CHARACTERISTICS OF SCREWDRIVING TORQUES IN WOOD-PLASTIC COMPOSITES

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Abstract. The characteristics of torque magnitudes for driving screws into wood-plastic composites (WPCs) were investigated through evaluating effects of different factors on seating torque (SET) and stripping torque (STT) commonly used to characterize the process of driving screws into a material. The factors were embedded screw orientation in WPCs, pilot-hole diameter, screw penetration depth, and screwdriver air pressure. Recorded torque-time curves of driving screws into WPCs evaluated in this study indicated that the complete screwdriving process can be described as a three-phase process of thread forming and screw seating, clamping, and screw stripping WPCs. Mean SET values for driving screws into WPCs can range from 0.47 to 1.83 N-m, STT values from 1.54 to 4.87 N-m, and their corresponding STT-to-SET ratios from 1.0 to 4.4. Statistical analyses indicated that mean SET and STT values of driving screws into WPCs increased as screw penetration depth increased from 12.7 to 25.4 in increments of 6.35 mm. The significance of pilot-hole diameter effects on mean SET and STT values is influenced by screw penetration depth. Mean SET values at 0.45 MPa air pressure level were higher than those at 0.62 MPa, whereas the significance of screwdriver air pressure effects on mean STT values is influenced by pilot-hole diameter and also screw penetration depth. The significance of

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embedded screw orientation effects on mean SET values is influenced by screw penetration depth and pilot-hole diameter and on mean STT values by screw penetration depth, pilot-hole diameter, and screwdriver air pressure.

Keywords: Wood-plastic composites, screws, seating torque, stripping torque, pilot-hole diameter, penetration depth, grain orientation.

INTRODUCTION

Wood-plastic composites (WPCs) are a mixture of wood (of any form) with thermosets or thermoplastics (Clemons 2002). In recent decades, wood-thermoplastic composites have had tremendous growth in material markets such as decking, fencing, landscape timbers, and furniture frame components.

Screws are commonly used mechanical fasteners for connection of parts in decking, fencing, and furniture construction. The driving of screws into parts made of WPCs can be an issue. Too much torque on turning screws can cause stripping problem, ie shearing off the formed threads in the material, which consequently can significantly decrease screw holding capacity in the material (Carroll 1970). Too little torque on screws will cause seating problems, which results in possible screw movement and slips. A significant difference between the torque of seating and stripping screws can prevent issues with stripped or nonseated screws (Eckelman 1990).

Studies were found on the characterization of the process of driving screws into materials such as plastic (Boulanger and Weekes 2009; Robert 2012; Stéphan et al 2012), human bone (Bahr 1994; Heidemann et al 1998), and particleboard (PB) and oriented strandboard (OSB) materials (Carroll 1970; Tor et al 2015; Yu et al 2015).

Limited literature is found in the characterization of torque behavior during the course of driving screws into WPCs, ie torque value changes during the progress of turning a screw. Therefore, the primary objective of this study was to obtain basic information on the characteristics of torques for driving screws into WPCs. The specific objectives were to 1) obtain torque-time curves describing torque change during the course of driving screws into WPCs; 2) determine critical torques for driving screws into WPCs such as seating torque (SET) and stripping torque (STT); and 3) investigate effects of embedded screw orientation, screw penetration depth, drilled screw pilot-hole diameter, and screwdriver air pressure on critical screwdriving torques. It is believed that the results from this screw torque study on WPCs will help companies, such as furniture manufacturers, who use WPCs to build their products to understand how critical torque values can affect their product quality in terms of seating screws properly and minimizing screw stripping in materials which hold screws. With this information, WPC manufacturers can better understand their product screw torque properties and engineer their products to better meet their customers' process requirement needs.

MATERIALS AND METHODS

Materials

Full-sized WPC lumbers provided by Advanced Environment Recycling Technologies, Inc., Arkansas, measured 4876.8 mm long × 137.16 mm wide × 25.4 mm thick. 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). No. 10-gage, 38.1-mm-long flathead and zinc-plated Phillips low carbon sheet metal screws purchased from a location hardware store were used in the experiment.

Experimental Design

A complete four-factor factorial experiment with 10 replications per combination was conducted to evaluate factors on SET and STT of driving screws into WPCs. The four factors were embedded screw orientation (face, edge, and end), screw penetration depth (12.7, 19.1, and 25.4 mm), pilot-hole diameter (0, 1.6, 2, 2.4, 3.2, and 3.6 mm, which were 0%, 45%, 56%, 67%, 89%, and 100% of the root diameter of a screw, respectively), and screwdriver air pressure (0.45 and 0.62 MPa). The edge of a tested block (Fig 1a) was the narrower side parallel to the length direction (machine extrusion direction) of WPC lumbers, whereas the face was the wider side parallel to the WPC length direction, and the end was the side perpendicular to the WPC length direction. Two screwdriver pressures represented two different screwdriver rotational speeds.

Therefore, a total of 1080 screwdriving tests were performed on 360 blocks, ie three torque tests of driving screws into the edge, end, and face of the same block were performed separately. Each testing block had nominal dimensions of 76.2 mm long (along machine extrusion direction) × 137.16 mm wide × 25.4 mm thick. In addition, the material density profile of its cross section perpendicular to machine extrusion direction was measured.

