THEORETICAL MODELING OF BONDING CHARACTERISTICS AND PERFORMANCE OF WOOD COMPOSITES. PART I. INTER-ELEMENT CONTACT

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ABSTRACT

This is the first of a four-paper series aiming to model fundamental bonding characteristics and performance of wood composites. In this paper, a mathematical model and a computer simulation model are developed to predict the variation of inter-element (strand) contact during mat consolidation. The mathematical predictions and the computer simulations agree well with each other. The results show that the relationship between the inter-element contact and the mat density is highly nonlinear and is significantly affected by the wood density and the element thickness. The effects of the element length and width are less significant. The models imply that use of less dense wood species and thinner strands are beneficial to lower product density while achieving adequate inter-element contact for bonding.

Keywords: Wood composites, modeling, simulation, relative contact area, consolidation, formation, bonding.

INTRODUCTION

Wood composites are manufactured by consolidation and gluing of wood constituent elements such as veneer, strands, particles, or fibers. The bonding between the wood elements is obviously one of the essential properties of wood composite products. Because of the relative low dosage of resin additives, sufficient bonding strength necessitates intimate contact between wood elements, which is obtained by a high degree of mat consolidation. On the other hand, the mat consolidation should be minimized to lighten the final products and maximize the volumetric recovery. Note that certain product properties, e.g. dimensional stability, will actually improve with lower densification. Unfortunately, most wood composites are 50% to 80% denser than the original wood elements, with the exception of veneer-based products. Minimizing

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product density while maintaining bonding strength is of critical importance to the sustainability and competitiveness of the wood composites industry.

The relationships between board density and properties (including bonding strength) have been broadly studied using predominantly trial-and-error approaches (e.g. Kelly 1977; Wang and Dai 2004). It was generally understood that bonding strength is linked to parameters such as resin type/content, board density and element geometry. While the previous research provided a general understanding, the traditional trial-and-error approaches often yielded inconclusive results due to experimental errors, which can be caused by many factors such as the inevitable variations in element geometry, resin distribution, and board structure. Some researchers therefore simplified the tests by using pairs of overlapped wood strands instead of random boards. The bonding properties between glued strands were then linked to the effects of resin distribution (Meinecke and Klauditz 1962; Smith 2003) and pressing temperature and time (Humphrey and Ren 1989). Others compromised by testing the properties of model boards made from cross-oriented continuous veneer strips. They were then able to draw conclusions regarding the effect of mat structure particularly horizontal density variation on board properties (Suchsland and Xu 1989; Dai et al. 2002).

The literature seems to point to a general relationship between bonding strength and board structure, resin distribution, and pressing conditions. Conceptually, bonding in wood composites should be governed by the contact between constituent elements, the resin coverage on element interfaces, and resin curing conditions. However, this relationship has yet to be systematically analyzed in the literature. Even the basic mechanisms of element contact and resin distribution are not well defined.

This series of papers will report our recent progress in modeling the bonding characteristics and performance of wood composites, particularly strand-based products. Built upon our previous models of mat formation and consolidation (Dai and Steiner 1993; Dai and Steiner 1994; Dai et al. 1997; Dai et al. 2005), the bonding models will be presented in a series of four papers. In this first paper, an advanced model will be presented to predict the inter-element contact in terms of such parameters as element dimensions, wood density, and mat density. Part II will focus on the resin distribution. In particular, mathematical and computer simulation models will be developed to characterize the spatial distribution of resin coverage on element surfaces. Part III will report the bonding strength of overlapped constituent elements. A model will be developed to link the bonding strength to the degree of element contact and resin coverage. In the fourth and final paper, a comprehensive model will be presented to predict the bonding properties of wood composites based on inter-element contact, resin distribution, and bond strength between overlapped elements.

The specific objectives of this paper are the following:

- To develop a mathematical model to predict the inter-element contact during mat consolidation,
- To validate the mathematical model using computer simulation, and
- To present typical predicted results on the effects of key processing parameters on element contact.

MODELING AND SIMULATION

The inter-element contact is characterized both analytically using mathematical equations and numerically using computer simulation. While the mathematical model offers a theoretical basis, the computer simulation can be very powerful to handle factors of complexity, e.g. nonuniform formation, irregular shape, and dimensions of constituent elements. Although it is a critical factor affecting bonding, the inter-element contact can be very difficult to quantify using experimental means. The outcomes of the mathematical model and the computer simulation can thus serve to validate each other.

