EFFECTS OF MICROSTRUCTURAL HETEROGENEITY IN CEMENT EXCELSIOR BOARD

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ABSTRACT

Heterogeneity in the properties and arrangement of constituents can have an important effect on a composite's properties. This paper evaluates the effects of variability in wood strand dimensions, mechanical properties. and orientation on the engineering properties of cement excelsior board. The finite element method is used to analyze a heterogeneous three-dimensional microstructure of strands, predicting elastic and strength properties. Results suggest that variability in strand mechanical properties can significantly lower composite tensile and compressive strengths. while composite stiffness is not affected. The model also predicts that relatively modest alignment of strands cast lead to significant increases in composite strength and stiffness in the direction of alignment.

Keywords: Heterogeneous microstructure, network modeling, progressive failure, wood composites.

INTRODUCTION

Many wood composites have disordered microstructures and particles with highly variable physical and mechanical properties. While micromechanical models have been used for decades to aid development and optimization of composite materials, the heterogeneity of many wood composites provides a new modeling challenge.

This paper describes the application of a micromechanical model to a heterogeneous wood-cement composite panel called cement excelsior board (CEB). The dimensions and mechanical properties of the wood strands in CEB are highly variable (Stahl 1996), and fabrication processes result in density and strand alignment variations throughout a CEB panel. These and other sources of heterogeneity can be included in the model used in this study.

BACKGROUND

The most common domestic use of CEB is as an exposed structural roofing panel. It is economical in this application when its acoustic and fire-resistive properties are advanta-

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geous. In Europe and Asia the material is used in more diverse applications, including factory-assembled stressed-skin panels and stay-in-place concrete formwork (deWit 1989; Shigekura 1989). CEB has recently received interest as a general purpose building panel for use in low-cost housing in developing countries. The composite is attractive for this application because it achieves a compromise between the properties of wood panel products and masonry materials, makes use of domestic natural resources and industries, and can be produced in small plants with relatively simple machinery (Pablo et al. 1990).

Few micromechanical models described in the literature can predict the effects of heterogeneities in a composite such as CEB. Raisanen et al. (1995) used the finite element method to analyze a heterogeneous network of fibers in paper, and found that geometric disorder had a strong effect on network strength but little effect on network stiffness. Dai and Steiner (1994) and Lang and Wolcott (1995) presented models to simulate the behavior of heterogeneous mats of wood particles during particleboard pressing. Their models included aspects of heterogeneity in particle size, prop erties, and orientation; but their analyses focused on the behavior of a mat during the manufacturing process rather than the mechanical behavior of a finished composite.

We have developed a procedure to generate and analyze a three-dimensional finite element model of the network microstructure in a small volume of CEB. The details of this model and its verification are presented by Stahl and Cramer (1997), but are briefly reviewed here for completeness.

Straight lines representing strand centerlines are placed according to probability density functions (PDFs) governing their orientations. A uniform PDF creates a truly random layout, and a nonuniform PDF creates partial alignment of the strands. Strands are added to the net work until the desired density is reached. This simulation procedure addresses each individual strand in the volume to be analyzed. Figure 1 shows the top view of a network representing a 50.8 × 25.4 × 12.7 mm volume of CEB. The finite element discretization consists of a node at each bond and an element for each segment of strand between bonds. The elements are three-dimensional frame elements with stiffness to resist bending moment and shear in two planes, as well as torsional moment and axial force. Each strand consists of a uniform wood core surrounded by a uniform cement paste sheath (Fig. 2-A). The core and sheath of each strand act together to create a composite strand; the wood and cement are assumed to be linear elastic materials. Bonds occur where strand volumes intersect (Fig. 2-B), creating a three-dimensional network. Bonds are assumed to be rigid, and include an offset caused by the three-dimensional character of the bonding (Fig. 2-C).

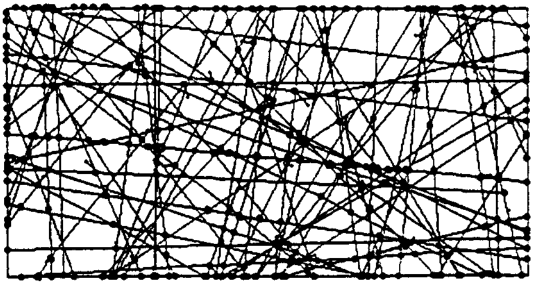

FIG. 1. Simulated network microstructure, with nodes indicated by dots.

