Static Lateral Load Capacity of Extruded Wood-plastic Composite-to-metal Single-bolt Connections, Considering Failure at the Ends

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The effect of the end distance was studied relative to the static ultimate lateral load capacity of a single-shear unconstrained wood-plastic-composite-to-metal single-bolt connection (SUWSC). Equations estimated the static ultimate lateral loads of the SUWSCs that failed during the end tear-out, splitting, and yield modes and were obtained using stress concentration factor regression- and mechanics-based approaches. The experimental results showed that the stress concentration factor was a linear function of the end-distance to bolt-diameter ratio for the SUWSCs that failed during end tear-out and splitting modes. The static ultimate lateral loads of the SUWSCs that failed during the yield modes were estimated using a mechanics-based equation. The minimum end distance for the SUWSCs that failed without end fracture (*i.e.*, only with yield mode) was 25.4 mm, which was four times larger than the bolt diameter.

Keywords: Single-shear bolted connections; Wood-plastic composites; End tear-out, Splitting, Shear strength; Tensile strength; Stress concentration factor

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INTRODUCTION

Wood-plastic composites (WPCs) are a mixture of any form of wood with thermosets or thermoplastics (Clemons 2002). Thermosets, such as epoxy and phenolic materials, are plastics that cannot be melted through heating once they are cured. Thermoplastics, such as high-density polyethylene and low-density polyethylene, are plastics that can be repeatedly melted. Recently, wood-thermoplastic composites have had tremendous growth in outdoor material markets such as decking, fencing, landscape timbers, and especially furniture applications.

A single-shear bolted WPC-to-metal connection is commonly used when jointing WPC structural components in outdoor furniture constructions, such as park benches. Such a connection is used because it provides an effective and convenient method for furniture installation, dismantling, and repair. Therefore, knowing the lateral load resistance capacity of a single-shear bolted WPC-to-metal connection is important for the strength and safety design of outdoor furniture that use WPCs as frame stocks.

Common failure modes of a single-shear metal-to-wood (or wood-based composite) single-bolt connection when subjected to a lateral load could include four different types: yield, tear-out, splitting, and net cross-section, as shown in Fig. 1 (Wang *et al.* 2017).

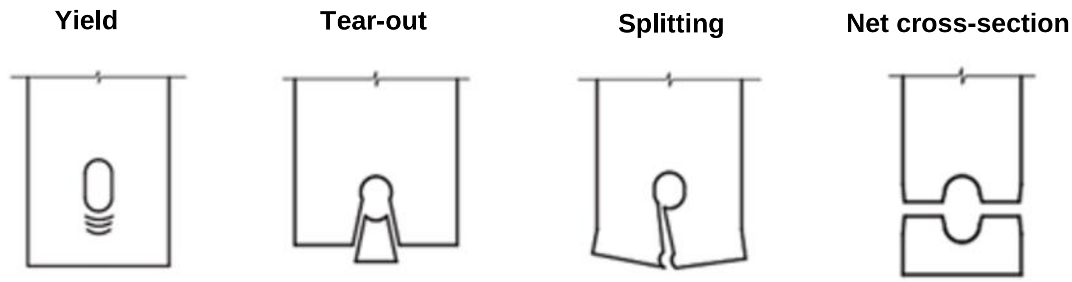


Fig. 1. Four types of failure modes commonly seen in a single-shear metal-to-wood or wood-based composite single-bolt connection

In general, the prediction equations for the lateral load of a single-shear metal-to-wood (or wood-based composite) single-bolt connection that failed with yield modes were obtained based on the European Yield Model (Johansen 1949; Wilkinson 1978; Blass 1995; ANSI/AISC 2010; AWC 2012; Kuang *et al.* 2017; Yu *et al.* 2017). Fundamentally, the mechanics-based approach was used with certain assumptions to calculate the equations by considering the bolt moment resistance and bolt-bearing resistance main member materials as main factors.

For the connections that failed during the fracture modes, such as tear-out, splitting, and net cross-section, the stress distribution (*i.e.*, stress concentration) that occurred at the shear section or tension cross-section caused by the bolt hole was complex at the point where the connection lateral resistance load capacity reached its ultimate value. The mechanics of the materials approach could not predict the high values of stress that existed in these failure components. The stress in these regions can in some cases be analyzed by applying the theory of elasticity, but it is more usual to rely on the experimental approach (Ugural and Fenster 1995) through the introduction of a stress concentration factor as shown in Eq. 1 below,

$$K = \frac{Maximum\ stress}{Nominal\ stress} \tag{1}$$

where K is the stress concentration factor and the nominal stress is the stress that would exist in the section in question in the absence of a geometric feature (*e.g.*, holes) causing the stress concentration. The main factors considered regarding the lateral load capacity of a single-shear bolt connection that failed in fracture modes included the strength properties of connection member materials such as shear strength, tensile strength, and member geometry including bolt hole-to-edge and end distances, hole-diameter, bolt-diameter, *etc*.

