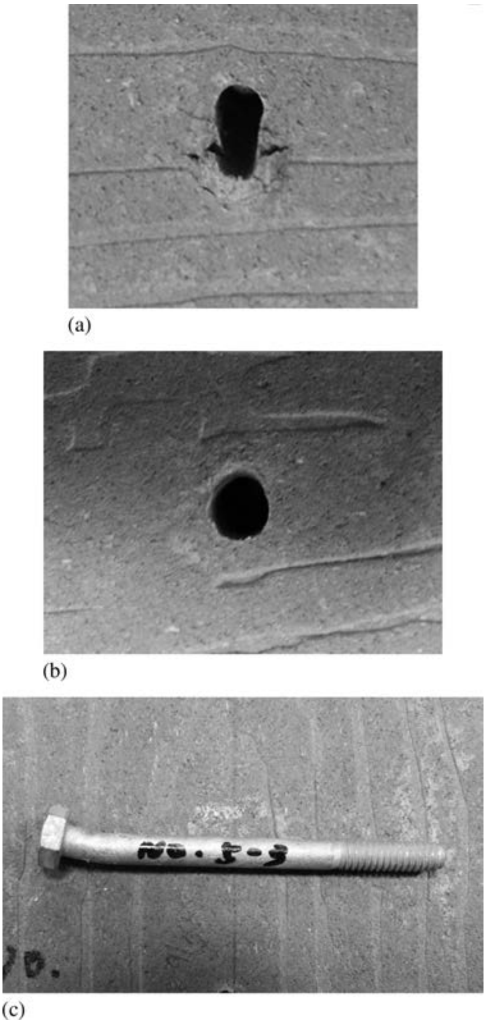


Figure 13. Typical failure modes of unconstrained wood-plastic composite (WPC)-to-metal single-bolt connections: (a) material compressively fractured at the end closest to the metal plate, (b) material barely compressed at the end away from the metal plate, and (c) bolt bent at the end closest to the metal plate.

values of M_{pl} and are plotted in Fig 15, which indicates that the difference decreased as the moment value reduced, and the difference was reduced to 1% when the moment value was set at the 70% of M_{pl}.

Yield model. Figure 16a shows the mechanical model proposed to derive equations for prediction of lateral resistance loads of unconstrained WPC-to-metal single-bolt connections at yield and ultimate points, including a free-body diagram of the portion of a bolt in the WPC main member (Fig 16b), where q_m is the unit bolt-bearing load (N/mm), $q_{m,\ B}$ is the unit bolt-bearing load at point B (N/mm), of the shear force, V_A is the shear force (N) at point A of the bolt, and M_A is the bending moment (N·mm) at point A of the bolt.

For yield load prediction, the assumptions are that 1) the WPC material above the bolt at the end close to the metal plate is compressed in its plastic deformation range and the compressed section AC reaches to its bolt-bearing strength at 5% yield point, $F_{em,\ y}$, ie the unit bolt-bearing 5% yield load $q_{m,\ y} = F_{em,\ y} \times D$ (N/mm); 2) the compressed surface of the WPC material along the hole beneath the bolt at the opposite end is in its elastic range and point B just reaches its unit bolt-bearing load, $q_{m,\ B,\ pl} = F_{em,\ pl} \times D$ (N/mm) at proportional limit; and 3) the bending moment in the bolt at point A just reaches its yield point, $M_{A,\ y}$ (N·mm).

For ultimate load prediction, the assumptions are that 1) the WPC material above of the bolt close to the metal plate end is compressed in its plastic deformation range and the compressed

Table 2. Mean summary and comparisons of tested values of lateral resistance loads of single-shear bolted connections at proportional limit, yield, and ultimate loads, and their corresponding predicted values.[a]

	Proportional limit			Yield			Ultimate		
	Tested	Predicted		Tested	Predicted		Tested	Predicted	
Loading direction	N		Ratio	N		Ratio	N		Ratio
Parallel	2057 (5.4) B	2189	1.06	3204 (5.2) B	3248	1.01	3883 (7.1) B	3871	0.99
Perpendicular	2195 (4.8) A	2351	1.07	3353 (5.1) A	3408	1.02	4498 (5.9) A	4517	1.00

[a] Means in each column not followed by a common letter are significantly different from one another at the 5% significance level.
Values in parentheses are coefficients of variation in percentage.