Analysis of the network produces its stress-strain response to a specific loading and its complete set of anisotropic elastic stiffness properties (Stahl and Cramer 1997). To simulate the response to a specific loading, such as uniaxial compression or pure bending, the network is repeatedly analyzed as displacement boundary conditions are incremented. At each step of this analysis, failures of individual elements are identified by comparing axial stresses to material strengths. If the cement sheath of an element fails, it is removed from that element; if the wood core of an element fails, the element itself is removed from the network. This incremental analysis creates a nonlinear stress-strain plot for the composite, with all nonlinearity due to the accumulation of damage in the microstructure.

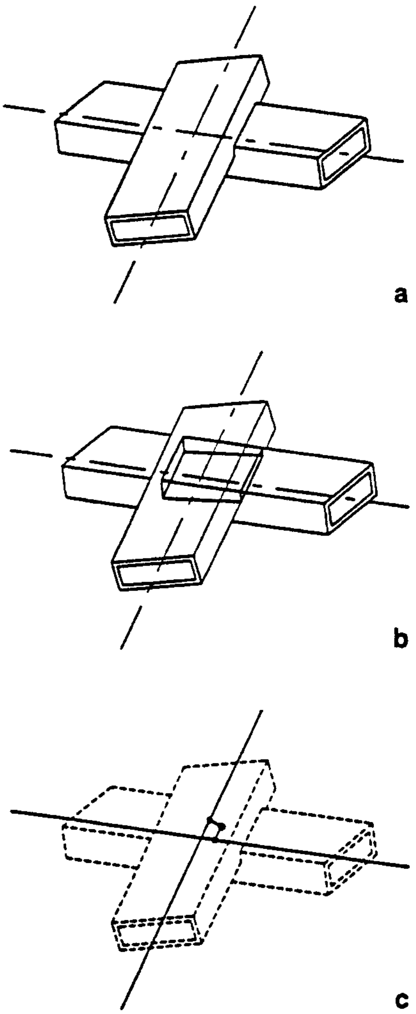

FIG. 2. Idealization of microstructure: a) wood strands with cement sheaths. b) bonds form when volumes intersect. c) bond has rigid offsets between strand centerlines.

Verification of the modeling procedure consisted of comparing test results with simulations from the model. Four sets of comparisons were made: CEB with two wood strand sizes was loaded in uniaxial compression and pure bending. For each set of comparisons, the predicted mean strengths were within 11% of mean test strengths (Stahl 1996). Within each set, the model correctly predicted the dependence of mechanical properties on the overall density of these small volumes (Stahl and Cramer 1997). Figure 3 shows typical moment-curvature plots for simulations and test specimens. This figure shows that the model's prediction of nonlinear response is fairly realistic up to the peak moment.

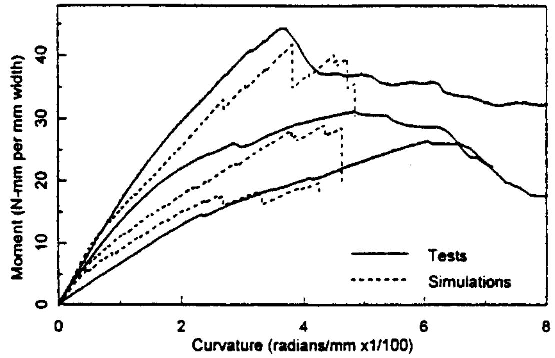

FIG. 3. Moment-curvature plots for bending tests and simulations.

OBJECTIVES

The objective of this paper is to demonstrate the importance of microstructural heterogeneity on the mechanical performance of a wood-cement composite. The model described above is used to predict the effects of variability in strand cross section dimensions, strand mechanical properties, and strand orientation on the elastic and strength properties of CEB. This information is useful for designing optimal composite panels.

PROCEDURES

The micromechanical model was used to simulate several groups of CEB specimens, either omitting or exaggerating one type of variability in constituent properties to illustrate the potential effects of this variability on the actual composite's properties.

