Factors Affecting Critical Screw-Driving Torques in Particleboard

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Factors influencing the vertical driving force magnitude applied to screws during the process of driving the screws into faces of particleboard materials were investigated. In particular, the screw penetration depth and screwdriver air pressure were evaluated relative to critical torques, such as seating and stripping torques. Experimental results indicated that vertical driving forces significantly affected the magnitude of critical driving torques when no pilot hole was drilled, but this influence became non-significant when 3.2-mm diameter pilot holes were drilled. Screw-driving power had no significant effect on the magnitude of critical driving torques in particleboard materials if no pilot hole was drilled, but if pilot holes were drilled, increasing the screwdriver air pressure from 0.45 to 0.62 MPa led to increases in stripping torques. Increasing the screw penetration depth from 12.7 to 19.1 mm can significantly increase seating and stripping torques.

Keywords: Screw; Pilot hole diameter; Penetration depth; Orientation; Seating torque; Stripping torque

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INTRODUCTION

One of the most important mechanical properties of wood-based materials is their screw-driving performance in terms of screw-driving torques. Screws that are insufficiently tightened to the materials with low driving torque might cause screw seating problems. Conversely, applying excessive driving torque on the screw can cause screw stripping problems for the materials. Additionally, over-torque can be equally damaging to the materials on account of the failure of a fastener from overstressing the screw and secured areas in the materials. Carroll (1970) measured the flush and maximum screw-driving torques in particleboard (PB) using a dial-type manual torque wrench at a loading rate of approximately 8 s per revolution. The flush condition was defined as that in which the screw head was fully touching the surface of the material. Carroll (1970) also reported that stripping of the wood screw occurs after one full turn of the wrench beyond the point where the lag screw was in full contact with the side member.

Limited research has been conducted on the investigation of factors on screw-driving torques in wood-based materials. Recent studies (Robert 2012; Yu *et al.* 2015; Tor *et al.* 2015, 2017) defined critical screw-driving torques based on the torque-time curves of screws in oriented strand-board (OSB), PB, and plastics. The torque value at the turning point where the screw seated, *i.e.*, the screw head fully touched the surface of the material, was termed as “seating torque” (SET). Turning the screw beyond the seating torque point began the process of tightening the tested material. The torque dropped dramatically when the turning torque passed its maximum value, which was the second peak, termed as "stripping torque" (STT). The sharp drop in the screw-driving torque was mainly because of the formed threads being stripped by the screws. Tor *et al.* (2015) evaluated the effects wood-based composite type, embedded screw orientation, and pilot hole diameters on critical torques through driving screws into 18.26-mm-thick OSB and PB materials. Yu *et al.* (2015) investigated the effects of pilot hole diameter, embedded screw orientation, and PB type (19-mm-thick) on critical torques through driving screws into 19-mm-thick PB materials. The combinations with ratios greater than three are suitable for using power tools, but for those combinations with ratios less than three, more skill is required for the operators (Robert 2012).

Studies have also shown that driving screws into any kind of material, either by manual or pistol-grip powered or battery-powered screwdrivers, may cause some health problems, such as cumulative injuries that occur in connective soft tissues, especially to tendons and their sheaths (Kroemer 1989). These kinds of injuries are called Cumulative Trauma Disorders (CTD) and are caused or aggravated by repetitive motions including forceful movements, sustained or constrained postures, vibrations, and are common in the hand-wrist-forearm area and in the shoulder and neck. This term is also called rheumatic disease, cervicobrachial disorder, over-use injury, cumulative trauma injury, repetitive motion injury, repetition strain injury, and osteoarthritis (Chatterjee 1987; Corlett 1988; Armstrong *et al.* 1999). Carpal tunnel syndrome is also one of the most common problems that increases pressure on the nerves, muscles, and tendons in the hand and wrist area due to highly repetitive manual tasks, such as using a screwdriver (Herbert *et al.* 2000). Another study by Johnson and Childress (1988) reported that tool weight was not a significant factor related to effort and stress when using a screwdriver in a vertical position with a properly adjusted tool balancer. However, the tool weight together with elevated arm lengths was always a significant factor in the terms of affecting the shoulder muscles (Ortengren *et al*. 1991; Cederqvist and Lindberg 1993).

