# PREDICTION OF INTERNAL BOND STRENGTH IN PARTICLEBOARD FROM SCREW WITHDRAWAL RESISTANCE MODELS

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ABSTRACT

Density, internal bond (IB) strength, and screw withdrawal resistance (SWR) data from 20 MS and M2 grade particleboards from two Canadian manufacturers were used to examine the correlations between face and edge SWR, and density and IB. SWR data were matched with previously published models for SWR as functions of density or IB, which were only reliable if they contained terms for screw dimensions and embedment depth. There was little or no correlation between the face or edge SWR of particleboards and their density, but sufficiently good correlation with IB ($r^2 > 0.7$) to support the development of SWR tests as a useful, rapid estimate of IB of particleboard panels. The proposed models are internally calibrated to 5/8-in.-thick board only and need to be developed and tested on other particleboards.

*Keywords:* Wood-based composites, particleboard, furniture, nondestructive evaluation, screw withdrawal resistance, internal bond, density.

## INTRODUCTION

In this paper SWR in particleboard is investigated as a means of estimating IB strength, a simple and rapid assessment tool that could be useful to manufacturers of furniture from particleboard. Internal bond testing using conventional ASTM recommendations has several drawbacks that include the need to cut samples to exact size (destroying the board), a supply of numerous metal blocks and glue, a universal testing machine, and time to prepare, condition, and test the samples (Lehmann 1965). For these reasons, numerous attempts have been made to find simpler and nondestructive methods of measuring and comparing IB strength of particleboard and other composites. Destructive tests include push-out tests (Lehmann 1965; Akcay and Eckelman 2001) and torsional tests (Gaudert 1974; Seetharamu et al. 1976; Passialis and Tsoumis 1982). Push-out tests use hole-saws of two different diameters to cut into the opposite faces of the board to leave an intact portion in the core. The smaller plug is loaded until the core material between the two plugs fails. Torsional tests use a torque wrench to measure the shear strength of circular plugs drilled out of the board and are based on the shear resistance of of the board being closely correlated with IB strength. A nondestructive method for in situ evaluation of bond strength in particleboard is ultrasonic stress wave propagation (Sun and Arima 1999), although this requires more specialized equipment.

Previous studies have found strong correlations between SWR, density, and IB of particle-

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board, and it is therefore possible that a simple SWR test, which disrupts a smaller volume of material in the board, could also provide information on less easily measured properties such as IB. SWR tests have been used previously to assess strength properties of wood composite panels, particularly for plywood. Data from Talbot (1982), Ross et al. (1992), and Winandy et al. (1998) have found sufficient correlation between SWR loads and bending strength in plywood to develop reliable models for bending strength based on SWR values. Winandy et al. (1998) used an electronic hand-held screw extraction force reader to gain a rapid in situ estimate of residual bending strength of heat damaged plywood panels from building fires.

No such work exists on the use of SWR tests to estimate strength properties in particleboard, although models have been developed in the past to predict SWR in particleboard based on its measured density or IB. Previous studies including Johnson (1967); Eckelman (1973, 1975); Yahya and Abdul-Kader (1998); Mallari et al. (1989), Wong et al. (1999); and Poblette et al. (1996), have found SWR of particleboard to be proportional to its density or specific gravity (SG). As such, linear or polynomial equations incorporating board density, screw dimensions, and depth of penetration have been developed to predict face and edge SWR (NPA 1968; Eckelman 1975; Barnes and Lyon 1978).

A simple linear model for face SWR (in lb) published by the National Particleboard Association (NPA 1968) based on the work of Johnson (1967) is:

$$SWR_{\text{edge}} = 11.32\rho + 274.3 \qquad (1)$$

where $\rho$ is the particleboard density (lb/ft$^3$).

This model did not account for the critical effects of screw dimensions or embedment depth on SWR and so subsequent work by Eckelman (1975) modified it to incorporate screw shank diameter and embedment depth. Eckelman's data resulted in a curvilinear relationship between SWR and board density. Models for face and edge SWR (in lb) developed by Eckelman (1975) that contain terms for screw shank diameter and depth of embedment are:

$$SWR_{\text{edge}} = 2055D^{0.5} \times (L\text{–}D/3)^{1.25} \times G \qquad (2)$$

$$SWR_{\text{face}} = 2655D^{0.5} \times (L\text{–}D/3)^{1.25} \times G \qquad (3)$$

where $D$ is the shank diameter of the screw (in.), $L$ the depth of embedment of the threaded portion of the screw (in.), and $G$ the air-dry specific gravity of the board at 10% MC.