Mathematical modeling

Figure 1 schematically shows the cross-section of an uncompressed strand mat. For an

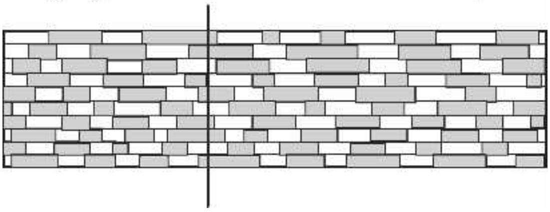

FIG. 1. Schematic of the cross-section of a randomly formed strand showing (i-1) potential contact interfaces existing in a stack of i overlapped strands.

overlap of i strands at a given point, there are (i-1) potential contact interfaces between the strands. Because of random mat formation, the strand-overlap number i and thus the inter-strand contact vary from location to location. Assume the mat formation is uniformly random (Dai and Steiner 1994). The maximum contact area between strands in a fully consolidated mat $CA_{\max}$ is calculated by (Dai and Steiner 1993 and 1994):

$$CA_{\max} = \sum_{i=2}^{\infty}(i-1)a_i = \mathrm{A}(\mathrm{n}-1+e^{-n}) \approx \mathrm{A}(n-1) \tag{1}$$

where:

a_i = total mat areas containing i strand overlaps,

A = total mat area [m^2], and

n = average number of layers and also the Poisson number, which is further defined by (Dai and Steiner 1994 and 1997):

$$\mathrm{n} = \frac{\lambda\omega \mathrm{N_f}}{\mathrm{A}} = \mathrm{C_r T_r} \tag{2}$$

where:

λ = strand length [m],

ω = strand width [m],

N_f = total number of strands in a mat,

C_r = compaction ratio: mat density over original wood density of strands, and

T_r = thickness ratio: mat thickness over strand thickness.

The approximation in Eq. (1) is justified considering that for an oriented strandboard (OSB) panel of 11.11-mm (7/16-in.) thickness, the average number of layers n is usually greater than 20. Thus, the maximum contact area between strands is approximately 19 times the mat (panel) area A, due to the loss of top and bottom panel faces. In the case of plywood, the maximum contact between layers can be realized with little densification because the layers are made of continuous veneer sheets. In the case of strand-based products, the layers are discontinuous (Fig. 1). To achieve maximum contact, a mat needs to be completely densified. Obviously, such is not the case in practice where the mat is usually partially consolidated in order to lower the product density.

Let us define the degree of inter-strand contact in a partially consolidated mat by using the term *relative contact area or RCA*. It is the ratio of total contact area in a partially consolidated mat CA and the maximum contact area CA_{max}. If a mat is consolidated to a thickness T [mm], contact can occur only in those mat areas a_i in which the local strand overlap i is greater than T/τ (τ is the strand thickness). The RCA is then given by:

$$RCA = \frac{CA}{CA_{\max}} = \frac{1}{CA_{\max}}\sum_{i=T/\tau}^{\infty}(i-1)a_i = \frac{1}{\mathrm{n}-1}\sum_{i=T/\tau}^{\infty}(i-1)\frac{a_i}{\mathrm{A}} \tag{3}$$

Assuming uniformly-random mat formation, a_i/A then obeys a Poisson distribution (Dai and Steiner 1993). Equation (3) can be rewritten as:

$$RCA = \frac{e^{-n}}{\mathrm{n}-1}\sum_{i=T/\tau}^{\infty}(i-1)\frac{\mathrm{n}^i}{i!} \tag{4}$$

Equation (4) is the analytical form of relative contact area RCA without considering the element edge effects.