Torque requirements for particular applications should be determined, and then the proper torque should be applied to induce clamping force, which is essential in providing a reliable screw assembly. This study investigated the effects of the magnitude of vertical driving forces applied on screws during the process of driving these screws into the face of PB materials, screw penetration depth, and screwdriver air pressure on critical screw-driving torques such as seating and stripping torques. The results of this research will provide and improve the understanding of variables that may affect screw performance in PB materials. If the relationships among critical driving torques and the effects of factors, like vertical driving force, pilot hole diameter, screw-driving power, screw penetration depth, and embedded screw orientation are known, the information can help wood product manufacturers to avoid producing connections with low strength mainly caused by stripping screws as well as minimize operator injuries due to operating screw guns under high torque range.

EXPERIMENTAL

Materials

Full-sized PB panels were provided by Lowe's Home Improvement, Starkville, MS, USA and measured 2440-mm-long × 1220-mm-wide × 18.26-mm-thick. The screws used were No. 10-gage, 38.1-mm-long flathead and zinc-plated Philips wood screws made of low carbon steel. The configuration and dimensions of the screw are shown in Fig. 1 and Table 1, respectively. To ensure the consistency of the screw penetration depth, 12.7- and 19.1-mm-thick metal plates (Fig. 3) made out of aluminum were used in the tests.

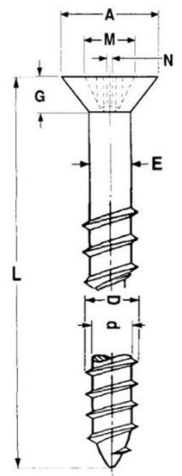


Fig. 1. Configuration of a wood screw; letters in the figure are defined in the table below

Table 1. Dimensions of a Wood Screw Used in this Study (mm)

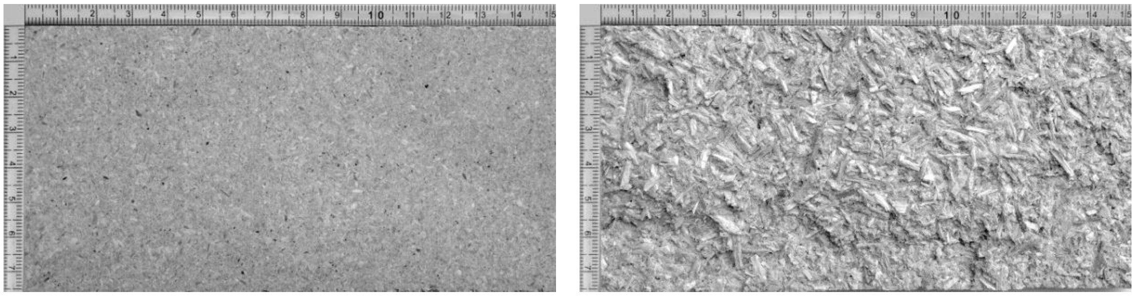
Length of Screw	Head Diameter (A)	Shank Diameter (E)	Dimension of Recess			Major Diameter (D)	Minor Diameter (d)	Number of Threads
			Diameter (M)	Depth (G)	Width (N)			
36.8 (1)[a]	9.4 (2)	3.6 (2)	3.6 (2)	4.1 (1)	0.81 (1)	4.6 (1)	3.4 (1)	12

[a] Values in parentheses are coefficient of variation (%)

Experimental Design

Two complete 2 × 2 × 3 factorial experiments with 10 replicates per combination were conducted to evaluate the effects of factors on SET and STT of driving screws into the face of PB materials. The three factors were screwdriver air pressure, screw penetration depth, and magnitude of vertical driving force. Experiment #1 had 12 combinations of two levels of screwdriver air pressure (0.45 and 0.62 MPa) by two levels of screw penetration depth (12.7 and 19.1 mm) by three levels of magnitude of vertical driving force (67, 78, and 89 N) when no pilot hole was drilled. Experiment #2 had 12 combinations of two levels of screwdriver air pressure (0.45 and 0.62 MPa) by two levels of screw penetration depth (12.7 and 19.1 mm) by three levels of magnitude of vertical driving force (44, 67, and 89 N) when a 3.2-mm diameter pilot hole was drilled.