Eckelman (1975) noted that both the NPA model (Eq. 1) and his own models (Eqs. 2 and 3) could be applied only to boards conditioned to 10% MC since there was no knowledge of the possible confounding effects of board MC. Barnes and Lyon (1978) compared Eckelman's models for face and edge SWR from particleboard with their own SWR data for both unweathered and weathered particleboard. As expected, only SWR from unweathered boards was well described by Eckelman's models. Eckelman's model for face SWR (Eq. 3) agreed well with data from unweathered boards tested by Barnes and Lyon (1978), with an average error of only 2%. Eckelman's model for edge SWR (Eq. 2) overestimated values for unweathered boards by approximately 5%. In the case of weathered boards, the predicted edge SWR values exceeded actual values by approximately 22%, suggesting that weathering and exposure to water contributed to deterioration of adhesive bonds and IB strength, which in turn reduced screw holding capacity.

In other studies, SWR in particleboard has been linked to its IB strength. Findings by Fujimoto and Mori (1983) suggest that the bending failure load of L-type joints of particleboard connected by screws is not only strongly affected by length of screw but is also under the influence of the IB strength of the particleboard. An appraisal of work on edge SWR of particleboard and MDF by Eckelman (1973) resulted in the development of an equation for edge SWR (in lb) based on screw dimensions, embedment depth, and IB as follows:

$$SWR_{\text{edge}} = 39(\sigma_{IB})^{0.85} \times D^{0.5} \times (L - D/3)^{1.25} \qquad (4)$$

where $D$ is the screw diameter (in.), $L$ the embedment depth of screw (in.), and $\sigma_{IB}$ the measured IB strength of the board (psi).

Equation (4) was based on 1-in. Type A sheet metal (self-tapping) screws with 12 threads per in. (tpi) that were no longer produced by 1973/74. These were replaced by type AB screws with 16 tpi, for which Superfesky (1974) did a comparative study with the Type A screws for particleboards and hardboards. The increased number of threads resulted in a consistent decrease in face and edge SWR in both board types, but this screw is nevertheless still recommended for measurement of SWR in ASTM D1037 (2000). Further work by Zaini and Eckelman (1993) adapted Eckelman's (1973) for face SWR and incorporated pilot hole diameter as a variable. They developed the following predictive model for face SWR, based on tests with Type A screws for gauges 10, 12, 14, and 16:

$$SWR_{\text{face}} = 14 \times D^{0.645} \times \sigma_{IB}{}^{1.025} \times (1 + H/100)^{0.3} \quad (5)$$

where $D$ is the screw diameter (in.), and $H$ the pilot hole diameter (in.). Note that this model contains no term for embedment depth.

Zaini and Eckelman (1993) were unable to produce any well-defined predictive model for edge SWR from particleboard due to its coarse, nonuniform core, and also recommended that a much broader range of boards be tested before their suggested model for face SWR for particleboard and MDF could be used as a general model.

Although the above-mentioned models are based on good correlations between SWR and IB of particleboard, in some other studies the relationships between SWR and IB in particleboard were less clear. For example, Coleman and Biblis (1976) manufactured particleboards from different proportions of heartwood and sapwood of sweetgum (*Liquidambar styraciflua*) and found that the IB of boards made from sapwood was 65% higher than boards made from heartwood. Despite this trend, there were no appreciable differences in the screw or nail-holding ability of the boards. Yahya and Abdul-Kader (1998) compared the IB and face SWR of particleboards bonded with melamine urea formaldehyde (MUF) and isocyanate resin manufactured to densities of 0.4, 0.5, and 0.6 g/cm$^3$; boards bonded with isocyanate resin had consistently higher IB than those bonded with MUF. Face SWR was strongly correlated with board density, but was completely unaffected by binder type and therefore was not correlated with the differences in IB resulting from the different binders.

The questions of how closely SWR in particleboard is linked to density and IB, or whether previous models are applicable to furniture grade particleboard, appear unresolved. The objectives of this study were therefore to:

1. Compare SWR data from modern furniture grade particleboards with past models of face and edge SWR based on board density and IB.
2. Examine relationships between density, IB, and SWR (face and edge) in furniture grade particleboard to determine whether SWR tests could provide a reliable estimate of IB for manufacturers of secondary products from particleboard.

## MATERIALS AND METHODS

Five 5/8-in. (15.87-mm)-thick particleboard panels each of MS and M2 grade measuring 4 × 8 ft (1.22 × 2.44 m) were sampled from two particleboard mills in Canada that manufactured both grades, denoted as press lines A and B, for a total of 20 panels. Each panel was divided into 8 sub-panels measuring 2 × 2 ft (610 × 610 mm) from which the same set of 12 test specimens were cut according to a template in which the specimens were positioned randomly on each sub-panel. Density, IB, and face and edge SWR were tested in accordance with ASTM D 1037 (2000). Face and edge SWR were tested using two 1-in.-long, gauge 10 sheet metal screws (Screw A with 16 threads per in., tpi and Screw B with 10 tpi). A full description of the measurements, statistical design and analyses, and results comparing the physical and mechanical properties (including MOR and MOE) of MS and M2 grade particleboards can be found in Semple et al. (2005a and b), but for clarity a summary of the experimental design showing fixed and random effects is given in Table 1. MOR and MOE were also measured but are omitted as they are not relevant to this study. The specimens for density, IB, and face and edge SWR were end- or side-matched, i.e. cut as groups that were situated in a different location on each sub-panel. A summary of the grade and press line averages and COV for density, IB, and SWR from Semple et al. (2005b) is given in Table 2. Data are pooled across nonsignificant main effects (see Table 1) and so *n* denotes the total number of specimens represented in each mean.