Around the edges of a wood strand, for example, the contact between its adjacent strands is difficult to achieve due to the existence of edge voids (Dai et al. 2005). To account for the contact loss around the edges, a more complete form of Eq. (4) would be:

$$RCA = \frac{e^{-n}}{\mathrm{n}-1}\sum_{i=T/\tau}^{\infty}(i-1)\psi_i\frac{\mathrm{n}^i}{i!} \tag{5}$$

where function ψ_i is added to factor in the edge effect. It is defined by:

$$\psi_i = 1 - \frac{a_{loss}}{a_{strand}} \tag{6}$$

where a_{loss} and a_{strand} are, respectively, the loss of contact area around the edges around a strand due to the edge voids and the projected area of a strand (i.e. $\lambda\omega$). Similarly to the calculation of edge voids (Dai et al. 2005), a_{loss} can be determined by:

$$a_{loss} = 2(e_\omega \lambda + e_\lambda \omega) \tag{7}$$

or:

$$\psi_i = 1 - \frac{2(e_\omega \lambda + e_\lambda \omega)}{\lambda\omega} = 1 - 2\left(\frac{e_\omega}{\omega} + \frac{e_\lambda}{\lambda}\right) \tag{8}$$

where e_ω and e_λ is linear loss due to edge voids along width and length of a strand, respectively. They are determined by:

$$e_\omega = \frac{T}{i}\sqrt{\frac{1}{4} + c_\omega^2} - \mu_\omega\left(1 - \frac{T}{i\tau}\right)\omega \tag{9}$$

and

$$e_\lambda = \frac{T}{i}\sqrt{\frac{1}{4} + c_\lambda{}^2} \tag{10}$$

where: c_ω and c_λ = coefficients given by: $(\omega/\omega_r)^{0.5}$ and $(\lambda/\lambda_r)^{0.5}$, respectively (Dai et al 2005). Here ω_r is a reference strand width for normalization (e.g., 0.025 m). Parameter λ_r is a reference strand length for normalization (e.g., 0.1 m).

μ_ω = Poisson (expansion) ratio along strand width (approximately 0.05, which is low compared to solid wood, due to surface constraint from contacting strands). Note that the Poisson ratio along strand length direction is assumed to be zero.

Computer simulation

The simulation is part of our master program developed previously to simulate the formation of strand-based composite mats (Dai and Steiner 1994; Dai et al. 1996; Dai et al. 1997). In this simulation program, a mat of certain area is represented by a large matrix i(x, y). While x and y define the location in the mat, i represents the strand overlap at such location. The process of mat formation consists of sequential depositions of strands with their centroid position (x_c, y_c) and orientation (θ). The strand coordinates x_c, y_c and θ are random numbers that can be generated using the Monte Carlo technique. At any given location (x, y), the contact area CA_i is calculated by:

$$CA_i = a_p^2[i(x,y) - 1] \tag{11}$$

if:

$$i(x,y)\tau - T \geq 0 \tag{12}$$

Otherwise, CA_i equals 0. Here, a_p [mm^2] is the area of each pixel.

The total contact area CA_t for a given mat thickness T is then calculated by:

$$CA_t = \sum_{i=T/\tau}^{\infty} CA_i \tag{13}$$

It should be noted that the calculations used in the computer simulation are independent of the mathematical model, although both are based on the same assumption, i.e. random positioning of strands.

RESULTS AND DISCUSSION

Model validation and implication

Contact development during mat consolidation.—Figure 2a depicts the variations of inter-strand contact with mat density in a typical mat consolidation process. It compares the results predicted using the mathematical model (Eq. 5) and the simulation model (Eq. 13). The models are mutually validated by the close agreements. The nonlinear relationship between the global strand contact and the mat density is attributed to the nonuniform variations of horizontal mat density (Dai and Steiner 1997 and 1994) and porosity (Dai et al. 2005). Before consolidation, the mat is very porous with its density just over 200