Limited literature was found regarding the evaluation and modeling of lateral load capacity of single-shear WPC-to-metal bolted connections that failed its fracture modes, such as end tear-out, splitting, *etc*., especially with a bolt diameter ≤ 6.35 mm, which is the common size used in outdoor furniture construction. Wang *et al.* (2017) investigated when the connections failed mainly in fracture modes when the main members of the connections were made from steel materials. Wang *et al.* (2017) investigated the effects of end distance, edge distance, and steel grade on the lateral load of single-shear one-bolt high strength steel connections that failed in fracture modes and discovered that there was a linear relationship between the stress concentration factor and the end-distance to the bolt-hole-diameter ratio using a regression analysis approach. Kim and Yura (1999) investigated the effects of the end distance, spacing, and steel strength on the bearing strength of one-bolt and two-bolt lap connections, and they concluded that the stress concentration factor of these connections is a fixed value. Duerr (2006) experimentally evaluated the strength of pinned connections that failed in tear-out, splitting, and net cross-section modes, and he concluded that the stress concentration factor of the connections is a quadratic function of the edge-distance to bolt-diameter ratio.

A series of studies were performed at the Department of Sustainable Bioproducts at Mississippi State University (Mississippi State, MS, USA) to investigate both the edge and end distances, the WPC shear and tensile strengths, and the bolt-bearing strengths in WPC materials on the static lateral load capacity of a single-shear unconstrained WPC-to-metal single-bolt connection (SUWSC) in outdoor seating furniture applications. Kuang *et al*. (2017) reported the results from investigating the SUWSCs that failed mainly with yielding failure modes. This paper reported the results from investigating the SUWSCs that mainly failed in fracture modes such as end tear-out and end splitting. Therefore, specific objectives of this study were to evaluate the shear strength of WPC materials parallel to the WPC extrusion direction, the tensile strength of WPC materials perpendicular to the WPC extrusion direction, the effect of the end distance on the static ultimate lateral load capacity of the SUWSCs, and to derive estimation equations for the ultimate lateral load of the SUWSCs.

EXPERIMENTAL

Materials

The commercial WPC lumber used in this study was provided by Advanced Environmental Recycling Technologies, Inc. (Springdale, AR, USA). The full-sized WPC lumber measured 4876.8 mm × 137.16 mm × 25.4 mm (length × width × thickness). The product was a mixture of wood fiber (45 wt% to 60 wt%), carbon black (< 1 wt%), and zinc borate (1 wt% to 2 wt%) in a thermoplastic matrix of polyethylene (40 wt% to 50 wt%). The ultimate bolt-bearing strength in the WPC lumber parallel to its extraction direction ($F_{em,\ ult}$) was 43.33 MPa (Kuang *et al.* 2017). The zinc-plated standard (SAE International, Warrendale, PA, USA) hex bolts (The Hillman Group, Cincinnati, OH, USA) measured 6.35 mm × 69.85 mm and were purchased from a local hardware store. The metal plate material was multipurpose Aluminum 6061 (Midwest Steel Supply, Rogers, MN, USA).

Experimental Design

Bolt connections

Figure 2a shows the general configuration of a SUWSC used in this study. The SUWSC consisted of a WPC main member attached to a metal side member through a single bolt without use of a nut and washer. The metal side member measured 223 mm × 51.8 mm × 8 mm (length × width × thickness) (Fig. 2b) and the bolt hole was 0.8 mm larger than the bolt diameter.

A complete one-factor factorial experiment with ten replications per combination was conducted to evaluate the effects of the end distance on the static ultimate lateral load of the SUWSCs that were parallel to the WPC extrusion direction of the main members.

The end distance (Fig. 2c) had six levels: 9.5 mm, 12.7 mm, 15.9 mm, 19.1 mm, 22.2 mm, and 25.4 mm, which were 1.5 times, 2 times, 2.5 times, 3 times, 3.5 times, and 4 times larger than the 6.4 mm bolt diameter, respectively. The edge distance was fixed at 50.8 mm.