One screw-driving torque test into one face-specimen was performed. Thus, a total of 240 screw-driving tests were performed on 240 PB testing blocks and 480 data points for torques were collected. Each testing block had dimensions of 76.2-mm-wide × 152.4-mm-long × 18.26-mm-thick. Figure 2 shows the particle size distribution of the core of the PB specimen. The PB core had 65% larger particles with their size ranging from 4- to 15-mm-long and 2.5- to 4-mm-wide and 35% smaller particles with their size ranging from 0.5- to 4-mm-long and 1- to 2-mm-wide.



(a) (b)

Fig. 2. Particle size distribution of surface of particleboard (a) and core of particleboard (b)

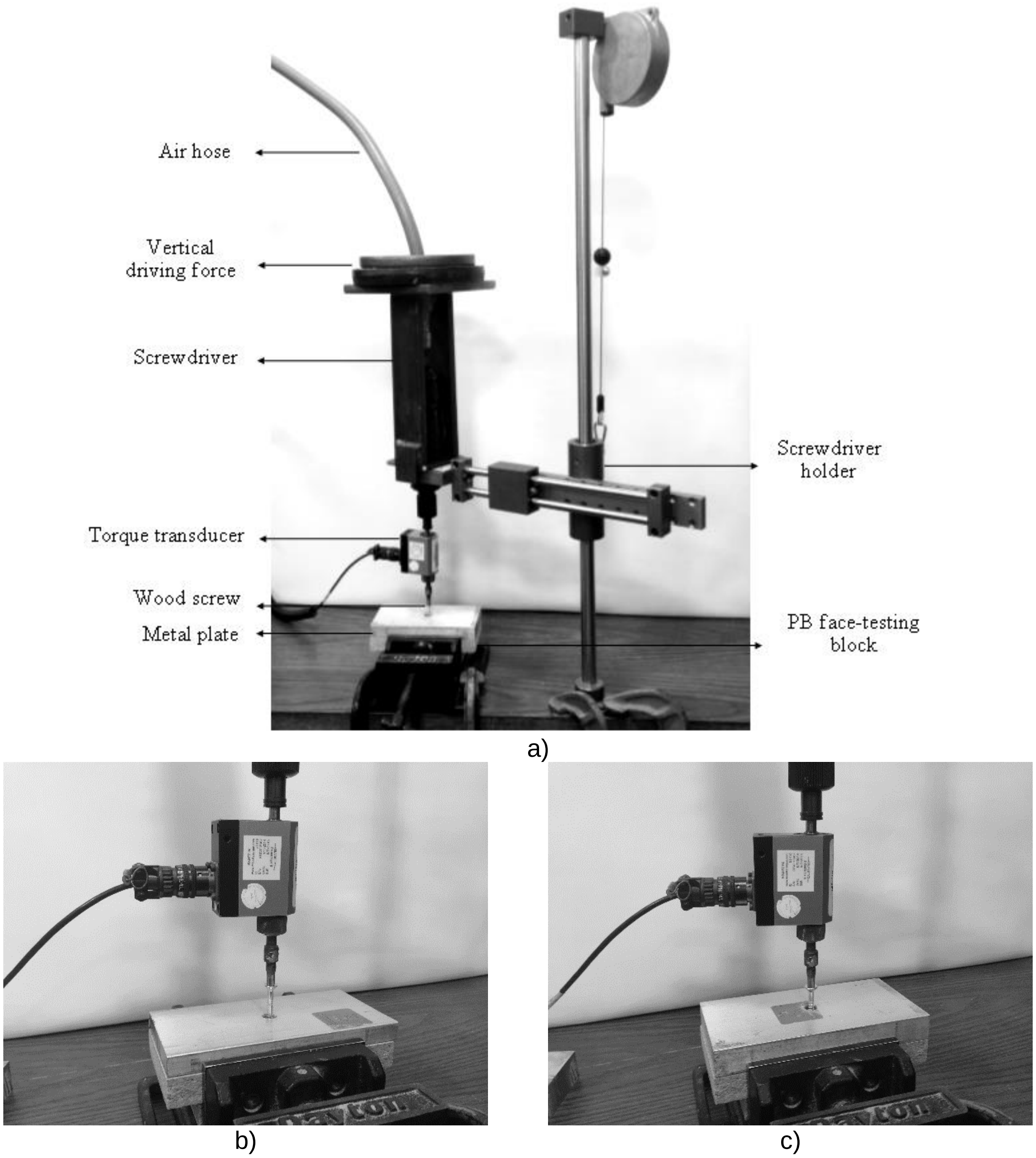


Fig. 3. Test setups for evaluation of torque behavior of driving screws into face PB specimen: a) general test setup; b) and c) test setups with the 12.7- and 19.1-mm-thick metal plate on a single face specimen, respectively

Methods

Specimen preparation and torque measurement

All testing blocks were cut from full-size sheets of 18.26-mm-thick PB panels (1.22 × 2.44 m^2), and conditioned at 20 ± 3 °C and 65 ± 5% relative humidity for two weeks. In each face testing block, the pilot holes were drilled into the center of its surface in accordance with ASTM D1761-06 (2010). Pilot hole depths were drilled at 9.5 and 14.3 mm for screw penetration of 12.7 and 19.1 mm, respectively. For torque testing blocks, all torque measurements were immediately performed after pilot holes had been drilled into the testing blocks. The physical and mechanical properties were evaluated in accordance with the procedure described in ASTM D4442-92 (2010) and ASTM D1037-06 (2010), respectively. The density profile of a PB specimen was measured using Quintek Measurement Systems' Density Profiler, Model QDP-01X (Knoxville, TN, USA)