The reviewed models are all based on imperial units, and so they were solved for different density or IB in imperial units and the resulting SWR values converted to SI units (i.e. N) and plotted against density or IB in SI units to enable direct comparison with our data. It should be noted, therefore, that the resulting line or curve is not described by the same equation as the original model.

## RESULTS AND DISCUSSION

### *Grade and press line comparisons*

Panels from press line A were lower in density but higher in IB, and face and edge SWR than those from press line B (Table 2). Note that there was less variation in core density between the two press lines. Variation in IB and edge SWR was high; COV for IB ranged from 11% to 19% and for edge SWR from 12% to 17.5%. In contrast, panel density and core density were more consistent with COV values between 1% and 3.5%. There was a very narrow range of average core density across grades and press lines (509 to 545 kg/m$^3$). These observations suggest that factors other than density may be influencing bonding and screw-holding capacity of the sampled particleboards.

### *Comparison of face and edge SWR results with previous models*

*Density-based models.*—The average face SWR values for each grade and press line are compared with the simple density function for face SWR of Eq. (1) (NPA 1968) in Fig. 1 and converted to SI units. Note that the averages for screws A and B have been kept separate because there was a statistically significant difference in face SWR between the two (Semple et al. 2005b). Averages for grades and press lines were only about 30% of the Eq. (1) predictions, likely owing to the fact that the model contains no terms for screw dimensions or embedment depth, and so correct values could not be calculated for our screws. If the model is based on different screws, and in particular greater embedment depth, then SWR will be much higher for any given panel density. This is because SWR is highly dependent on screw embedment depth (Eckelman 1973, 1975; Bachman and

TABLE 1. *Experimental design showing fixed and random effects on face and edge SWR, IB, and density.*

| Property | Fixed effects | Levels | Random effects | Levels |
|---|---|---|---|---|
| Edge SWR | Press line* | A, B | Board | 1 to 5 |
| | Grade* | M2, MS | Sub-panel | 1 to 8 |
| | Machine direction | ∥, ⊥ | Specimen | 1 to 4 |
| | Screw type | 16, 10 | | |
| Face SWR | Press line* | A, B | Board | 1 to 5 |
| | Grade* | M2, MS | Sub-panel | 1 to 8 |
| | Screw type* | 16, 10 | Specimen | 1,2 |
| IB, density | Press line* | A, B | Board | 1 to 5 |
| | Grade* | M2, MS | Sub-panel | 1 to 8 |
| | | | Specimen | 1,2 |

∥ denotes testing parallel to machine direction of the mat, ⊥ is perpendicular to machine direction.
* denotes significant effect at $\alpha = 0.05$.

TABLE 2. *Means and COV of physical and mechanical properties of M2 and MS boards from two press lines.*

| Property | $n$ | Press line / Grade | A M2 | A MS | B M2 | B MS |
|---|---|---|---|---|---|---|
| Density | 80 | mean (kg/m$^3$) | 681.0 | 633.5 | 706.7 | 684.4 |
| | | COV (%) | 1.3 | 3.4 | 2.7 | 3.8 |
| Core density | 80 | mean (kg/m$^3$) | 545.1 | 508.3 | 536.3 | 527.7 |
| | | COV (%) | 2.5 | 3.4 | 3.6 | 3.5 |
| IB | 80 | mean (MPa) | 0.70 | 0.58 | 0.43 | 0.34 |
| | | COV (%) | 11.2 | 14.5 | 18.9 | 14.0 |
| Face SWR-A | 40 | mean (N) | 1098.2 | 956.6 | 837.2 | 729.1 |
| | | COV (%) | 12.3 | 9.6 | 11.5 | 12.8 |
| Face SWR-B | 40 | mean (N) | 1166.1 | 987.4 | 883.1 | 748.2 |
| | | COV (%) | 6.6 | 8.7 | 11.2 | 13.5 |
| Edge SWR | 160 | mean (N) | 972.9 | 763.8 | 634.4 | 555.6 |
| | | COV (%) | 12.4 | 12.9 | 17.4 | 15.9 |

COV = coefficient of variation, i.e., mean/standard deviation, in %. $n$ = sample size per press line and grade; edge SWR values are pooled across the nonsignificant effects of machine direction (2) and screw type (2) to give $n$ = 160. Face SWR averages are given separately for screws A and B due to significant differences.