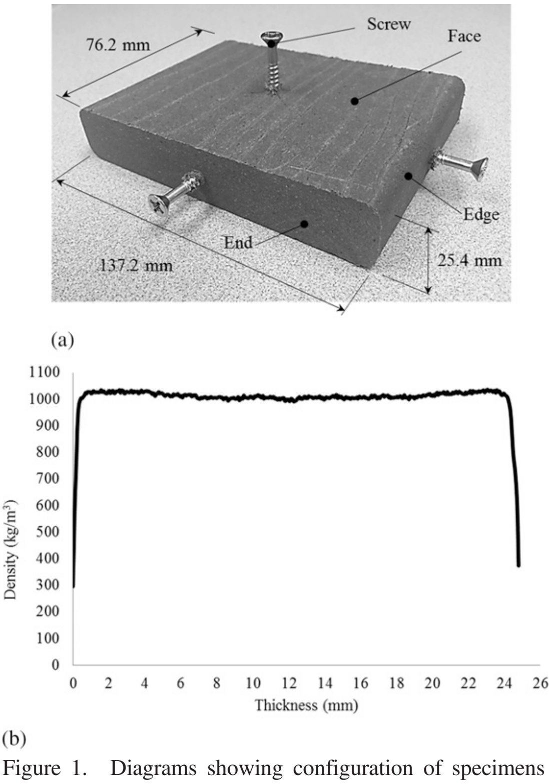

Figure 1. Diagrams showing configuration of specimens for evaluating torque behavior of driving screws into wood-plastic composites (a), and a typical density profile of wood-plastic composites evaluated in the study (b)

Specimen Preparation and Torque Measurement

All 76.2-mm-long torque testing blocks were cut along the length direction of full-sized WPC lumbers and were conditioned in an EMC chamber controlled at 20 ± 2°C and 50 ± 5% RH for 40 h in accordance with ASTM (2011). Pilot holes were drilled into the center of the face, end, and edge of a testing block in accordance with ASTM (2010). Pilot-hole depths were drilled 9.5, 14.3, and 19.1 mm deep for screw penetration depths of 12.7, 19.1, and 25.4 mm, respectively. For torque testing blocks with pilot holes, all torque measurements were performed right after pilot holes were drilled into the testing blocks.

Figure 2 shows the setup for driving screws into testing blocks and recording torque-time curves. The system consisted of a TT500FH dial pneumatic screwdriver, a screwdriver holder frame, an RTSX 100i rotary transducer (Mountz, Foley, AL), and a laptop computer installed with a Mountz torque & force analyzer, which has a CFIL PCMCIA card and Wizard Plus software (Mountz, San Jose, CA). The screwdriver holder helped the screwdriver being pushed and slid vertically to ensure screws being driven perpendicularly into the surfaces of testing blocks. The transducer operating torque range was from 1.13 to 11.3 N-m. The torque data collecting rate was 50 points per second. Three thicknesses, 12.7, 19.1, and 25.5 mm of metal plates were used to ensure consistent screw penetration depths in the testing blocks. The whole screwdriving process ended in about 3-4 s. Critical torque values were acquired from torque-time curves recorded. The physical properties of WPC were evaluated in accordance with ASTM (2011). Density profiles of WPC specimens were measured using Quintek Measurement Systems' (Knoxville, TN) Density Profiler Model QDP-01X.

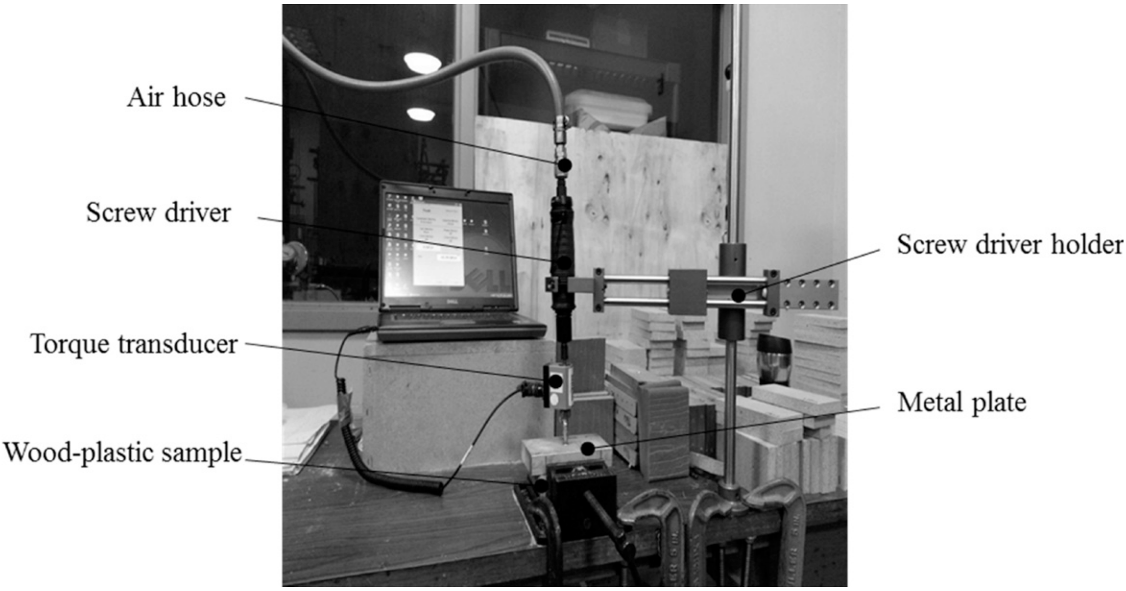

Figure 2. Test setup for evaluating torque behavior of driving screws into wood-plastic composites.