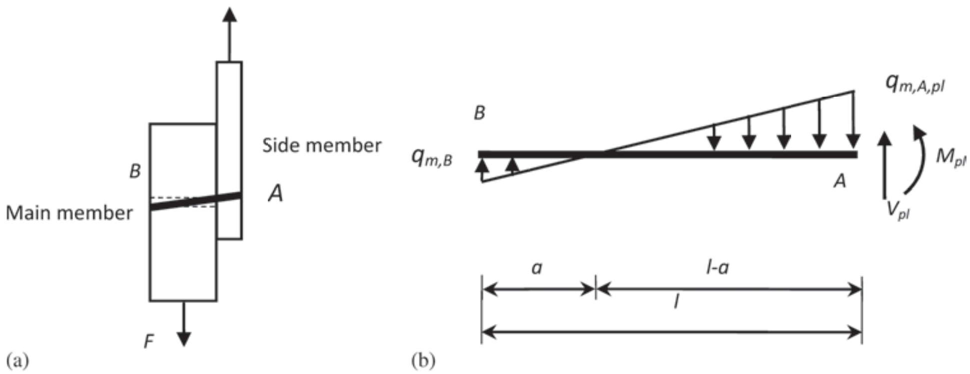


Figure 14. The mechanical model of (a) an unconstrained wood-plastic composite (WPC)-to-metal single-bolt connection and (b) a free-body diagram of the portion of a bolt in the WPC main member.

section AC reaches its bolt-bearing strength at ultimate point, $F_{\mathrm{em,\ ult}}$, ie the unit bolt-bearing ultimate load, $q_{\mathrm{m,\ ult}} = F_{\mathrm{em,\ ult}} \times D$ (N/mm); 2) the compressed surface above the bolt at the opposite end is its elastic range and point B just reaches its unit bolt-bearing 5% yield load, $q_{\mathrm{m,\ B,\ y}} = F_{\mathrm{em,\ y}} \times D$ (N/mm); and 3) the bending moment in the bolt at point A just reaches its yield point, $M_{\mathrm{A,\ y}}$.

Summarizing all forces (Fig 16b) in the vertical direction, F_{V}, to zero, yields the following equation for calculation of the shear force, V_{A} (N), at point A of the bolt:

$$\sum F_{\mathrm{V}} = 0$$
$$V_A = \mathrm{q_m}(l-a) - \frac{\mathrm{q_{m,\ B}}a}{2} \tag{4}$$

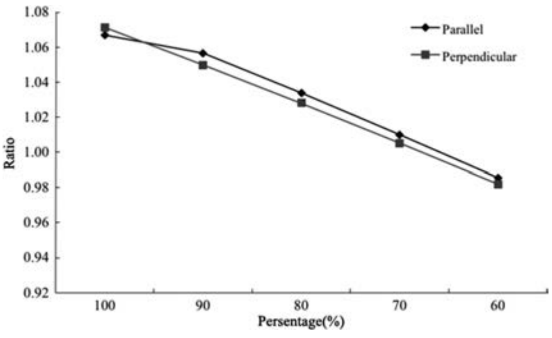


Figure 15. Ratios of predicted-to-tested values of lateral resistance loads of unconstrained wood-plastic composite (WPC)-to-metal single-bolt connections as a function of bending moment in the bolt, in terms of the percentage of its value at proportional limit.

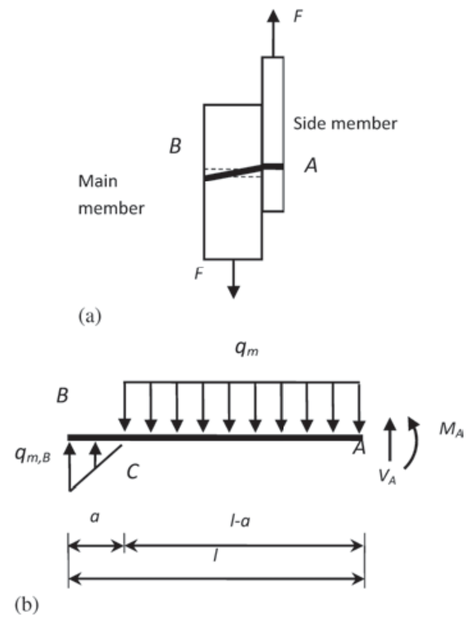


Figure 16. The mechanical model of (a) an unconstrained wood-plastic composite (WPC)-to-metal single-bolt connection and (b) a free-body diagram of WPC main member subjected to lateral loads passing yield point.

Summarizing all moments (Fig 16b), M, to zero at pivot point A yields the following equation:

$$\sum M = 0$$

$$M_A = \frac{q_m(1-a)^2}{2} - \frac{q_{m,B}a\left(1-\frac{a}{3}\right)}{2}$$

$$\left(\frac{q_{m,B}}{6}+\frac{q_m}{2}\right)a^2-\left(\frac{q_{m,B}l}{2}+q_m l\right)a+\frac{q_m l^2}{2}-M_A=0$$

$$k_1a^2 - k_2a + k_3 = 0 \qquad (5)$$

where $k_1 = \frac{q_{m,B}}{6}+\frac{q_m}{2}$, $k_2 = \frac{q_{m,B}l}{2}+q_m l$, $k_3 = \frac{q_m l^2}{2} - M_A$.