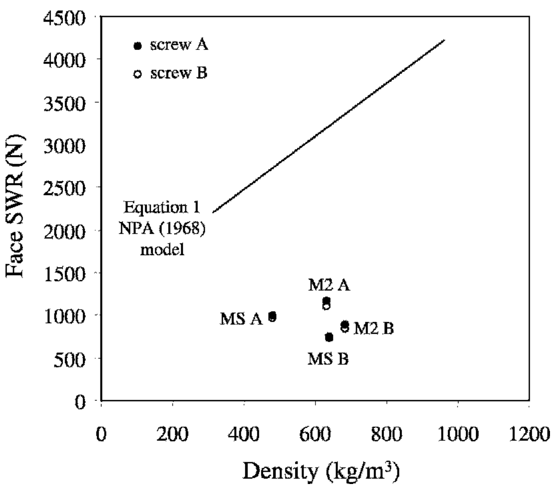


FIG. 1. Predicted change in face SWR with board density from NPA (1968) and converted to SI units. Average values for MS and M2 grade particleboard from press lines A and B are shown for comparison.

Hassler 1975). Another contribution to the discord between the model and our data could be that the particleboard upon which the NPA (1968) model is based had much higher bond strength relative to density than the particleboards sampled here.

Eckelman's (1975) models for SWR based on particleboard density from Eqs. (2) and (3) and converted to SI units are shown in Fig. 2a for $SWR_{edge}$, and 2b for $SWR_{face}$. As there was no significant effect of screw type on $SWR_{edge}$ the averages in Fig. 2a for each grade and press line are pooled across screw types. The values from press line A for $SWR_{edge}$ corresponded reasonably well to the predicted values from Eckelman's model for edge SWR, Eq. (2), based on the specific gravity of the board. The M2 grade particleboard from press line A (average SG of 0.68) matched Eckelman's model exactly, while the MS grade was slightly below model prediction. The average $SWR_{edge}$ of M2 and MS grade products from press line B were 40% and 44% below model predictions, respectively.

Again, there were only small differences between $SWR_{face}$ of boards from press line A and Eckelman's (1975) model, Eq. (3), calculated for the same density and screw conditions, as shown in Fig. 2b. In contrast, panels from press line B were almost 40% lower in $SWR_{face}$ than predicted by Eq. (3), indicating that SWR in particleboard may obey a density-based model only if panels have consistently high IB strength relative to density. Panels from press line B had low IB relative to their density, suggesting that SWR may be more closely linked to IB than density. Note also from Fig. 2b that Eckelman's model is not sensitive to the difference in shank diameter of the two screws used in this study. Actual $SWR_{face}$ was more sensitive to screw

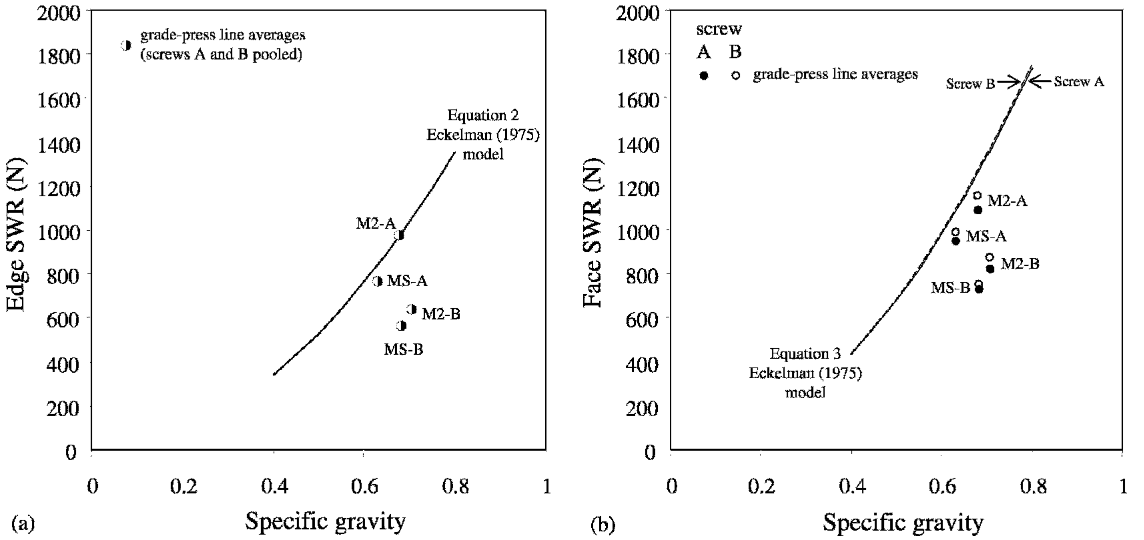


FIG. 2. Predicted change in (*a*) edge SWR and (*b*) face SWR with board specific gravity from Eckelman's (1975) models, converted to SI units. Average values from MS and M2 grade particleboard from press lines A and B are shown for comparison.

type, suggesting that other factors such as thread pitch and thread height that were not included in the model may affect SWR in particleboard more so than shank diameter over the narrow range of shank diameter used here.