Statistical Analyses

A four-factor analysis of variance (ANOVA) general linear model (GLM) procedure was performed first for each of SET and STT data sets to analyze significances of four main effects and their interactions. Mean comparisons using the protected least significant difference (LSD) multiple comparisons procedure were performed if any significant interaction was identified, otherwise main effects were concluded. All statistical analyses were performed at the 5% significance level.

RESULTS AND DISCUSSION

WPC lumbers used in this study had a uniform density profile across their thickness direction (Fig 1b). WPC lumber density averaged 999 kg/m^3 with its coefficient of variation at 1.1%. It was observed that wood fibers in WPCs were mainly oriented in the lumber length direction.

Torque-time Curve

Figure 3 describes a typical torque-time curve of driving screws into faces and sides (including edges and end orientations) of tested WPCs. The complete process of driving screws WPCs can be divided into three phases of thread forming and screw seating (phase I), clamping (phase II), and screw stripping (phase III), which is similar to the torque-time behavior of driving a screw into plastics (Robert 2012). In phase I, the screwdriving torque increased with a decreasing rate as the screw was forming threads without cutting material, meanwhile overcoming friction between the contacting surface of a screw and WPC material, and then the screw became seated once the torque value reached its SET. The thread forming observed is different from driving screws into

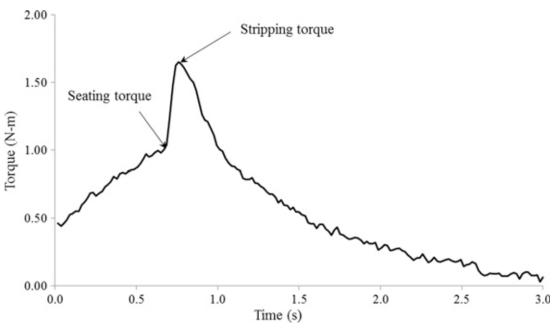

Figure 3. Typical torque-time curves of driving screws into faces and sides of tested wood plastic composite materials.

OSB and PB, which showed that screwdriving torque increased with an increasing rate as the screw was forming threads with cutting materials (Tor et al 2015; Yu et al 2015). In phase II, right after reaching its SET, the screw started its tightening process with sharply increasing torque to its STT. In phase III, once the torque passed STT, its value dropped sharply.

Mean Torque Comparisons and Factor Analyses

Tables 1 and 2 summarize mean SET and STT values of driving screws into WPC materials, respectively. In general, the mean SET values ranged from 0.47 to 1.83 N-m, whereas the STT ranged from 1.54 to 4.87 N-m. Table 3 gives STT-to-SET ratios, showing that there were only 8 of 108 WPC materials with ratios equal to or greater than 3 and 72 of 108 WPC materials with ratios less than 3 but greater than 2, and the remaining 28 had ratios equal to or less than 2. These results indicate that the STT-to-SET ratios of driving screws into WPCs are lower than those for driving screws into PB (3.08 to 3.29) and OSB (3.18 to 3.53) materials (Tor et al 2015). Driving similar screws used in this WPC study into PB and OSB materials under the condition of a 19.1 mm penetration depth and a pilot-hole diameter ranging from 0 to 2.4 mm yielded the ratio ranging from 3.08 to 3.50. Table 3 also shows that there is an increase trend of the ratio with the increase of the pilot-hole diameter. The ratios greater than 3 are suitable for power tools, but for those materials with ratios less than 3, more skills are required for the operators (Robert 2012). Therefore, special attention needs to be paid for driving screws into WPCs using power tools because of its lower STT-to-SET ratios.

In general, mean STT values were significantly higher than SET (Tables 1 and 2). Hence, the ANOVA and mean comparison analyses on torques were performed on SET and STT data, separately. Table 4 summarizes ANOVA results obtained from the GLM procedure performed for each of two torque data sets. The four-factor interaction of each of two data sets was significant. This suggested that further analyses should be focused on the significant interaction for each data set.

Table 1. Summary of mean values of screw seating torque in wood-plastic composites and their mean comparisons for pilot-hole diameter effect.