Figure 3 shows the test setup for obtaining torque data through the process of driving screws into face testing blocks. The torque measurement apparatus consisted of a TT500FH dial screwdriver attached to a RTSX 100i rotary transducer (Mountz, Foley, AL, USA), and a laptop computer installed with Mountz torque and force analyzer, which has a CFII PCMCIA card and a Wizard Plus software (Mountz, San Jose, CA, USA). The pneumatic power screwdriver was held by its holder and could be pushed and slid vertically to ensure that screws were driven perpendicularly into the testing blocks. The operating torque range of torque transducer was from 1.13 to 11.3 N·m, of which the collecting rate was 50 points per second. Two screwdriver pressures represented two different screwdriver rotational speeds. The screw-driving process ended in approximately 3 to 4 s with the material stripped. Critical torque values were obtained from torque-time curves in the torque measuring system. The physical and mechanical properties were evaluated in accordance with the procedure described in ASTM D4442-92 (2010) and ASTM D1037-06 (2010), respectively.

RESULTS AND DISCUSSION

Table 2 summarizes the mean values of some physical and mechanical properties, such as measured density, moisture content (MC), and internal bond, for the PB specimens evaluated in this study. The density profile of the PB material used in this study was a symmetrical "U-shape" based on its panel thickness, which had a higher density on the face layers than in the core of the material (Leng *et al.* 2017; Wang and Zhang 2018).

Table 2. Physical and Mechanical Properties of PB Specimens

Density (g/cm^3)				
Overall	Core	Surface	MC (%)	Internal bond (MPa)
0.59 (14)[a]	0.46 (4)	0.85 (5)	8.0 (3)	0.75 (4)

[a] Values in parentheses are coefficient of variation (%).