*IB-based models.*—The two models for face and edge SWR that have been developed based on the IB of particleboard, Eq. (4) from Eckelman (1973) for edge SWR, and Eq. (5) from Zaini and Eckelman (1993) for face SWR, are compared with the means for both grades and press lines in Fig. 3a and b, respectively. As in Fig. 2a, the two-tone black and white symbols in Fig. 3a for edge SWR represent the averages for each grade and press line pooled across screw type. Note that averages for press line B, being lower in IB and SWR were closer to Eqs. (4) and (5), whereas those of press line A were further below predicted values in the upper range of IB. This is contrary to the comparisons of face and edge SWR means with the density-based models shown in Figs. 2a and b, whereby panels from press line B were much lower than predicted values.

The model of Zaini and Eckelman (1993), Fig. 3b, for face SWR predicts a much steeper increase of face SWR with IB; i.e., 1356 N for an IB of 0.4 MPa and 2802 N for an IB of 0.8 MPa. Only MS grade panels from press line B were similar to predicted face SWR, whereas the higher the IB of panels, the greater the deviation from predicted face SWR. The model of Zaini and Eckelman (1993) appears to greatly overestimate the effect of increasing IB on face SWR in furniture grade particleboards, most likely because it was developed based on a ¾-in.-thick panel rather than the 5/8-in. panels tested here. Unfortunately it does not contain a term for embedment depth that would enable the effect of particleboard thickness to be accounted for. Like Eckelman's (1975) model, the Zaini and Eckelman (1993) model also contained no terms for screw thread pitch and likewise showed less sensitivity to the differences between screws A and B than the actual data.

### *Relationships between SWR, density and IB of sampled panels*

*Panel density.*—Due to the wide variation of core density to IB strength ratio among sampled panels of both grades, there was no obvious relationship between core density and IB (Fig. 4). In the figure, data points are shown for press

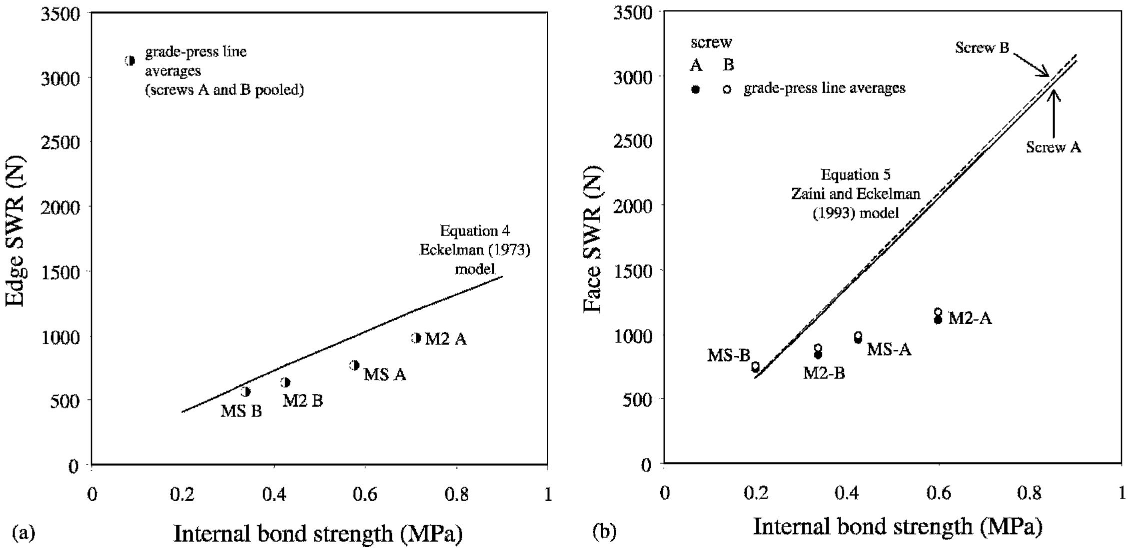


FIG. 3. Predicted change in (*a*) edge SWR from Eckelman (1973), and (*b*) face SWR from Zaini and Eckelman (1993) with IB, converted to SI Units. Average values from MS and M2 grade particleboards from press lines A and B for each screw type are shown for comparison.

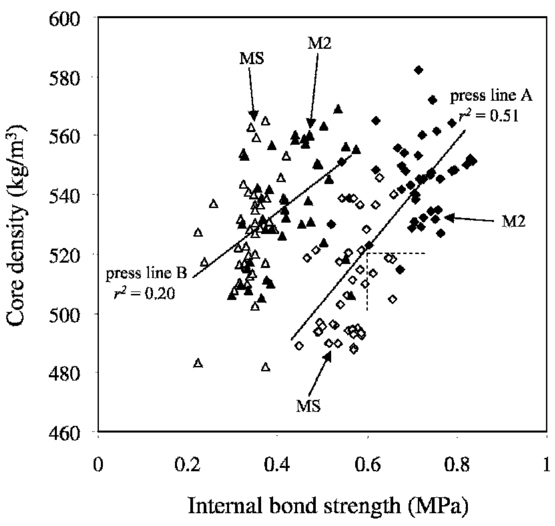


FIG. 4. Correlations between core density and IB strength for samples, separated by grade, from press lines A and B. Least squares fits to the means for each screw type are shown for comparison. Dashed lines highlight samples with high IB (>0.6 MPa) but low core density (<520 kg/m$^3$).

lines and grades and indicate that a reasonable correlation between core density and IB exists only among samples from press line A ($r^2$ = 0.51). The relationship in the case of press line B is confounded by most of their M2 samples being similar in density, and in many cases IB, to their MS grade, whereas samples of MS grade from press line A were lower than their M2 grade in both density and IB.