			Pilot-hole diameter (mm)					
Penetration depth	Air pressure		0	1.6	2	2.4	3.2	3.6
(mm)	(MPa)	Orientation	(N-m)					
12.7	0.45	Face	0.88(5)C[a]	0.99(5)A	0.95(10)AB	0.93(5)BC	0.98(14)AB	0.62(9)D
12.7	0.45	Edge	0.99(5)AB	1.04(4)A	0.99(10)AB	0.95(6)B	0.79(9)C	0.59(8)D
12.7	0.45	End	0.93(5)B	0.96(6)AB	0.94(9)B	1.01(3)A	0.86(6)C	0.58(11)D
12.7	0.62	Face	0.86(6)B	0.97(6)A	0.79(16)C	0.88(5)B	0.87(6)B	0.47(10)D
12.7	0.62	Edge	0.89(11)B	0.97(6)A	0.89(7)B	0.85(7)B	0.87(12)B	0.52(11)C
12.7	0.62	End	0.95(6)A	0.94(6)AB	0.88(5)BC	0.84(7)C	0.88(5)BC	0.50(11)D
19.1	0.45	Face	1.36(4)C	1.48(5)AB	1.49(3)AB	1.53(7)A	1.44(4)B	1.41(4)C
19.1	0.45	Edge	1.30(4)C	1.42(4)A	1.42(4)A	1.37(6)AB	1.31(4)BC	1.28(6)C
19.1	0.45	End	1.27(5)B	1.42(9)A	1.45(5)A	1.40(4)A	1.42(4)A	1.39(4)A
19.1	0.62	Face	1.30(4)CD	1.44(4)A	1.40(4)AB	1.44(4)A	1.34(7)BC	1.24(7)D
19.1	0.62	Edge	1.28(4)A	1.31(4)A	1.29(4)A	1.28(4)A	1.28(4)A	1.18(5)B
19.1	0.62	End	1.24(0)C	1.37(2)AB	1.38(3)AB	1.40(4)A	1.37(7)AB	1.33(3)B
25.4	0.45	Face	1.64(3)B	1.77(4)A	1.66(3)B	1.83(2)A	1.54(4)C	1.48(4)C
25.4	0.45	Edge	1.36(5)D	1.51(5)B	1.62(3)A	1.54(4)B	1.31(4)D	1.42(4)C
25.4	0.45	End	1.37(8)D	1.59(4)B	1.66(5)A	1.70(5)A	1.49(5)C	1.48(5)C
25.4	0.62	Face	1.60(3)AB	1.51(5)C	1.56(3)BC	1.63(3)A	1.56(3)BC	1.45(3)D
25.4	0.62	Edge	1.55(3)A	1.37(6)DE	1.49(6)AB	1.45(5)BC	1.40(5)CD	1.31(4)E
25.4	0.62	End	1.37(7)D	1.59(4)B	1.66(8)A	1.70(4)A	1.49(4)C	1.48(3)C

[a] Values in parentheses are coefficient of variation (%), and means not followed by a common letter are significantly different from one another at the 5% significance level.

Table 2. Summary of mean values of screw stripping torque in wood-plastic composites and their mean comparisons for pilot-hole diameter effect.

Penetration depth (mm)	Air pressure (MPa)	Orientation	Pilot-hole diameter (mm) 0 (N-m)	1.6	2	2.4	3.2	3.6
12.7	0.45	Face	1.82(4)D[a]	1.95(7)BC	2.03(5)AB	2.14(4)A	1.90(7)CD	1.86(6)CD
12.7	0.45	Edge	1.66(4)D	1.95(7)A	1.84(4)AB	1.94(4)A	1.79(5)BC	1.67(3)CD
12.7	0.45	End	1.71(2)D	1.97(5)BC	2.03(4)B	2.18(2)A	2.01(2)B	1.86(7)C
12.7	0.62	Face	1.70(2)B	1.85(6)A	1.92(6)A	1.97(10)A	1.93(7)A	1.89(5)A
12.7	0.62	Edge	1.64(3)CD	1.84(3)AB	1.75(4)ABC	1.86(3)A	1.74(3)BC	1.54(9)D
12.7	0.62	End	1.74(3)B	1.99(3)A	1.94(3)A	1.99(3)A	1.99(4)A	1.89(5)A
19.1	0.45	Face	3.02(11)C	3.14(2)B	3.40(4)A	3.34(6)A	3.18(4)B	3.30(5)A
19.1	0.45	Edge	2.58(3)C	2.67(4)BC	2.83(3)A	2.83(6)A	2.78(5)AB	2.80(4)A
19.1	0.45	End	2.69(3)D	2.99(4)C	3.18(3)B	3.39(3)A	3.20(2)B	3.19(3)B
19.1	0.62	Face	2.95(4)C	3.11(2)B	3.14(4)B	3.27(4)A	3.11(2)B	3.07(6)B
19.1	0.62	Edge	2.54(2)E	2.67(4)D	2.72(4)CD	2.79(3)BC	2.85(3)B	3.05(2)A
19.1	0.62	End	2.75(2)D	3.03(2)C	3.14(1)BC	3.25(3)B	3.23(2)B	3.39(5)A
25.4	0.45	Face	4.03(3)D	4.24(5)C	4.50(4)B	4.87(4)A	4.55(2)B	4.21(3)C
25.4	0.45	Edge	3.34(3)D	3.57(4)C	4.05(3)A	3.85(4)B	3.68(5)C	3.62(2)C
25.4	0.45	End	3.67(6)D	4.02(3)C	4.24(3)B	4.71(6)A	4.35(2)B	4.25(2)B
25.4	0.62	Face	4.03(6)D	4.44(5)A	4.10(1)CD	4.08(3)CD	4.17(4)BC	4.23(4)B
25.4	0.62	Edge	3.57(5)B	3.55(4)B	3.72(2)A	3.74(4)A	3.75(5)A	3.83(3)A
25.4	0.62	End	3.81(3)D	4.23(3)B	4.07(4)C	4.32(3)AB	4.42(1)A	4.38(5)A

[a] Values in parentheses are coefficient of variation (%), and means not followed by a common letter are significantly different from one another at the 5% significance level.

In addition, three main effects of each of two data sets were all significant with their p values less than 0.0001. Further checking of the F values of these significant main effects found that their relative magnitudes were different. In the case of SET data set, screw penetration depth had a much greater F value of 8986 than pilot-hole diameter with an F value of 239, screwdriver air pressure with an F value of 247, and screwdriving orientation with an F value of 122. A similar situation

Table 3. Ratios of stripping to seating torques of screws driven into wood-plastic composites.