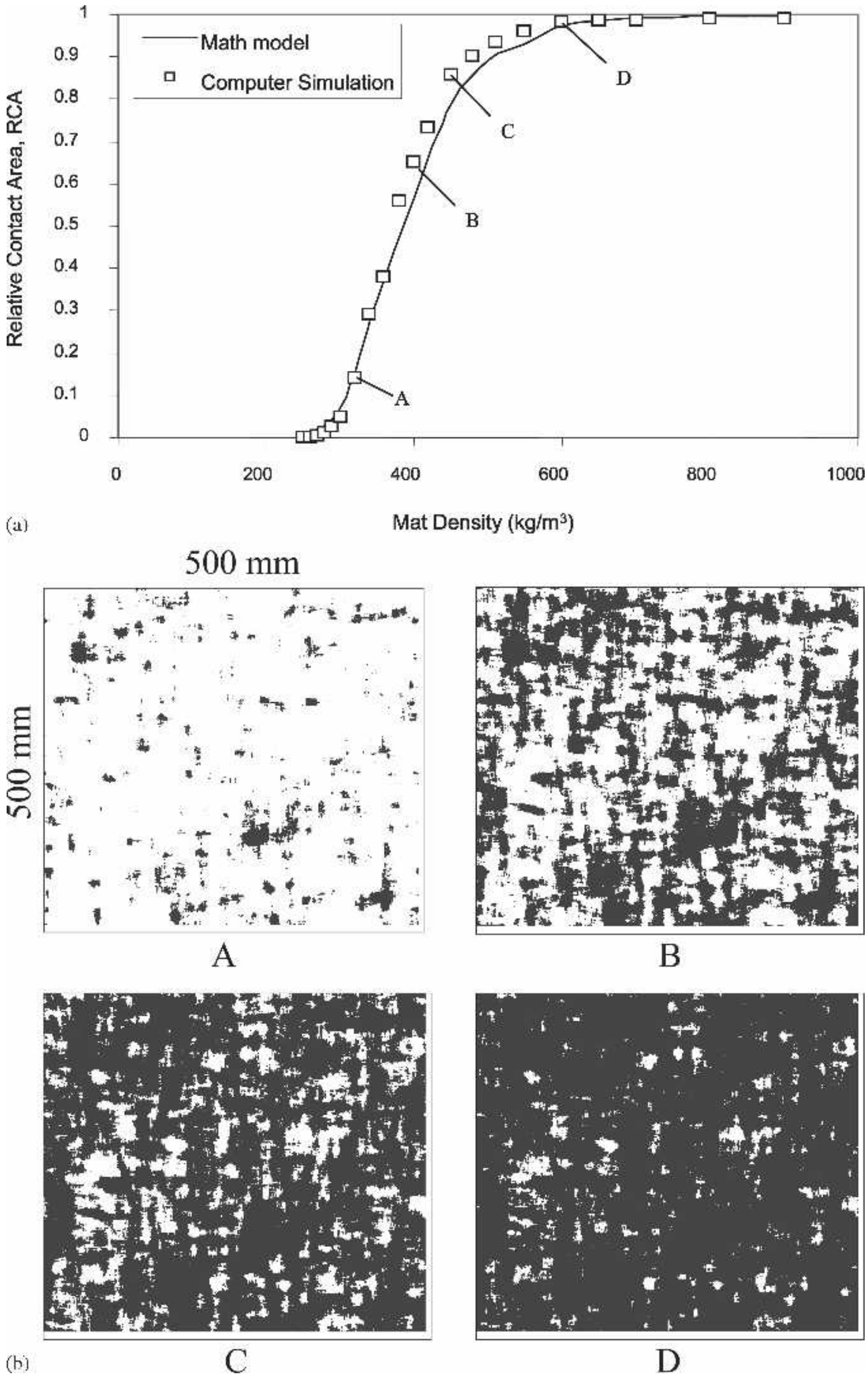

FIG. 2. Comparing relative contact area RCA between the mathematical model prediction and computer simulation as well as simulated spatial distributions of RCA: a) RCA and mat density relationship, and b) spatial distribution of RCA in a three-layer OSB mat (strand length: 80 mm, width: 10 mm, and thickness: 0.7 mm).

kg/m^3. The early consolidation thus results in a rapid removal of the voids, but a relatively slow development of strand contacts. This is because the contacts can only be developed in a small percentage of the mat areas where the local densities (strand overlaps) are very high. As the consolidation progresses, more contacts can be made gradually from the high overlap areas to the medium overlap areas. Particularly, the medium overlaps always count for the greatest mat area percentage, simply due to the nature of the bell-shaped (Poisson) strand overlap distribution (Dai and Steiner 1994). As a result, the contacts increase sharply as the mat density increases after the initial delay. Figure 2a shows that before the mat density passes that of original wood density (400 kg/m^3), the mat consolidation process is highly efficient for developing the strand contacts. However, once the contacts are reached, localized wood densification will result from further consolidation, which causes a slowdown of the contact development. As shown in Fig. 2a, the contact increase levels off noticeably after the mat density reaches about 500 kg/m^3. Further mat densification results in little increase in the strand contact, but rather direct increase in wood density. In general, the trade-off depends on the strand geometry, wood density, and mat densification.