Solving the Eq 5 yields the following solution for a:

$$a = \frac{k_2 - \sqrt{k_2{}^2 - 4k_1k_3}}{2k_1}$$

Substitution of the value, a, into the Eq 4 yields the following equation for calculation of the lateral resistance load of an unconstrained WPC-to-metal single-bolt connection at yield and ultimate loads.

$$V_A = q_m\left(l - \frac{k_2 - \sqrt{k_2{}^2 - 4k_1k_3}}{2k_1}\right) - \frac{q_{m,B}\dfrac{k_2 - \sqrt{k_2{}^2 - 4k_1k_3}}{2k_1}}{2} \qquad (6)$$

Therefore, the lateral resistance load of an unconstrained WPC-to-metal single-bolt connection at yield point, $V_{A,y}$, can be estimated with substitution of $q_{m,B} = q_{m,B,pl}$, $q_m = q_{m,y}$, and $M_A = M_{A,y}$ into Eq 6. For the ultimate lateral load, $V_{A,ult}$, the substitution of $q_{m,B} = q_{m,B,y}$, $q_m = q_{m,ult}$, and $M_A = M_{A,y}$ into Eq 6, yields its estimated value.

Table 2 shows predicted lateral resistance loads of unconstrained WPC-to-metal single-bolt connections at yield and ultimate loads using Eq 6. Ratio values of 1.01 to 1.02 for yield loads, and 0.99 to 1.00 for ultimate loads, indicate that the prediction Eq 6 derived from the proposed yield model can estimate lateral resistance loads of unconstrained WPC-to-metal single-bolt connections at yield and ultimate points reasonably well.

CONCLUSIONS

Experimental results indicate that a tested WPC-to-metal connection has a significantly higher lateral resistance load if the WPC main member is loaded in the direction perpendicular to WPC material extruded direction than the parallel one. The average lateral resistance loads perpendicular to the extrusion direction at proportional limit, yield, and ultimate loads were 6.71%, 4.65%, and 15.83% higher than those parallel to the extrusion direction, respectively. It was observed that tested connections failed with bolts having one plastic hinge bend developed at the interface between metal plate and WPC main member, accompanied by WPC main members having a compressive yield fracture at their sides close to the metal plate, but no obvious compressive mark was observed at opposite sides.

Proposed linear and yield mechanical models based on connection failure modes observed were verified experimentally as a valid means for deriving estimation equations of lateral resistance loads of unconstrained WPC-to-metal single-bolt connections evaluated in this study. These derived prediction equations can be used only for the connections constructed with the same bolt and WPC materials used in this study. Further validation is required if they are used for general applications.

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REFERENCES

American Society for Testing and Materials (ASTM) (2010) Standard specification for establishing performance ratings for wood-plastic composite deck boards and guardrail systems (guards or handrails). D7032-10. American Society for Testing and Materials, West Conshohocken, PA.

American Society for Testing and Materials (ASTM) (2013a) D 5652-95. Standard test methods for bolted connections in wood and wood-based Products. American Society for Testing and Materials, West Conshohocken, PA.

American Society for Testing and Materials (ASTM) (2013b) Standard test method for evaluating dowel-bearing strength of wood and wood-based products. D5764-97. American Society for Testing and Materials, West Conshohocken, PA.

American Society for Testing and Materials (ASTM) (2013c) Standard test method for determining bending yield moment of nails. F1575-03. American Society for Testing and Materials, West Conshohocken, PA.

American Wood Council (AWC) (2012) National design specification for wood construction with commentary. American Wood Council, Leesburg, VA.

Balma DA (1999) Evaluation of bolted connections in wood plastic composites. Master thesis, Washington State University, Pullman, WA. 76 pp.

Clemons C (2002) Wood-plastic composites in the United States-the interfacing of two industries. Forest Prod J 52(6):10-18.

Klyosov AA (2007) Wood-plastic composites. John Wiley & Sons. Inc., Hoboken, NJ. pp. 202-224.

McLain TE, Thangjitham S (1983) Bolted wood-joint yield model. J Struct Eng 109(8):1820-1835.

Parsons WR, Bender DA (2004) Energy-based design of dowel connections in wood-plastic composites hollow sections. J Struct Eng 130:681-689.

Pedersen MU (2002) Dowel type timber connections strength modeling. Technical University of Denmark, Kongens Lyngby, Denmark.

Wilkinson TL (1978) Strength of bolted wood joints with various ratios of member thickness. Research Paper FPL 311, FPL-FS/USDA, Madison, WI.