Air pressure (MPa)	Orientation	Penetration depth (mm)	Pilot-hole diameter (mm) 0	1.6	2	2.4	3.2	3.6
0.45	Face	12.7	2.1	2.0	2.1	2.3	1.9	3.0
0.45	Face	19.1	2.2	2.1	2.3	2.2	2.2	2.3
0.45	Face	25.4	2.5	2.4	2.7	2.7	3.0	2.8
0.45	Edge	12.7	1.7	1.9	1.9	2.0	2.3	2.8
0.45	Edge	19.1	1.3	1.9	2.0	2.1	2.1	2.2
0.45	Edge	25.4	1.2	2.4	2.5	2.5	2.8	2.5
0.45	End	12.7	1.8	2.0	2.2	2.2	2.3	3.2
0.45	End	19.1	1.3	2.1	2.2	2.4	2.2	2.3
0.45	End	25.4	1.2	2.5	2.6	2.8	2.9	2.9
0.62	Face	12.7	1.9	1.9	2.4	2.2	2.2	4.0
0.62	Face	19.1	1.3	2.2	2.2	2.3	2.3	2.5
0.62	Face	25.4	1.0	2.9	2.6	2.5	2.7	2.9
0.62	Edge	12.7	1.9	1.9	2.0	2.2	2.0	3.0
0.62	Edge	19.1	1.3	2.0	2.1	2.2	2.2	2.6
0.62	Edge	25.4	1.1	2.6	2.5	2.6	2.7	2.9
0.62	End	12.7	1.8	2.1	2.2	2.4	2.3	3.8
0.62	End	19.1	1.3	2.2	2.3	2.3	2.4	2.5
0.62	End	25.4	1.2	2.7	2.4	2.5	3.0	3.0

Table 4. Summary of analysis of variance results obtained from the general linear model procedure performed on four factors for each of two torque data sets.

Source	Seating torque		Stripping torque	
	F value	*p* value	F value	*p* value
Pressure	247	<0.0001	45.44	<0.0001
Diameter	239	<0.0001	190	<0.0001
Orientation	122	<0.0001	933	<0.0001
Penetration	8986	<0.0001	24660	<0.0001
2-way interactions	0.45-71.97	0.6399-<0.0001	3.67-97.52	0.0257-<0.0001
3-way interactions	2.16-11.16	0.0716-<0.0001	3.57-11.55	<0.0001
4-way interaction	4.00	<0.0001	4.16	<0.0001

was found in STT data set, where screw penetration depth had a much greater F value of 24,660 than pilot-hole diameter with an F value of 190, screwdriver air pressure with an F value of 45, and screwdriving orientation with an F value of 933. Therefore, the interpretation of screw penetration depth effects on SET and STT values was based on their main effect mean comparisons because of their much greater F values (Freund and Wilson 1997).

Effects of other three factors on SET and STT values were analyzed by considering their significant four-factor interactions. A one-way classification of 108 treatment combinations was created for each of two SET and STT data set, respectively, to evaluate mean differences among those combinations using the protested LSD multiple comparison procedure. Tables 1, 5, and 6 summarize mean comparisons of SET values in WPC materials for pilot-hole diameter, embedded screw orientation, and screwdriver air pressure, respectively, using the single LSD value of 0.06 N-m. Tables 2, 7, and 8 summarize mean comparisons of STT values in WPC materials for pilot-hole diameter, embedded screw orientation, screwdriver air pressure, respectively, using the single LSD value of 0.16 N-m.

Embedded screw orientation effects. Table 5 indicated that at 12.7-mm penetration depth, in general, there were no significant differences in SET values among the three embedded screw orientations. When penetration depths were 19.1 and 25.4 mm, the mean SET of driving screws into the face of tested WPCs tended to be higher than into the edge and end of the materials, followed by end and then edge orientation if pilot-hole diameters ranged from 1.6 to 3.6 mm, but if no pilot holes were drilled then edge specimens tended to have a higher SET than end specimens (Tor et al 2015).

Table 7 indicated that, in general, mean STT values of screws driven into the edges of tested WPCs were significantly lower than into the faces and ends (Tor et al 2015). There was no significant difference in the mean STT between driving screws into the faces and the ends of tested WPCs when screw penetration depth was 12.7 mm. In the case of penetration depths being 19.1 and 25.4 mm and screwdriver air pressure being 0.45 MPa, the mean STT of driving screws into the faces of tested WPCs tended to be significantly higher than into the ends when pilot-hole diameter is less than 2 mm (Tor et al 2015), as the pilot-hole diameter increased the significance become less. In the case of screwdriver air pressure being 0.62 MPa and penetration depths being 19.1 and 25.4 mm, the significance in the mean STT between the face and end orientation was altered as pilot-hole diameter increased from 0 to 3.6 mm, starting with driving screws into the faces of tested WPCs with significantly higher mean STT values and ending with driving screws into the ends with significantly higher mean STT values.

Screw penetration depth effects. Mean comparisons of SET and STT data sets for screw penetration depth based on main effect mean comparisons indicated that both SET and STT values increased significantly as screw penetration depth increased from 12.7 to 25.4 with an increment of 6.35 mm. In addition, mean comparisons of SET and STT data sets based on the

Table 5. Mean comparisons of seating torques for embedded screw orientation within each combination of screwdriver air pressure, pilot-hole diameter, and penetration depth.