Torque-time Curves

Figure 4 shows a typical torque time curve recorded during the complete course of driving screws into the faces of tested PB materials. This process could be divided into three phases of: thread forming and screw seating (phase I), clamping (phase II), and screw stripping (phase III) (Robert 2012; Tor *et al.* 2015; Yu *et al.* 2015; Kuang *et al.* 2017). In phase I, the screw-driving torque gradually increased as the screw cut PB materials to form threads meanwhile overcoming friction force between the contacting surface of a screw and PB materials, and then the screw became seated once the torque reached its SET value. In phase II, right after reaching its SET value, the screw started its tightening process with sharply increasing torque to its STT value. In phase III, the torque value dramatically dropped once the torque passed its STT point.

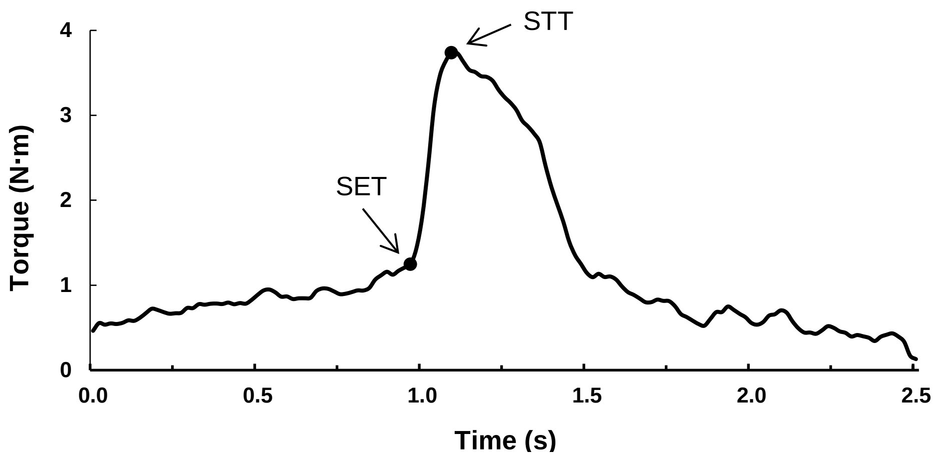


Fig. 4. A typical torque time curve of driving screws into faces of tested PB materials

Mean Driving Torque Comparisons

Table 3 summarizes the mean SET and STT values of driving screws into faces of PB materials for each combination of screwdriver air pressure (pressure) by screw penetration depth (depth) by magnitude of vertical driving force (force) by pilot hole diameter (diameter) evaluated in this study and also their corresponding STT-to-SET ratios, indicating that mean SET values ranged from 0.87 to 1.65 N·m while mean STT values ranged from 2.71 to 5.21 N·m. For their corresponding STT-to-SET ratios, there were 18 of 24 combinations of pilot hole diameter by screwdriver air pressure by screw penetration depth by magnitude of vertical driving force with ratios equal to or greater than 3, and the remaining six had ratios less than three but greater than 2. These results indicated that the combinations with ratios greater than three were suitable for using power tools, but for those combinations with ratios less than three, more skill is required for the operators (Robert 2012).

Table 3 also indicates that STT had clearly higher values than SET (Tor *et al.* 2015). Therefore, an analysis of variance (ANOVA) and mean comparisons were separately performed on the SET and STT for each of two different pilot hole data sets. A three-factor ANOVA general linear model (GLM) procedure was performed for each of the two data sets (with and without pilot holes drilled) at the 5% significance level to analyze three main effects and their interactions on the means of SET and STT for driving screws into faces of the evaluated PB materials. Table 4 summarizes the ANOVA results obtained from the GLM procedure performed on SET and STT data sets within each of two pilot hole diameter levels.