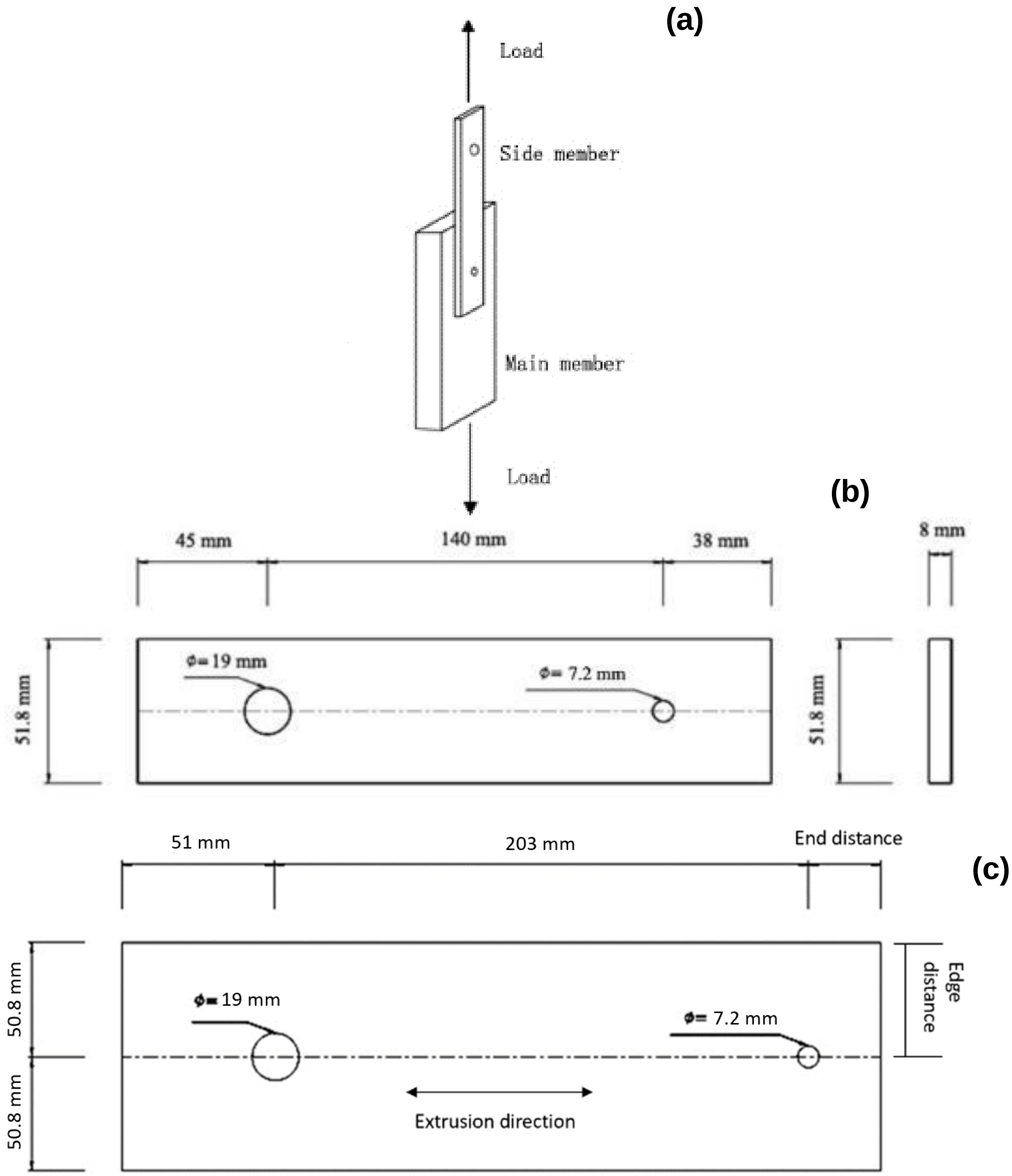


Fig. 2. General configurations of (a) a single-shear unconstrained WPC-to-metal single-bolt connection, (b) detailed dimensions of a metal plate side member, and (c) WPC main member parallel its extrusion direction

Basic material properties

Shear strengths of WPC lumber parallel to the WPC extrusion direction were evaluated according to ASTM D7031-11 (2011) and ASTM D143-14 (2014). Figure 3 shows the general configurations and detailed dimensions of WPC specimens used to evaluate the shear strengths of WPC lumber parallel (Fig. 3) to its extrusion direction. Ten replicates were tested for the orientation.

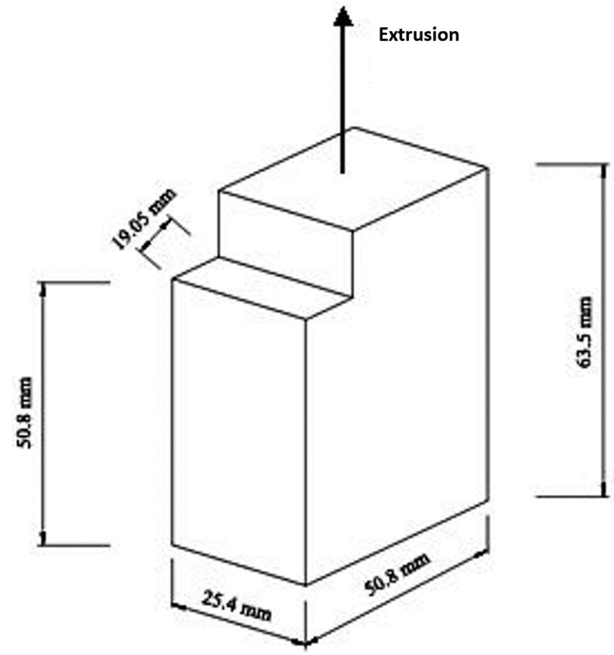


Fig. 3. General configuration of specimens used in this study for testing shear strengths of wood-plastic composite lumber parallel to its extrusion direction