According to Johnson (1967), NPA (1968), and Barnes and Lyon (1978), particleboard density is the single most important factor controlling SWR. In contradiction to this, there were mostly only weak correlations between core density and $SWR_{edge}$ and board density and $SWR_{face}$, as shown in Figs. 5a and b, respectively. From Fig. 5a, correlation between $SWR_{edge}$ and core density was only slightly better for press line A, while no discernible relationship exits for press line B. Although the results represent particleboards from just two mills, board quality was markedly different between them, and there was high variation in IB relative to density. This is most likely to have confounded any relationships between SWR and density and suggests that SWR might be more closely related to IB. IB is influenced by many factors including resin formulation, content, distribution, press schedule, and curing conditions (Kelly 1977; Maloney 1977), specific details of which were unknown for the commercially produced boards here. Nevertheless, the lack of re-

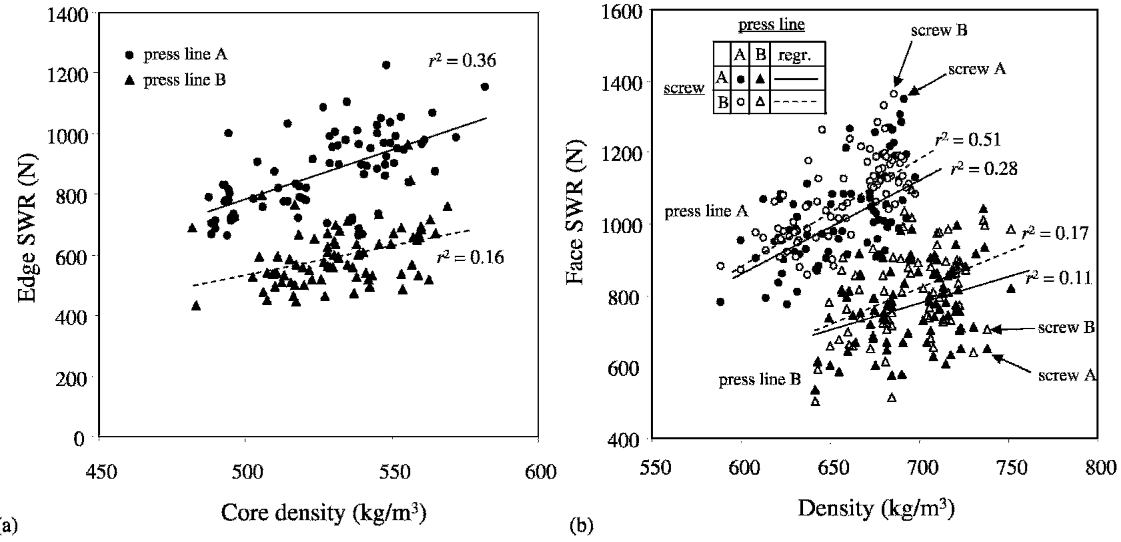


FIG. 5. Correlations between (*a*) edge SWR and core density, and (*b*) face SWR and board density by screw type for press lines A and B.

lationship with board density contradicts the assumptions in previous models developed to predict SWR that were based solely on board density, suggesting that a revised, non-density-based model is needed.

*IB strength.*—The relationship between IB and edge SWR of furniture grade particleboards is shown in Fig. 6a with each point representing the average of both screw types; a clear distinction between press lines A and B in both IB and SWR can be seen. As might be expected, SWR was strongly correlated with IB strength. This strong correlation suggests that the IB strength between particles is less than the compressive strength of the particles, i.e. the stress exerted by loading the screw threads pulls adjacent particles apart before it deforms them. Even at the individual specimen level, the correlation coefficient was high, $r^2 = 0.83$, and the linear equation of best fit is as follows:

$$SWR_{edge} = 1053.9\sigma_{IB} + 195.33 \qquad (6)$$

This equation permits one to estimate the minimum IB strength required if furniture grade particleboard is to meet standard requirements for SWR. The survey of MS and M2 grade particleboard (Semple et al. 2005b) noted that the average edge SWR values for the MS grade panels from both press lines were below the 800 N required for this grade by ANSI A208.1 (1999). When Eq. (6) is expressed in terms of $\sigma_{IB}$ and solved for an average edge SWR of 800 N, then $\sigma_{IB}$ must be at least 0.575 MPa. However the variation in the data in Fig. 6a shows that above an IB of 0.65 there were no samples below 800 N in edge SWR, as indicated by the dashed lines. Only 7.5% of the IB samples of MS board from press line A were above 0.65 MPa. This suggests that the IB of MS grade particleboard may need to be increased to between 0.6 and 0.65 MPa to ensure that the majority of samples will meet the ANSI A208.1 minimum recommendations for edge SWR. This does not necessarily require an increase in density; note from the plot of core density vs. IB for press line A in Fig. 4 the presence of samples to the right of and below the dashed lines that were above 0.6 MPa in IB but below 520 kg/m$^3$ in core density.