Penetration depth	Pilot-hole diameter	Air pressure	Screw orientation		
			Face	Edge	End
(mm)	(mm)	(MPa)	(N-m)		
12.7	0	0.45	0.88B[a]	0.99A	0.93B
12.7	0	0.62	0.86B	0.89AB	0.95A
12.7	1.6	0.45	0.99AB	1.04A	0.96B
12.7	1.6	0.62	0.97A	0.97A	0.94A
12.7	2	0.45	0.95A	0.99A	0.94A
12.7	2	0.62	0.79B	0.89A	0.88A
12.7	2.4	0.45	0.93B	0.95AB	1.01A
12.7	2.4	0.62	0.88A	0.85A	0.84A
12.7	3.2	0.45	0.98A	0.79C	0.86B
12.7	3.2	0.62	0.87A	0.87A	0.88A
12.7	3.6	0.45	0.62A	0.59A	0.58A
12.7	3.6	0.62	0.47A	0.52A	0.50A
19.1	0	0.45	1.36A	1.30AB	1.27B
19.1	0	0.62	1.30A	1.28A	1.24A
19.1	1.6	0.45	1.48A	1.42A	1.42A
19.1	1.6	0.62	1.44A	1.31B	1.37B
19.1	2	0.45	1.49A	1.42B	1.45AB
19.1	2	0.62	1.40A	1.29B	1.38A
19.1	2.4	0.45	1.53A	1.37B	1.40B
19.1	2.4	0.62	1.44A	1.28B	1.40A
19.1	3.2	0.45	1.44A	1.31B	1.42A
19.1	3.2	0.62	1.34A	1.28B	1.37A
19.1	3.6	0.45	1.41A	1.28B	1.39A
19.1	3.6	0.62	1.24B	1.18C	1.33A
25.4	0	0.45	1.64A	1.36B	1.37B
25.4	0	0.62	1.60A	1.55A	1.48B
25.4	1.6	0.45	1.77A	1.51C	1.59B
25.4	1.6	0.62	1.51A	1.37B	1.46A
25.4	2	0.45	1.66A	1.62A	1.66A
25.4	2	0.62	1.56A	1.49B	1.45B
25.4	2.4	0.45	1.83A	1.54C	1.70B
25.4	2.4	0.62	1.63A	1.45C	1.53B
25.4	3.2	0.45	1.54A	1.31B	1.49A
25.4	3.2	0.62	1.56A	1.40B	1.54A
25.4	3.6	0.45	1.48A	1.42A	1.48A
25.4	3.6	0.62	1.45A	1.31B	1.50A

[a] Means not followed by a common letter are significantly different at the 5% level.

four-factor interactions for screw penetration depth were also investigated, and the results indicated that in general both SET and STT values increased significantly as screw penetration depth increased from 12.7 to 25.4 with an increment of 6.35 mm. There were only three cases where SET values increased, but not significantly, and these three cases were found in driving screws into WPC edges, among them two had pilot-hole diameters of 0 and 3.2 mm, respectively, while their air pressure is 0.45 MPa, and one had a pilot-hole diameter of 1.6 mm under an air pressure of 0.62 MPa.

Pilot-hole diameter effects. Table 1 indicated that within the 12.7-mm penetration depth there was no significant decreasing trend for SET values as pilot-hole diameter increased from 0 to 3.2 mm, till 3.6 mm where SET values dropped significantly. Within penetration depths of 19.1 and

Table 6. Mean comparisons of seating torques for screwdriver air pressure within each combination of pilot-hole diameter, embedded screw orientation, and penetration depth.

Pilot-hole diameter (mm)	Screw orientation	Penetration depth (mm)	Air pressure (MPa) 0.45 (N-m)	Air pressure (MPa) 0.62 (N-m)
0	Face	12.7	0.88A[a]	0.86A
0	Face	19.1	1.36A	1.30A
0	Face	25.4	1.64A	1.60A
0	Edge	12.7	0.99A	0.89B
0	Edge	19.1	1.30A	1.28A
0	Edge	25.4	1.36B	1.55A
0	End	12.7	0.93A	0.95A
0	End	19.1	1.27A	1.24A
0	End	25.4	1.37B	1.48A
1.6	Face	12.7	0.99A	0.97A
1.6	Face	19.1	1.48A	1.44A
1.6	Face	25.4	1.77A	1.51B
1.6	Edge	12.7	1.04A	0.97B
1.6	Edge	19.1	1.42A	1.31B
1.6	Edge	25.4	1.51A	1.37B
1.6	End	12.7	0.96A	0.94A
1.6	End	19.1	1.42A	1.37A
1.6	End	25.4	1.59A	1.46B
2	Face	12.7	0.95A	0.79B
2	Face	19.1	1.49A	1.40B
2	Face	25.4	1.66A	1.56B
2	Edge	12.7	0.99A	0.89B
2	Edge	19.1	1.42A	1.29B
2	Edge	25.4	1.62A	1.49B
2	End	12.7	0.94A	0.88A
2	End	19.1	1.45A	1.38B
2	End	25.4	1.66A	1.45B
2.4	Face	12.7	0.93A	0.88A
2.4	Face	19.1	1.53A	1.44B
2.4	Face	25.4	1.83A	1.63B
2.4	Edge	12.7	0.95A	0.85B
2.4	Edge	19.1	1.37A	1.28B
2.4	Edge	25.4	1.54A	1.45B
2.4	End	12.7	1.01A	0.84B
2.4	End	19.1	1.40A	1.40A
2.4	End	25.4	1.70A	1.53B
3.2	Face	12.7	0.98A	0.87B
3.2	Face	19.1	1.44A	1.34B
3.2	Face	25.4	1.54A	1.56A
3.2	Edge	12.7	0.79B	0.87A
3.2	Edge	19.1	1.31A	1.28A
3.2	Edge	25.4	1.31B	1.40A
3.2	End	12.7	0.86A	0.88A
3.2	End	19.1	1.42A	1.37A
3.2	End	25.4	1.49A	1.54A
3.6	Face	12.7	0.62A	0.47B
3.6	Face	19.1	1.41A	1.24B
3.6	Face	25.4	1.48A	1.45A
3.6	Edge	12.7	0.59A	0.52B
3.6	Edge	19.1	1.28A	1.18B
3.6	Edge	25.4	1.42A	1.31B