Table 3. Mean Values of SET and STT of Driving Screws into Faces of PB Materials Evaluated in this Study

Pressure (MPa)	Diameter (mm)	Depth (mm)	Force (N)	Torque Type (N·m)		Ratio STT/SET
				SET	STT	
0.45	0	12.7	67	1.17 (5)[a]	2.95 (10)	2.5
			78	1.23 (7)	3.40 (14)	2.8
			89	1.23 (8)	3.89 (15)	3.2
		19.1	67	1.49 (9)	4.39 (9)	2.9
			78	1.70 (7)	5.11 (16)	3.0
			89	1.62 (5)	5.21 (15)	3.2
	3.2	12.7	44	0.89 (7)	3.09 (8)	3.5
			67	0.93 (8)	3.13 (9)	3.4
			89	0.87 (12)	2.89 (13)	3.3
		19.1	44	1.06 (7)	3.70 (4)	3.5
			67	1.09 (16)	3.73 (6)	3.4
			89	1.14 (10)	3.90 (7)	3.4
0.62	0	12.7	67	1.14 (14)	3.10 (7)	2.6
			78	1.18 (8)	3.54 (10)	3.1
			89	1.24 (6)	3.88 (9)	3.1
		19.1	67	1.59 (4)	4.55 (5)	2.9
			78	1.64 (5)	4.63 (4)	2.8
			89	1.65 (7)	5.04 (8)	3.1
	3.2	12.7	44	0.88 (8)	3.05 (12)	3.5
			67	0.88 (8)	2.71 (9)	3.1
			89	0.90 (6)	2.81 (9)	3.1
		19.1	44	1.11 (10)	4.31 (11)	3.9
			67	0.99 (5)	4.22 (11)	4.2
			89	1.14 (14)	4.63 (10)	4.1

[a] Values in parentheses are coefficient of variation (%)

Table 4. Summary of ANOVA Results Obtained from the GLM Procedure Performed on Three Factors for SET and STT Data Sets within Each of Two Pilot Hole Diameters

	Diameter (mm)							
	0				3.2			
	SET		STT		SET		STT	
Source	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Force	6.95	0.0014	25.74	< 0.0001	1.80	0.1706	1.26	0.2891
Pressure	0	0.9928	0.16	0.6918	0.37	0.5444	12.57	0.0006
Depth	506	< 0.0001	249	< 0.0001	111	< 0.0001	343	< 0.0001
Force × Pressure	4.15	0.0184	1.31	0.2747	2.31	0.104	2.27	0.1082
Force × Depth	3.4	0.037	0.51	0.6033	3.40	0.037	5.59	0.0049
Pressure × Depth	2.01	0.1594	2.07	0.1529	0.04	0.8397	41.51	< 0.0001
Force × Pressure × Depth	0.42	0.6572	1.18	0.3127	0.75	0.4748	0.83	0.4373

In general, the ANOVA results indicated that the main effect of screw penetration depth was considered statistically significant at the 5% level for each of the four data sets (Table 4). Further checking the magnitudes of the F values of all factors within each of the four data sets indicated that screw penetration depth had its value of 506, 249, 111, and 343, respectively, which were all much larger than their corresponding other two factors. This could imply that the significance of the screw penetration depth effect on torque values was much stronger than the other two factors, *i.e.*, magnitude of vertical driving force and screwdriver air pressure. Therefore, the screw penetration depth effect on torque values was performed based on mean comparisons of the main effect directly. The mean comparison results indicated that in general, screws with a penetration depth of 19.1 mm had a significantly higher torque value, *i.e.*, either SET or STT, than those with a penetration depth of 12.7 mm for all 12 combinations evaluated.