Similarly for face SWR, shown in Fig. 6b, the correlation with IB was significant ($r^2 > 0.6$) for both screw types tested (screw A with 16 tpi and screw B with 10 tpi). The correlation coefficients for face SWR and IB were not as high as for edge SWR, which is to be expected since for

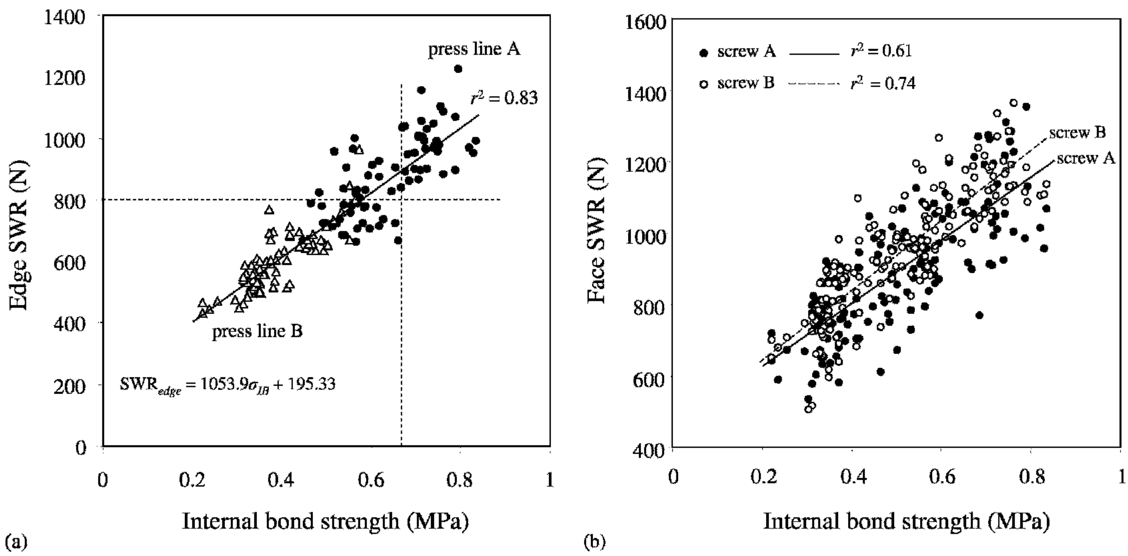


FIG. 6. Correlations between (*a*) edge SWR and IB strength, separated by press line, and (*b*) face SWR and IB strength, separated by screw type.

the face SWR test the screw is embedded through the stronger surface layers of the board as well as the core, but the bond strength of the surface layers is not reflected in the IB test.

### *Model sensitivity to IB*

Edge SWR might be expected to be similar or more sensitive to changes in IB since the screws are inserted only into the weakest zone of the board. Recall from Fig. 3 that comparison of the models by Eckelman (1973) for edge SWR and Zaini and Eckelman (1993) for face SWR suggested that face SWR may be more sensitive to changes in IB than is edge SWR. In Eq. (5) IB is raised to a higher power ($\sigma_{IB}^{1.025}$) than in Eq. (4) ($\sigma_{IB}^{0.85}$), thus making face SWR more sensitive to changes in IB. The regression lines from Fig. 6a and b for $SWR_{edge}$ and $SWR_{face}$ (screws A and B) are shown together on the same scale in Fig. 7 for comparison. The notion that face SWR is more sensitive to IB than edge SWR is questionable since the slopes of the lines for face and edge SWR are similar. The least squares fit for edge SWR was slightly steeper than that of face SWR tested using screw A, but similar in slope to face SWR tested using screw B, which had

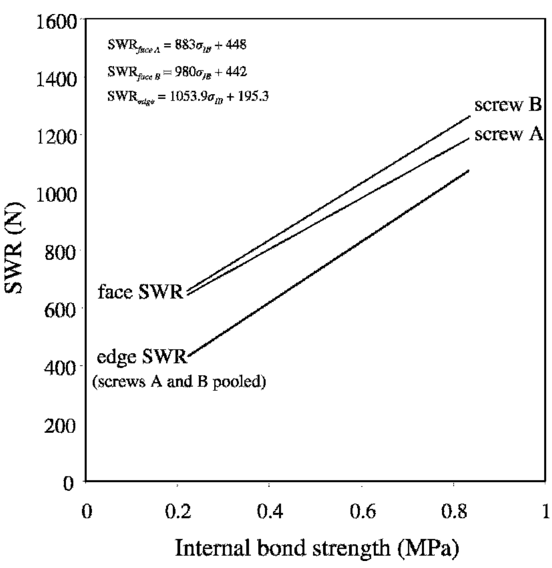


FIG. 7. Comparison of least squares fits of face SWR for screws A and B and of edge SWR (pooled across screws A and B) as functions of IB strength.