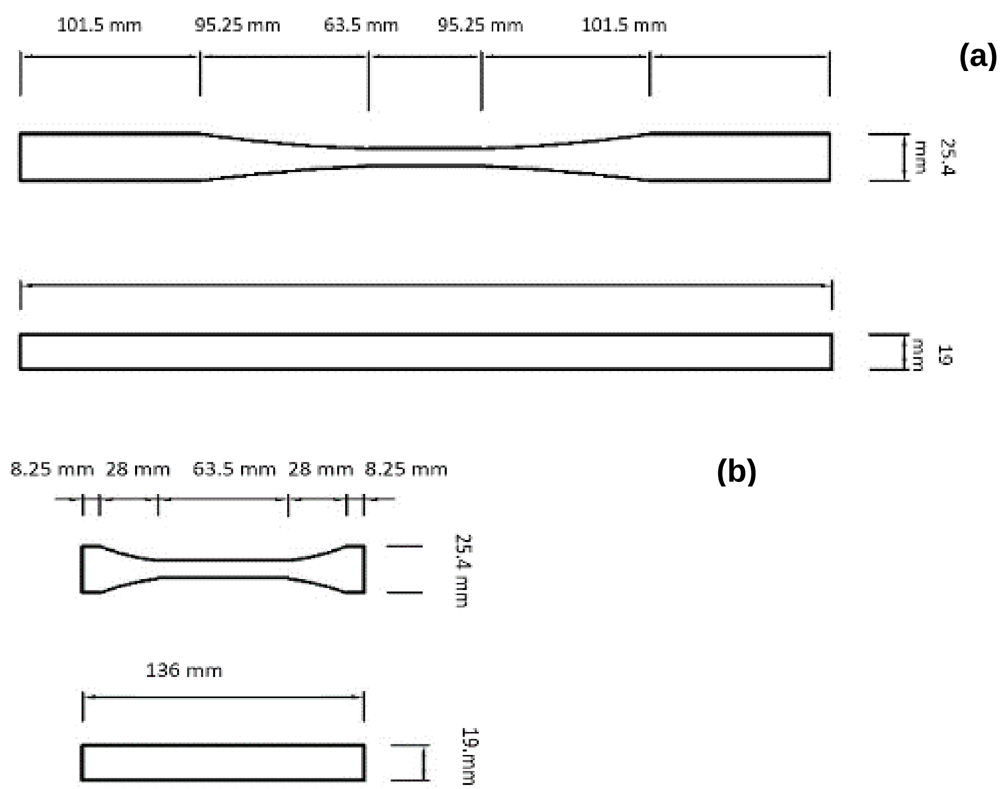


Fig. 4. General configurations of specimens used in this study for testing tensile strengths of wood-plastic composite lumber parallel (a) and perpendicular (b) to its extrusion direction

Tensile strengths of WPC lumber parallel and perpendicular to the WPC extrusion direction were evaluated in referencing to ASTM D638-14 2014), ASTM D7031-11(2011), and ASTM D4761-18 (2018). Figure 4 shows the general configurations of and detailed dimension of WPC specimens used to evaluate the tensile strengths of WPC lumber parallel (Fig. 4a) and perpendicular (Fig. 4b) to its extrusion direction. Ten replicates were tested for each of two orientations.

Specimen Preparation and Testing

All specimens for evaluating WPC basic mechanical properties were cut from the center pieces of full-size WPC lumber as shown in Figs. 5a and 5b. All connection specimens were cut from two end pieces (Fig. 5a).

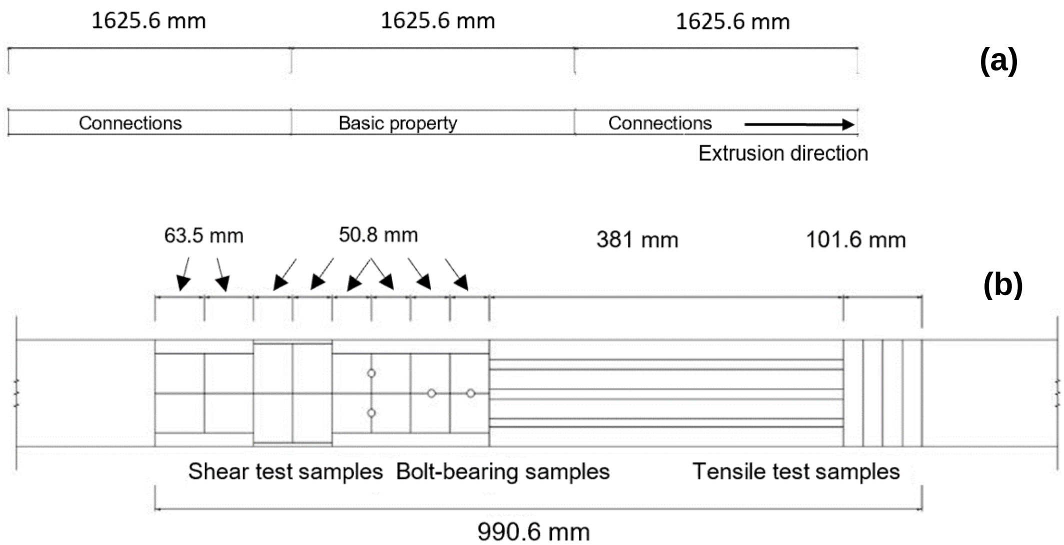
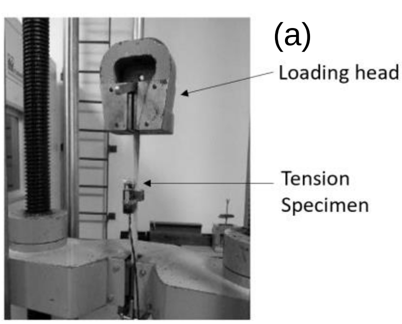


Fig. 5. Cutting patterns showing: (a) where WPC mechanical property and connection specimens were cut from full-size WPC lumber and (b) how WPC mechanical property specimens were cut

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 D7032-17 (2017). Density and density profiles of WPC specimens cut off from connection main members were measured using a density profiler (model QDP-01X; Quintek Measurement Systems, Knoxville, TN, USA).