Figure 2b also shows the simulated spatial variation of local strand contact at different mat densities. The increase in strand contact with mat density is obviously not uniform due to variation of local (horizontal) mat densities. The higher the local mat densities, the greater the relative contact areas. This contact variation is also affected by strand geometry, strand orientation, and mat (panel) thickness in a similar manner to their effects on horizontal mat density variation (Dai and Steiner 1994 and 1997). The contact variation will cause variations of bonding and other properties of the final product.

Balancing product performance and wood recovery.—Bonding and other product performance relies on intimate strand-to-strand contact. Densification promotes the strand contact and therefore the bonding performance, but scarifies the volumetric recovery. Figure 3 depicts the typical predicted relationships between the strand contact, volumetric recovery, and mat

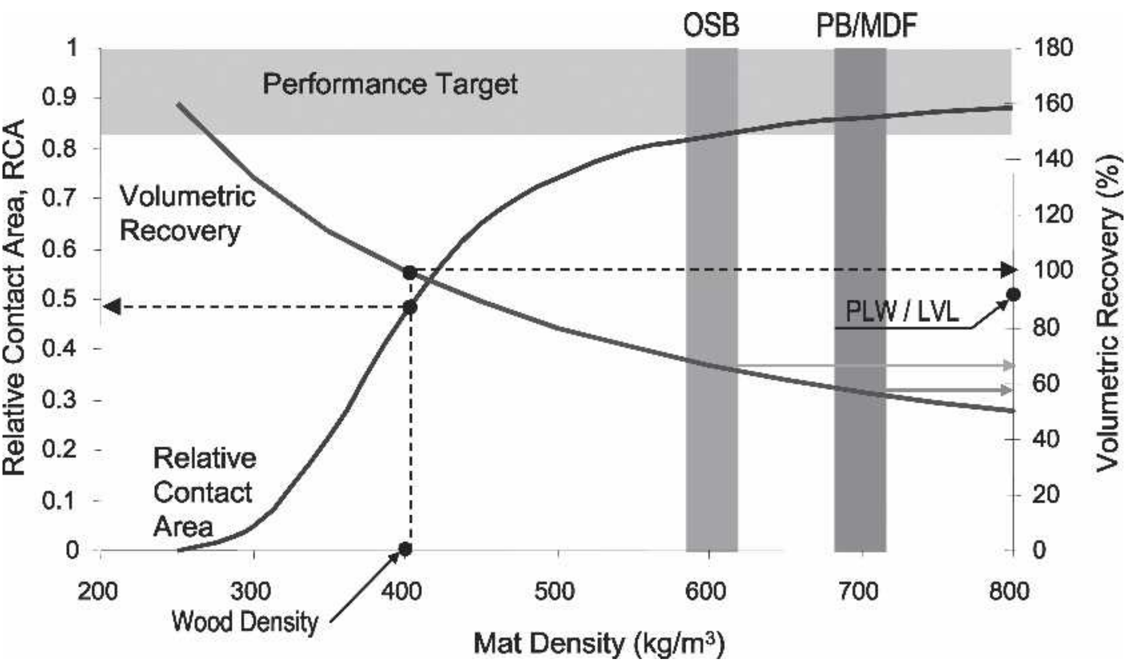

FIG. 3. Predicted relationships between relative contact area and volumetric recovery and mat density.

density. Here the original wood density is 400 kg/m^3. If the final product could be made with the same density, the wood recovery would be 100%. At such a low density, however, the relative contact area would be less than 50%, which is obviously too low to achieve the performance target.

Currently, most strand-based composites such as OSB have densities around 600 kg/m^3. At such a high density, the predicted degree of contact seems to reach its plateau (about 85%), and the volumetric recovery is well below 100% (about 65%). For particleboard (PB) and medium density fiberboard (MDF), the recovery is even lower. The numbers are significantly below those of veneer-based products. For plywood or LVL, the degree of contact is probably close to 100%, and the volumetric recovery is usually greater than 90%. The difference is primarily caused by the discontinuity of strands, the random mat formation and, to some extent, the furnish dimensions. Therefore the key to lowering product density may lie with the improvement in mat formation and furnish preparation.