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Table 6. Continued.

Pilot-hole diameter (mm)	Screw orientation	Penetration depth (mm)	Air pressure (MPa) 0.45 (N-m)	0.62
3.6	End	12.7	0.58A	0.50B
3.6	End	19.1	1.39A	1.33A
3.6	End	25.4	1.48A	1.50A

[a] Means not followed by a common letter are significantly different at the 5% level.

Table 7. Mean comparisons of stripping torques for embedded screw orientation within each combination of screwdriver air pressure, pilot-hole diameter, and penetration depth.

Penetration depth (mm)	Air pressure (MPa)	Pilot-hole diameter (mm)	Screw orientation (N-m) Face	Edge	End
12.7	0.45	0	1.82A[a]	1.66B	1.71AB
12.7	0.45	1.6	1.95A	1.95A	1.97A
12.7	0.45	2	2.03A	1.84B	2.03A
12.7	0.45	2.4	2.14A	1.94B	2.18A
12.7	0.45	3.2	1.90AB	1.79B	2.01A
12.7	0.45	3.6	1.86A	1.67B	1.86A
12.7	0.62	0	1.70A	1.64A	1.74A
12.7	0.62	1.6	1.85B	1.84B	1.99A
12.7	0.62	2	1.92A	1.75B	1.94A
12.7	0.62	2.4	1.97AB	1.86B	1.99A
12.7	0.62	3.2	1.93A	1.74B	1.99A
12.7	0.62	3.6	1.89A	1.54B	1.89A
19.1	0.45	0	3.02A	2.58B	2.69B
19.1	0.45	1.6	3.14A	2.67C	2.99B
19.1	0.45	2	3.40A	2.83C	3.18B
19.1	0.45	2.4	3.34A	2.83B	3.39A
19.1	0.45	3.2	3.18A	2.78B	3.20A
19.1	0.45	3.6	3.30A	2.80B	3.19A
19.1	0.62	0	2.95A	2.54C	2.75B
19.1	0.62	1.6	3.11A	2.67B	3.03A
19.1	0.62	2	3.14A	2.72B	3.14A
19.1	0.62	2.4	3.27A	2.79B	3.25A
19.1	0.62	3.2	3.11B	2.85C	3.23A
19.1	0.62	3.6	3.07B	3.05B	3.39A
25.4	0.45	0	4.03A	3.34C	3.67B
25.4	0.45	1.6	4.24A	3.57C	4.02B
25.4	0.45	2	4.50A	4.05C	4.24B
25.4	0.45	2.4	4.87A	3.84C	4.71B
25.4	0.45	3.2	4.55A	3.68C	4.35B
25.4	0.45	3.6	4.21A	3.62B	4.25A
25.4	0.62	0	4.03A	3.57C	3.81B
25.4	0.62	1.6	4.44A	3.55C	4.23B
25.4	0.62	2	4.10A	3.72B	4.07A
25.4	0.62	2.4	4.08B	3.74C	4.32A
25.4	0.62	3.2	4.17B	3.75C	4.42A
25.4	0.62	3.6	4.23B	3.83C	4.38A

[a] Means not followed by a common letter are significantly different at the 5% level.

Table 8. Mean comparisons of stripping torques for screwdriver air pressure within each combination of pilot-hole diameter, embedded screw orientation, and screw penetration depth.