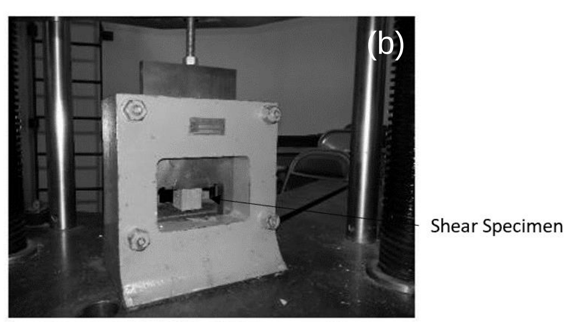


Fig. 6. Test setups for evaluating tensile (a) and shear (b) strengths of WPC lumber used in this study

All tensile and shear tests were performed on a Tinius-Olsen universal testing machine (Tinius Olsen TMC- United States, Horsham, PA, USA). Figure 6 shows the setups for evaluating tensile (a) and shear (b) strengths of WPC lumber.

All connection tests were performed on a hydraulic SATEC universal testing machine (Instron, Norwood, MA, USA). Figure 7 shows the setups for evaluating lateral resistance loads of unconstrained single shear WPC-to-metal single-bolt connections. The loading speed was 1 mm/min as per ASTM D 5652-15 (2015). The ultimate loads and failure modes of all tested connections were recorded.

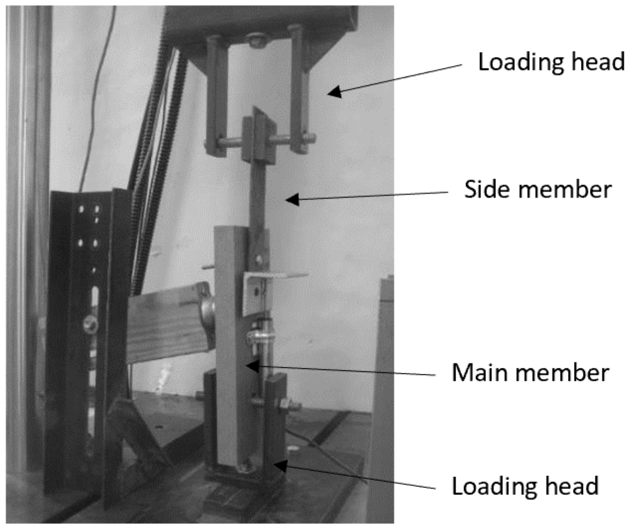


Fig. 7. Test setups for evaluating ultimate lateral resistance loads of unconstrained single-shear single-bolt connections in wood-plastic composite lumber parallel to its extrusion direction

RESULTS AND DISCUSSION

Basic Material Properties

The 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. The mean values (with their corresponding COV values) of ultimate tensile strength of WPC lumber perpendicular to its extrusion direction, $\sigma_{t,\perp}$, was 5.83 (9.6%) MPa. The mean values (with their corresponding COV values) of the ultimate shear strength of WPC lumber parallel to its extrusion direction, $\tau_{//}$, was 7.32 (6.7%) MPa in this study. The COV values and basic statistics were processed using Microsoft Excel software (Microsoft Corporation, Office 365 version, Seattle, WA, USA).

Bolt Connections

Failure modes

Figure 8 shows three types of failure modes of the tested SUWSCs observed at WPC main members when the applied lateral load passed its ultimate value point. Type I was end tear-out, *i.e.*, the end of a tested WPC main member sheared off (Fig. 8a) in its extraction direction without the bolt bent. The connections with their end distances equal to and less than 2.5 time the diameter (*d*) (15.9 mm) all failed with Type I mode (Table 1), indicating that the ultimate lateral loads of these SUWSCs were governed by the WPC shear strength parallel to WPC extrusion direction.

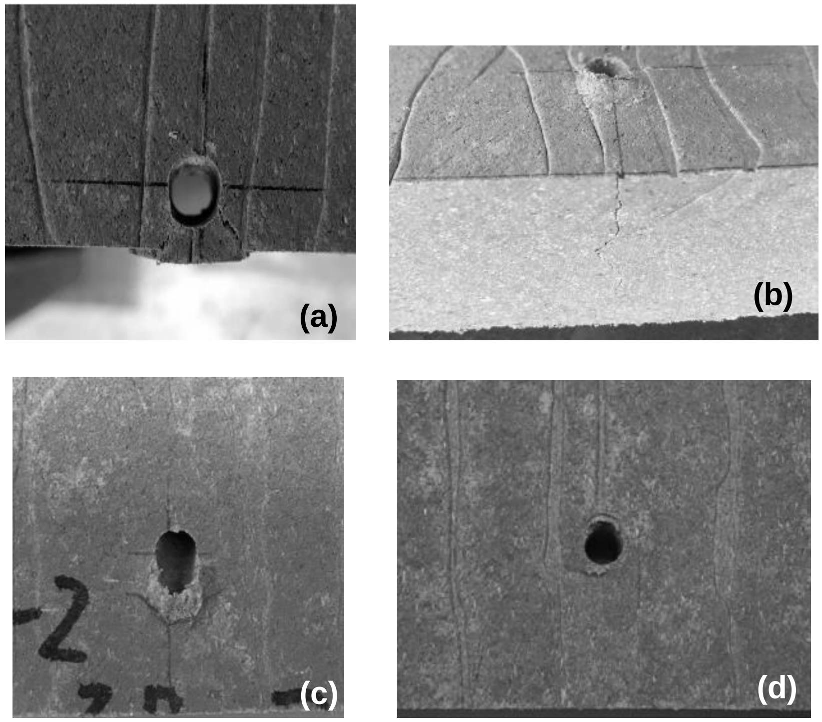


Fig. 8. Typical failure modes observed in evaluating the ultimate lateral load of single-shear unconstrained WPC-to-metal single-bolt connections when subjected to static lateral loading parallel to the WPC extrusion direction: end tear-out (a); end splitting (b); material compressively fractured at the end closest to (c) and away from (d) the metal plate