The effects of the other two factors, magnitude of vertical driving force and screwdriver air pressure, on the mean torque value for each of the four data sets in Table 4 were analyzed by considering their corresponding non-significant three-way interaction. They were analyzed in this way because the nature of conclusions from interpretation of main effects also depends on the relative magnitudes of the interaction and individual main effects (Freund and Wilson 1997). The mean comparison results of the torque values for magnitude of vertical driving force and screwdriver air pressure are summarized in Tables 5 and 6, respectively. These results were based on a one-way classification created with 12 treatment combinations with respect to the three-factor interaction for each of the four data sets in Table 4. The protected least significant difference (LSD) multiple comparisons procedure at the 5% significance level was performed to determine mean differences among those treatment combinations. The LSD values of 0.09 and 0.42 N·m were used to determine mean differences among different treatments for SET and STT data sets (Table 5), respectively, when no pilot hole was drilled.

Table 5. Mean Comparisons of SET and STT for Magnitude of Vertical Driving Force within Each Combination of Pilot Hole Diameter by Screwdriver Air Pressure by Screw Penetration Depth

Diameter (mm)	Pressure (MPa)	Depth (mm)	Torque Type					
			SET			STT		
			Force (N)					
			67	78	89	67	78	89
			---------- (N·m) ----------					
0	0.45	12.7	(1.17) A*	(1.23) A	(1.23) A	(2.95) C	(3.40) B	(3.89) A
		19.1	(1.49) B	(1.7) A	(1.62) A	(4.39) B	(5.11) A	(5.21) A
	0.62	12.7	(1.14) B	(1.18) AB	(1.24) A	(3.10) B	(3.54) A	(3.88) A
		19.1	(1.59) A	(1.64) A	(1.65) A	(4.55) B	(4.63) AB	(5.04) A
			Force (N)					
			44	67	89	44	67	89
			---------- (N·m) ----------					
3.2	0.45	12.7	(0.89) A	(0.93) A	(0.87) A	(3.09) A	(3.13) A	(2.89) A
		19.1	(1.06) A	(1.09) A	(1.14) A	(3.70) A	(3.73) A	(3.90) A
	0.62	12.7	(0.88) A	(0.88) A	(0.9) A	(3.05) A	(2.71) B	(2.81) AB
		19.1	(1.11) A	(0.99) B	(1.14) A	(4.31) B	(4.22) B	(4.63) A

*Means with the same capital letter in the same row are not statistically significant at the 5% level

The LSD values of 0.09 and 0.30 N·m were used for SET and STT data sets, respectively, when a 3.2-mm diameter pilot hole was drilled. Mean comparisons summarized in Table 6 utilized a single LSD value of 0.09 and 0.42 N·m for SET and STT data sets, respectively, when no pilot hole was drilled into the PB material; while an LSD value of 0.09 and 0.30 N·m was used for SET and STT data sets, respectively, when a 3.2-mm diameter pilot hole was drilled.

In addition, mean comparisons of torque values based on the non-significant three-way interaction for screw penetration depth yielded the same results obtained from mean comparisons with respect to main effect only. This further confirmed the results from the main effect mean comparison indicating that screws with a penetration depth of 19.1 mm had a significantly higher torque value, *i.e.*, either SET or STT, than those with a penetration depth of 12.7 mm for all 12 combinations evaluated in this study.

Table 6. Mean Comparisons of SET and STT for Screwdriver Air Pressure within Each Combination of Pilot Hole Diameter by Screw Penetration Depth by Vertical Driving Force

Diameter (mm)	Depth (mm)	Force (N)	Torque Type			
			SET		STT	
			Pressure (MPa)			
			0.45	0.62	0.45	0.62
			------------------------- (N·m) ------------------------			
0	12.7	67	(1.17) A*	(1.14) A	(2.95) A	(3.10) A
		78	(1.23) A	(1.18) A	(3.40) A	(3.54) A
		89	(1.23) A	(1.24) A	(3.89) A	(3.88) A
	19.1	67	(1.49) B	(1.59) A	(4.39) A	(4.55) A
		78	(1.7) A	(1.64) A	(5.11) A	(4.63) B
		89	(1.62) A	(1.65) A	(5.21) A	(5.04) A
3.2	12.7	44	(0.89) A	(0.88) A	(3.09) A	(3.05) A
		67	(0.93) A	(0.88) A	(3.13) A	(2.71) B
		89	(0.87) A	(0.9) A	(2.89) A	(2.81) A
	19.1	44	(1.06) A	(1.11) A	(3.70) B	(4.31) A
		67	(1.09) A	(0.99) B	(3.73) B	(4.22) A
		89	(1.14) A	(1.14) A	(3.90) B	(4.63) A