the higher correlation coefficient. The results suggest that face and edge SWR tests are not intrinsically different in their sensitivity to IB. However, changing the screw type used in the tests has a slight effect on the sensitivity of the model. Note also that the line for edge SWR is shifted downwards by approximately 25%, which is in agreement with the general trend for edge SWR of particleboard to be about 25% lower than face SWR (Eckelman 2003).

### *SWR and torque resistance tests as surrogates for IB*

From Fig. 6b, the greater sensitivity and strongest correlation, $r^2 = 0.74$, between face SWR and IB resulted from the use of screw B, which had a slightly higher shank diameter and fewer threads per inch than screw A. The results suggest that a simple test for face SWR on discarded pieces of particleboard using a similar screw to screw B could form a simple and useful tool for estimating and monitoring of IB strength of particleboard sheets. Although edge SWR gave higher correlations with IB, face SWR tests may be preferable since they are more readily applied over the surface of boards without the need for cutting to expose edges, and also give a better estimate of overall bond strength through the board thickness. For use with 5/8-in.-board, a no. 10 screw with 10 tpi and a shank diameter of approximately 0.19-in. is recommended in the absence of similar data using thicker or thinner screws. The proposed models for IB based on face and edge SWR need to be tested on a new set of particleboards for verification, and alternative models will be necessary for boards of other thicknesses since the screw embedment depth changes. The change in ratio of surface to core material may also influence the correlation between SWR and IB. The suitability of SWR tests for estimating flexural strength of particleboard should also be investigated.

In the absence of equipment capable of measuring screw withdrawal resistance, screw holding tests in particleboard are still commonly performed in RTA furniture factories using a torque wrench. A screw is driven into the board until the surrounding material fails or is stripped and the torque at that moment recorded. Carroll (1972) developed a useful torque-to-tension converter designed for spot testing the face SWR on large sheets of particleboard without having to cut test samples. It is therefore necessary to know how torque resistance correlates with SWR and IB to determine whether such tests could be used to predict IB strength. Carroll (1970) found a linear relationship between maximum torque and conventional screw withdrawal resistance values in the case of laboratory-made low density particleboard (<640 kg/m$^3$). However, this was not the case for commercial boards greater than 640 kg/m$^3$ in density. The relationship was thought to be confounded by increased friction. There is expected to be greater contact between the screw and the substrate of denser boards resulting in greater shear forces normal to the plane of the board, which may have a greater confounding effect on the relationship to tensile load resistance of the substrate. Work by Fujimoto and Mori (1983) also found no clear relationship between SWR and torque resistance for commercial particleboard. They observed that torque resistance increases with increasing screw diameter whereas SWR decreases. This suggests that torque resistance may not correlate well with SWR over a wide range of particleboard types, and it may be preferable to use a hand-held screw extraction force tool that reads tensile load resistance directly.

## CONCLUSIONS

1. Without terms for screw dimension and embedment depth, previous models for SWR were unable to be reliably matched with our data. Eckelman (1975) generated density-based models for face and edge SWR with terms for screw dimensions and embedment depth, but only samples from press line A with high IB relative to density matched these models when solved for the same screw conditions.
2. The measured face and edge SWR of panels with low IB relative to density were markedly lower than the density-based model predictions. There was also little correlation between face and edge SWR and density, suggesting that SWR is more closely linked to bond strength.
3. As expected, correlation between SWR values and panel IB was high, particularly for

edge SWR. This could provide a basis for spot tests on particleboards at a furniture factory to provide a rapid assessment of panel IB.

4. Predictions of previous models for face and edge SWR based on IB corresponded with the data from sampled boards only when their IB and SWR were low. At higher IB, the two previous models (edge SWR from Eckelman 1973 and face SWR from Zaini and Eckelman 1993) overestimated SWR, particularly in the case of face SWR where the model sensitivity to IB was much higher.
5. A comparison of two earlier models for face and edge SWR based on IB indicated that face SWR would be much more sensitive to changing IB than edge SWR. In contrast, comparison of least squares fits to measured face and edge SWR as a function of IB showed that sensitivity to changing IB was similar for face and edge SWR, although edge SWR was consistently around 25% lower than face SWR. Results from face SWR tests showed that changing the screw type changes the slope of the trend line between face SWR and IB, altering the sensitivity of the model to changing panel IB. Sensitivity to IB was greater for screw B with fewer tpi, making it a better candidate for screw pull tests than the screw currently used in ASTM D-1037, i.e., screw A.

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