Type II was end splitting, *i.e.*, the end splitting of a tested WPC main member started underneath the hole along its extraction direction without the bolt bent (Fig. 8b). The connections with their end distance equal to 3 *d* (19.1 mm) all failed with Type II mode (Table 1), while 20% of connections with their end distance equal to 3.5 *d* (22.2 mm) failed in Type II mode. These observations indicated that the ultimate lateral loads of SUWSCs failed in Type II mode were governed by the WPC tensile strength perpendicular to its extrusion direction.

Type III was WPC material yield, *i.e.*, a tested WPC main member failed with WPC materials beneath and above the bolt compressively fractured at the main member sides close to the metal plate (Fig. 8c) and the opposite side (Fig. 8d). A total of 80% of connections with their end distance equal to 3.5 *d* (22.2 mm) failed with Type III mode, while the connections with their end distance equal to 4 *d* (25.4 mm) all failed with Type III mode (Table 1). These observations indicated that the ultimate lateral loads of SUWSCs failed in Type III mode were governed mainly by the bolt-bearing strength in WPCs parallel to its extrusion direction.

Prediction on ultimate lateral resistance loads

The mean values of ultimate lateral loads of SUWSCs evaluated in this study and their corresponding coefficients of variation are summarized in Table 1. Figure 9 plots the mean ultimate lateral loads of SUWSCs *versus* their corresponding (*e/d*) values together with mean comparison results. The mean comparisons were performed using the protected least significant difference (LSD) multiple comparisons procedure at the 5% significance level, *i.e.*, a single LSD value of 159 N was used to determine the mean differences among six means (Freund and Wilson 1997).

Table 1. Summary of Failure Modes, Stress Concentration Factor Calculated for Regression Approach, and Predicted Ultimate Lateral Loads Using Mechanics-based Approach of Single-shear Unconstrained WPC-to-metal Single-bolt Connections Evaluated in this Study

Regression Approach					
End Distance (mm)	Failure Mode	Nominal	Ultimate	Equation	Stress Concertation Factor
		----- (N) ------			
		$2te\tau_{\parallel}$	$F_{ult\text{-}sh}$		K_{sh}
9.5 (1.5 *d*)	100% Tear-out	3542	983 (6)	(2)	0.28
12.7 (2 *d*)	100% Tear-out	4723	1530 (7)	(2)	0.32
15.9 (2.5 *d*)	100% Tear-out	5903	2180 (13)	(2)	0.37
		$te\sigma_{t,\perp}$	$F_{ult\text{-}sp}$		K_{sp}
19.1 (3 *d*)	100% Splitting	5642	2789 (6)	(3)	0.49
Mechanics-based Approach					
		Predicted	Observed	Eq.	Ratio (O/P)
			$F_{ult\text{-}y}$		
22.2 (3.5 *d*)	80%Yield + 20% Splitting	2893	2932 (5)	(8)	1.01
25.4 (4 *d*)	100% Yield	2893	3021 (4)	(8)	1.04

Note: Values in parentheses of ultimate loads are coefficients of variation in percentage; means not followed by a common capital letter are significantly different one from another at p = 0.05 level

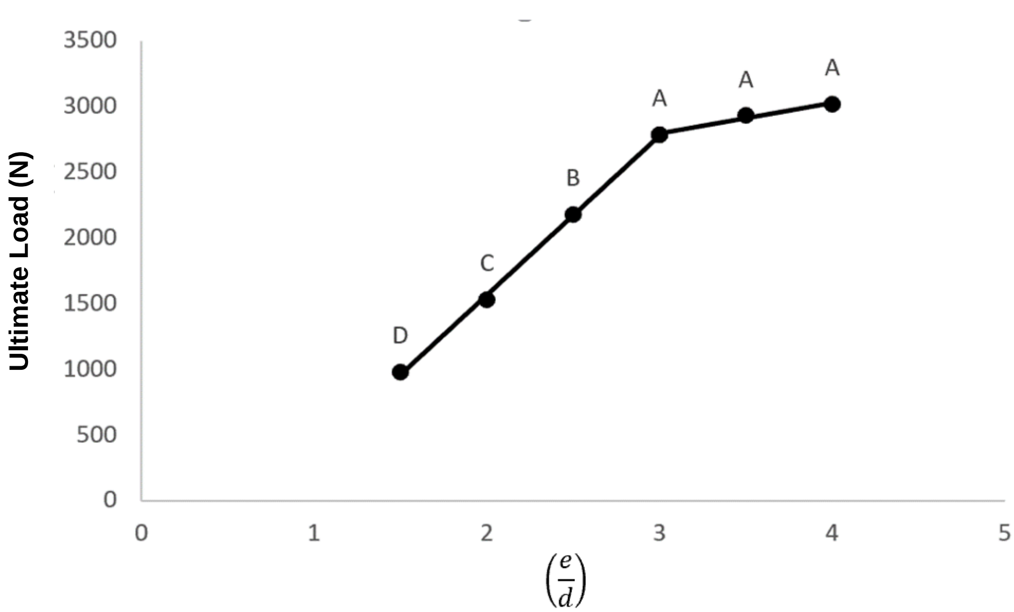


Fig. 9. Mean ultimate lateral loads of SUWSCs evaluated in this study as a function of $\left(\frac{e}{d}\right)$