*Means with the same capital letter in the same row are not statistically significant at the 5% level

Vertical driving force effects

In general, when no pilot hole was drilled, mean SET and STT values both showed an increased trend as vertical driving force increased (Table 5). There was no significant increase in mean for both SET and SST values when vertical driving force increased from 78 to 89 N. Mean SST values at vertical driving forces of 78 and 89 N were significantly higher than ones at 67 N, but this significance only occurred in two situations for mean SET values. In the case of 3.2-mm diameter pilot holes drilled, there was no significant increase or decrease trend observed for both mean SET and STT values. All these results indicated that the magnitude of a vertical driving force applied on a screw during the process of driving the screw into PB materials significantly affected the magnitude of driving torques if there was no pilot hole drilled, but these significant influences were not observed in the process of driving screws into PB materials when 3.2-mm diameter pilot holes were drilled.

Screwdriver air pressure effects

There was no obvious increasing or decreasing trend for both mean SET and STT values when no pilot holes were drilled (Table 6), indicating that screwdriver air pressure levels evaluated in this study had no significant effect on the magnitude of driving torques in particleboard materials for the situation with no pilot holes drilled (Kuang *et al.* 2017). This observation is the same as the mean comparisons of SET and STT data sets for screwdriver air pressure based on main effect mean comparison only.

In the case of 3.2-mm diameter pilot holes drilled, there was also no obvious increase or decrease trend for the magnitude of driving torques observed in most experimental combinations, except for the situations where screws were driven into particleboard materials with a penetration depth of 19.1 mm. In this case, mean STT values for driving screws into particleboard materials with a screwdriver air pressure of 0.62 MPa were significantly higher with a screwdriver air pressure of 0.45 MPa.

Screw penetration effects

Mean comparison results indicated that the screw penetration depth level evaluated in this study significantly affected both the mean SET and STT values for all combinations of pilot hole diameter by vertical driving force by screwdriver air pressure, *i.e.*, screws with a penetration depth of 19.1 mm had a significantly higher torque value, either SET or STT, than those with a penetration depth of 12.7 mm.

CONCLUSIONS

1. The effects of vertical driving force, screwdriver air pressure, and screw penetration depth on the magnitude of critical torques, SET and STT torques, for driving screws into particleboard materials were investigated. Experimental results indicated that the magnitude of a vertical driving force applied on a screw during the process of driving the screw into particleboard materials significantly affected the magnitude of critical driving torques like SET and STT if no pilot hole was drilled, but this influence became non-significant if 3.2-mm diameter pilot holes were drilled.
2. The screwdriver air pressure had no significant effect on the magnitude of critical driving torques in particleboard materials if no pilot hole was drilled, but when a pilot hole was drilled, increasing the screwdriver air pressure from 0.45 to 0.62 MPa can lead to increased mean STT values.
3. In general, increasing a screw penetration depth from 12.7 to 19.1 mm significantly increased the SET and STT values. The conclusions were limited to the PB materials evaluated in this study.
4. The results based on the relationship among the factors can help PB manufacturers to reduce their operators' cumulative injuries in the hand-wrist-forearm area and in the shoulder and neck.

ACKNOWLEDGMENTS

The authors are grateful to the Department of Sustainable Bioproducts at Mississippi State University for providing experimental facilities for this study.

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Article submitted: March 27, 2019; Peer review completed: June 29, 2019; Revised version received and accepted: June 30, 2019; Published: June 30, 2019.
DOI: 10.15376/biores.14.3.6645-6656