Typical predicted results

Effect of strand thickness.—Figure 4 shows the predicted relationships between the strand contact and the strand thickness. Obviously, the strand thickness plays a significant role in defining how fast and how close the strand contact can develop during the course of mat consolidation. Thinner strands result in faster and more intimate strand contact than thicker strands. In theory, thinner strands mean greater number of strands to be used for a given product density, and hence make the mat formation more uniform. Also thinner strands significantly reduce the voids between strands especially those around the strand edges (Dai et al. 2005). The model seems to imply that one may use thinner strands to lower product density without scarifying strand contact or performance.

Effect of strand width and length.—As shown in Fig. 5, the strand width has greater impact on strand contact than the length, although neither is as significant as strand thickness. The impact of the width and length is attributed to their effects on edge voids (Dai et al. 2005). Longer or wider strands have fewer edge voids and hence better contact around the strand edges.

Effect of wood species.—Species is one of the most important variables in wood composites, often because of their variations in density. Figure 6 shows the predicted effect of wood density on strand contact during mat consolidation. Among all the variables, the impact of wood density seems to be the most significant. At a given mat density, the higher the wood density, the lower the degree of strand contact. This is because denser wood requires fewer strands to

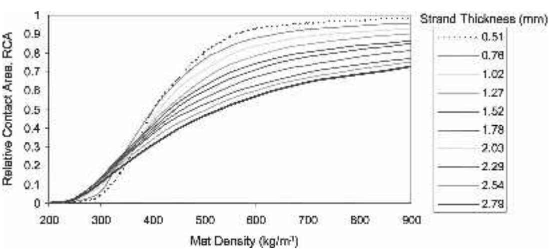

FIG. 4. Predicted effect of strand thickness on relative contact area (wood density: 400 kg/m^3, strand length: 100 mm and strand width: 25 mm).

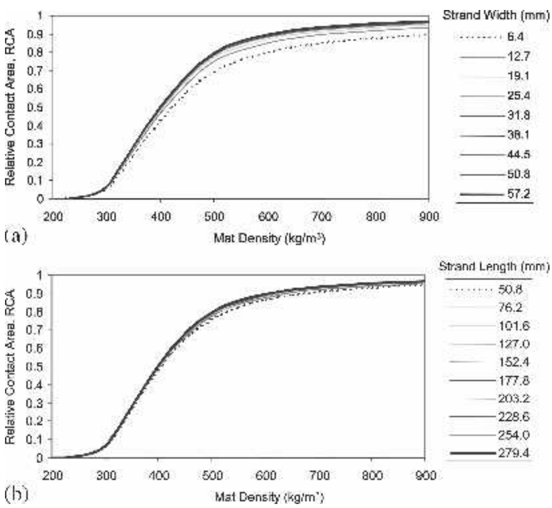

FIG. 5. Predicted effects of strand width and length on relative contact area: a). Effect of strand width (wood density: 400 kg/m^3, strand length: 100 mm, and strand thickness: 0.75 mm), and b). Effect of strand length (wood density: 400 kg/m^3, strand width: 25 mm, and strand thickness: 0.75 mm).

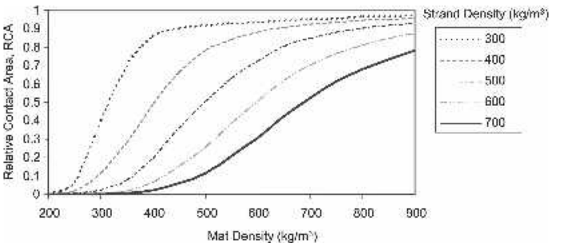

FIG. 6. Predicted effect of strand wood density on relative contact area (strand length: 100 mm, strand width: 25 mm, and strand thickness: 0.75 mm).

make the same density product. Fewer strands mean more voids and hence fewer contacts between strands. This is the main reason why products made from denser wood species are heavier in order to achieve similar bonding performance.

SUMMARY AND CONCLUSIONS

With the overall goal of improving the fundamental understanding of the bonding characteristics of wood composites, this first of the four-paper series discusses the development of a mathematical model and a computer simulation model of the inter-element (strand) contact during mat consolidation. Assuming random mat formation, the models predict and simulate the variation of inter-strand contact during the course of mat consolidation. The results from the mathematical model prediction and computer simulation agree closely with each other. It was shown that the mat density and the strand thickness have the most significant effects. The strand length and width have much less significant effect. The models imply that the use of less dense wood species and thinner strands are beneficial to lower product density.

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