Pilot-hole diameter		Penetration depth	Air pressure (MPa)	
			0.45	0.62
(mm)	Screw orientation	(mm)	(N-m)	
0	Face	12.7	1.82A[a]	1.70B
0	Face	19.1	3.02A	2.95A
0	Face	25.4	4.03A	4.03A
0	Edge	12.7	1.66A	1.64A
0	Edge	19.1	2.58A	2.54A
0	Edge	25.4	3.34B	3.57A
0	End	12.7	1.71A	1.74A
0	End	19.1	2.69A	2.75A
0	End	25.4	3.67B	3.81A
1.6	Face	12.7	1.95A	1.85A
1.6	Face	19.1	3.14A	3.11A
1.6	Face	25.4	4.24B	4.44A
1.6	Edge	12.7	1.95A	1.84A
1.6	Edge	19.1	2.67A	2.67A
1.6	Edge	25.4	3.57A	3.55A
1.6	End	12.7	1.97A	1.99A
1.6	End	19.1	2.99A	3.03A
1.6	End	25.4	4.02B	4.23A
2	Face	12.7	2.03A	1.92A
2	Face	19.1	3.40A	3.14B
2	Face	25.4	4.50A	4.10B
2	Edge	12.7	1.84A	1.75A
2	Edge	19.1	2.83A	2.72A
2	Edge	25.4	4.05A	3.72B
2	End	12.7	2.03A	1.94A
2	End	19.1	3.18A	3.14A
2	End	25.4	4.24A	4.07B
2.4	Face	12.7	2.14A	1.97B
2.4	Face	19.1	3.34A	3.27A
2.4	Face	25.4	4.87A	4.08B
2.4	Edge	12.7	1.94A	1.86A
2.4	Edge	19.1	2.83A	2.79A
2.4	Edge	25.4	3.85A	3.74A
2.4	End	12.7	2.18A	1.99B
2.4	End	19.1	3.39A	3.25B
2.4	End	25.4	4.71A	4.32B
3.2	Face	12.7	1.90A	1.93A
3.2	Face	19.1	3.18A	3.11A
3.2	Face	25.4	4.55A	4.17B
3.2	Edge	12.7	1.79A	1.74A
3.2	Edge	19.1	2.78A	2.85A
3.2	Edge	25.4	3.68A	3.75A
3.2	End	12.7	2.01A	1.99A
3.2	End	19.1	3.20A	3.23A
3.2	End	25.4	4.35A	4.42A
3.6	Face	12.7	1.86A	1.89A
3.6	Face	19.1	3.30A	3.07B
3.6	Face	25.4	4.21A	4.23A
3.6	Edge	12.7	1.67A	1.54B
3.6	Edge	19.1	2.80B	3.05A
3.6	Edge	25.4	3.62B	3.83A

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Table 8. Continued.

Pilot-hole diameter (mm)	Screw orientation	Penetration depth (mm)	Air pressure (MPa) 0.45 (N-m)	0.62
3.6	End	12.7	1.86A	1.89A
3.6	End	19.1	3.19B	3.39A
3.6	End	25.4	4.25B	4.38A

[a] Means not followed by a common letter are significantly different at the 5% level.

25.4 mm the general trend was that SET values increased significantly as pilot-hole diameter increased from 0 to 1.6 mm, and there was no significant increasing trend observed as pilot-hole diameter increased from 1.6 to 2.4 mm, then significant drops in SET values were observed as pilot-hole diameter increased from 2.4 to 3.6 mm.

Table 2 indicated that within the 12.7-mm penetration depth there was a significant increase for STT values as pilot-hole diameter increased from 0 to 1.6 mm, then after that there was no significant change till pilot-hole diameter reached 2.4 mm, and as pilot-hole diameter increased from 2.4 to 3.2 mm drops in STT values occurred and most of these drops were significant. Within penetration depths of 19.1 and 25.4 mm the general trend was that STT values increased significantly as pilot-hole diameter increased from 0 to 1.6 mm, which is similar to SET values, then it seems there was no significant change trend observed as pilot-hole diameter further increased.

Screwdriver air pressure effects. Table 6 indicated that the general trend was that the SET at 0.45 MPa was higher than at 0.62 MPa, and the significance mostly occurred in the tested specimens with pilot-hole diameters ranging from 1.6 to 2.4 mm, and also 3.6 mm. Table 8 indicated that in the case of pilot-hole diameters from 0 to 1.6 mm, where if screw penetration depths were 12.7 and 19.1 mm the screwdriver air pressure tended to show no significant influence on the mean STT, but at the penetration depth of 25.4 mm, the STT at 0.62 MPa yielded a higher mean value than at 0.45 MPa. As screw pilot-hole diameters increased to 2 and 2.4 mm, the STT at 0.45 MPa tended to be higher than at 0.62, and the significant difference mostly occurred at the 25.4-mm penetration depth. There is no significant difference in the STT between the two air pressure levels at the 3.2-mm pilot-hole diameter. At the 3.6-mm pilot-hole diameter, the STT at 0.62 MPa tended to be higher than at 0.45 MPa.

CONCLUSIONS

Torque-time curves of driving screws into evaluated WPCs indicated that the complete screw-driving process has three phases of thread-forming without material cut and screw seating, clamping, and screw stripping. Mean SETs range from 0.47 to 1.83 N-m, STTs from 1.54 to 4.87 N-m, and their corresponding ratios from 1.0 to 4.4.

Statistical analyses indicated that the SET and STT increased as screw penetration depth increased from 12.7 to 25.4 in increments of 6.35 mm. The significance of pilot-hole diameter effects on torques is influenced by screw penetration depth. Mean SETs at 0.45 MPa air pressure were higher than those at 0.62 MPa, whereas the significance of screwdriver air pressure effects on STTs is influenced by pilot-hole diameter and screw penetration depth. The significance of embedded screw orientation efforts on SETs is influenced by screw penetration depth and pilot-hole diameter, whereas on STTs by screw penetration depth, pilot-hole diameter, and screwdriver air pressure.

The conclusions were limited to the WPC materials evaluated in the study. However, general conclusions such as torque-time curves being a three-phase process and driving screws into WPC materials tending to yield lower STT-to-SET ratios than PB and OSB materials can be stated. Therefore, special attention needs to be paid for driving screws into WPCs using power tools, for instance, setting right torque for a given WPC material with knowing its SET and STT. Operating manual tools requires skilled and well-trained operators.

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