The mean comparison results indicated that mean ultimate lateral loads of SUWSCs increased significantly as the end distance increased from 9.5 to 19.1 mm with an increment of 3.2 mm, the further increase of end distance from 19.1 to 25.4 mm with an increment of 3.2 mm increased mean ultimate lateral loads of SUWSCs, but it was not significant. This insignificant increase in mean ultimate lateral loads of SUWSCs indicated that mean ultimate lateral loads of SUWSCs failed in fracture modes of end tear-out and that splitting can reach its limit, where the connection failure mode changed from end splitting to the compressive yield failure mode of the materials underneath and above the bolt. This observation also indicates that the minimum end distance for a SUWSC evaluated in this study should be equal or greater than 4 d, *i.e.*, four times the bolt diameter to avoid having fracture failure modes like end tear-out and splitting.

The major failure modes observed in SUWSCs with end distances up to 19.1 mm were end tear-out and splitting, indicating that the ultimate lateral load of SUWSCs were governed by the shear and tensile strength properties of WPC materials used as main member materials. Commonly, the stress distribution at the shear or tension section of a failed connection is complex. The stress in these failure regions is commonly analyzed by relying on experimental approach (Ugural and Fenster 1995) through the introduction of a stress concentration factor and using the regression method to obtain a function relationship between the stress concentration factor and end distance to bolt-diameter ratio of the connections.

The mean values of the stress concentration factors of SUWSCs that failed in end tear-out, K_{sh}, and end splitting, K_{sp}, (Table 1), were calculated using Eqs. 2 and 3, respectively,

$$K_{\mathrm{sh}} = \frac{F_{\mathrm{ult-sh}}}{2te\tau_{\parallel}} \tag{2}$$

$$K_{\mathrm{sp}} = \frac{F_{\mathrm{ult-sp}}}{te\sigma_{t,\perp}} \tag{3}$$

where t is the main member thickness (mm), e is the end distance (mm), $\tau_{//}$ is the ultimate shear strength of WPC lumber parallel to its extrusion direction (MPa), and $\sigma_{t,\perp}$, is the ultimate tensile strength of WPC lumber perpendicular to its extrusion direction (MPa).

The mean value of the stress concentration factor of SUWSCs that failed in the modes of end tear-out and end splitting were plotted as a function of (e/d), shown in Fig. 10, indicating a linear relationship existed between the stress concentration factor and end-distance to bolt-diameter ratio of SUWSCs evaluated in this study. Therefore, a linear function by Eq. 4,

$$K = a + b\left(\frac{e}{d}\right) \tag{4}$$

was proposed to fit data points by the method of least squares, where a and b are regression constants. The regression analysis yielded the following significant least squares Eq. 5,

$$K = 0.053 + 0.139\left(\frac{e}{d}\right) \tag{5}$$

with a coefficient of determination, r^2, valued at 0.92, indicating the equation could be useful for predicting the mean value of stress concentration factor based on (e/d) ratios for SUWSCs failed in end tear-out and end splitting modes.

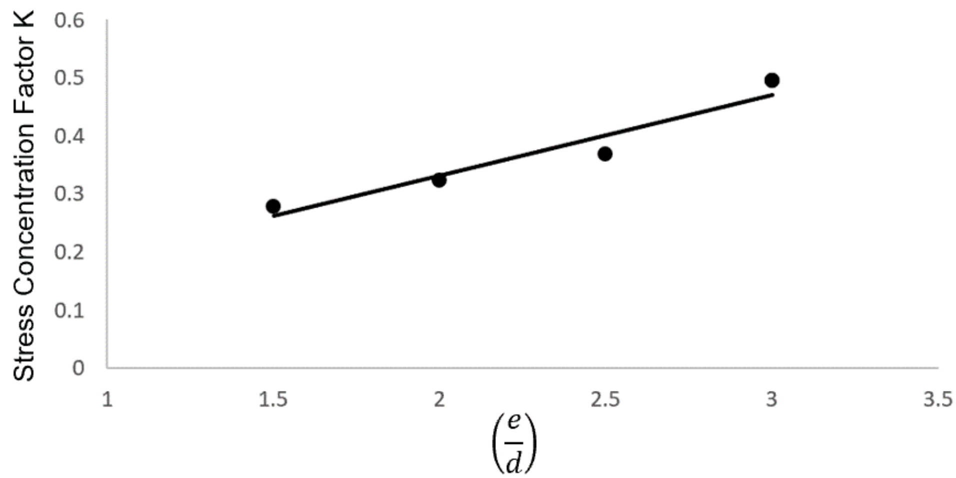


Fig. 10. Mean values of stress concentration factor, *K*, were plotted as a function of end-or edge-distance to bolt-diameter ratio, (*e/d)*, for single-shear unconstrained wood-plastic composite-to-metal single-bolt connections failed in end tear-out and net cross-section modes

Therefore, mean ultimate lateral loads of SUWSCs failed in end tear-out and end splitting modes can be estimated using Eqs. 6 and 7, respectively,

$$F_{ult-sh} = 2te\tau \parallel \left[0.053 + 0.139 \left(\frac{e}{d}\right)\right] \tag{6}$$

$$F_{ult-sp} = te\sigma_{t,} \perp \left[0.053 + 0.139 \left(\frac{e}{d}\right)\right] \tag{7}$$

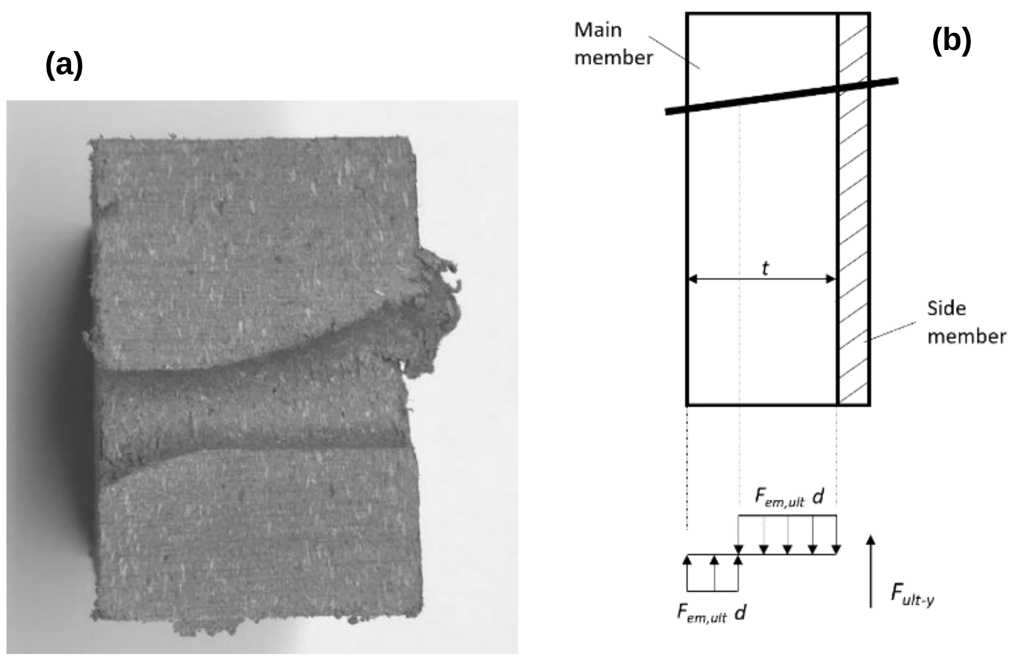


Fig. 11. The typical deformed shape (a), and the mechanical model of single-shear unconstrained wood-plastic composite-to-metal single-bolt connections subjected to static lateral loads parallel to the WPC extrusion direction (b)

For the SUWSCs that failed mainly in yield mode at the end of a main member, the mean ultimate lateral load was estimated using a mechanics-based approach. Figure 11 illustrates the mechanical model of SUWSCs together with the free-body diagram of a bolt, and the deformed shape of the cut from the main member in supporting the yield model proposed.

Based on the yield model proposed, the mean ultimate lateral load of a SUWSC can be estimated using Eq. 8 (Johansen 1949),

$$F_{\mathrm{ult-y}} = 0.414 F_{\mathrm{em,ult}} \times d \times t \tag{8}$$

where d is the bolt diameter (mm), t is the main member thickness (mm), and $F_{\mathrm{em,\,ult}}$ is the ultimate bolt-bearing strength (N) in WPC lumber parallel to its extraction direction.

Table 1 shows the predicted ultimate lateral loads of SUWSCs using Eq. 8. The ratio values ranging from 1.01 to 1.04 indicated that the prediction from Eq. 8 could reasonably well estimate the ultimate lateral loads of SUWSCs that failed in yield without bending of the bolt.

CONCLUSIONS

1. Three typical failure modes, end tear-out, end splitting, and yield, were observed in the main members of SUWSCs evaluated in this experiment. The end tear-out mode occurred at the end distance equal or less than 2.5 times the bolt diameter. The end splitting mode happened at the end distance equal to 3 times the bolt diameter. The end distance 3.5 times the bolt diameter was the failure mode transition point where the failure mode changed from end splitting to yield. At the end distance of 4 times the bolt diameter, all SUWSCs failed in yield mode.
2. The minimum end distance for SUWSCs failed without end fracturing, like end tear-out and splitting, *i.e.*, only with yield mode, was 25.4 mm that was 4 times the bolt diameter.
3. The stress concentration factor was a linear function of end-distance to bolt-diameter ratio for SUWSCs failed in end tear-out and splitting modes. The derived linear equation could be used for the connections constructed with the same bolt and WPC materials used in this study. Further validation is required if these derived equations are used for general applications.
4. The static ultimate lateral loads of SUWSCs failed in the yield modes could be estimated reasonably well using the mechanics-based equation.

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