Properties of the composite's wood and cement constituents presented in Table 1 were collected from tests and taken from the literature. Cement paste properties and wood specific gravity were assumed to be constant for all strands in a volume, but other properties conform to statistical distributions. Properties conforming to a normal distribution are given in Table 1 as N(mean value, standard devia-

TABLE 1. *Constituent properties.*[a]

Property	Value	Data source
Wood strand specific gravity	0.36	USDA (1987)
Wood strand dimensions (mm)	Width = N(6.07, .20) Thickness = N(.41, .10)	Measurements (Stahl 1996)
Wood strand MOE (MPa)	N(6260, 1440)	Tests (Stahl 1996)
Wood strand tensile strength (MPa)	N(28.3, 12.4)	Tests, adjusted (Stahl 1996)
Wood strand compressive strength (MPa)	N(28.3, 12.4)	Assumed (Stahl 1996)
Cement specific gravity	1.82	Mindess and Young (1981)
Cement MOE (MPa)	9650	Tests, calculation (Stahl 1996)
Cement compressive strength (MPa)	40.0	Soroka (1980)
Cement tensile strength (MPa)	3.72	Shah and Ouyang (1991)

[a] Normal distribution given as N(mean value, standard deviation).

tion). Dimensions of the aspen strands were measured with a micrometer, and tensile tests of plain and cement-coated strands were conducted to determine wood modulus of elasticity (MOE) and tensile strength as well as cement MOE. Wood mechanical properties are, in general, partially correlated (Bodig and Jayne 1982); correlation coefficients of 0.9 for wood strand MOE with tensile or compressive strength and 0.9 for tensile strength with compressive strength were assumed.

After initial runs of the model produced unrealistically high composite tensile strengths, the wood tensile strength input value was reduced to equal the wood compressive strength. We believe that the properties of the wood itself are altered by the chemical reactions resulting from exposure to the cement, but we have not quantified this effect. The exact nature of the chemical and physical interaction between wood and cement is not well understood (Hachmi and Campbell 1989).

The properties in Table 1 describe the constituents themselves, but the thickness of the cement coating and the total length of wood strand per unit volume of composite are required to describe the arrangement of the constituents in the composite. Given the mass of wood in a mixture, the wood specific gravity and the average wood cross section dimensions, calculation of the total length of wood strand in the composite is straightforward. This information, plus the mass and specific gravity of hydrated cement, allows one to determine the average cement paste thickness. The mass ratio of oven-dry wood to cement powder was 0.4, and the overall specific gravity for the composite was 0.5. These values describe a CEB with 13.7 cm of strand per cubic cm composite, and a thickness of hydrated cement paste equal to 0.113 mm.

Simulating variability in strand properties

The effects of variability in wood strand dimensions and wood strand mechanical properties on the mechanical performance of the composite were isolated using the procedure described here. A "baseline" set of twenty simulations was made with no variability in strand dimensions or mechanical properties, so that all strands in the networks had dimensions, strength, and stiffness equal to the mean values given in Table 1. All networks had a specific gravity of 0.50. A uniform PDF was used to generate the in-plane strand angles, creating a random arrangement in-plane. Out-of-plane orientation was controlled by a normal distribution with mean of zero and standard deviation of three degrees, to approximate the distribution measured in real CEB panels (Stahl 1996). All simulation volumes were 50.8 × 25.4 × 12.7 mm.

Two additional sets of twenty simulations were made; one set included variability in wood strand dimensions and one set had variability in wood strand mechanical properties. Both sets had the same PDFs for strand orientation as the baseline set. The set with variable wood strand dimensions had three times the wood cross section variability given in Table 1, with width = N(6.07,0.60) mm and thickness = N(0.41,0.30) mm. The wood strand strength and stiffness properties for this set were constant at the mean values of Table 1. The set of simulations with variable wood strand mechanical properties had twice the variability in wood mechanical properties given in Table 1, so wood strand tensile strength conformed to the distribution N(28.3,24.8) MPa, wood strand compressive strength = N(28.3,24.8) MPa, and MOE = N(6260,2880) MPa. These variables were assumed to be fully correlated for this set of simulations, so a strand with high MOE also had high tensile and compressive strengths. This set of simulations used constant wood strand cross section dimensions (mean values from Table 1 were used).

Simulating variability in strand orientation

The effects of controlled in-plane strand orientation on panel stiffness and strength were isolated by the following procedure. A preferred strand direction can be imparted into the network during its lay-up by moving a hopper over a stationary mat or by moving the mat on a production line under a stationary hopper. Deng and Dodson (1994) use a simple PDF to describe the in-plane orientation of fibers in paper:

$$f(\theta) = \frac{1}{\pi} + \frac{c}{\pi} \cos(2\theta) \qquad (1)$$

In this equation θ is the fiber orientation angle in the plane of the paper sheet, measured as the angle between the fiber axis and the paper's machine direction, f (θ) is the probability of a strand having this orientation, and c is a constant. If c is zero, the function is uniform, so a fiber is equally likely to have any orientation. As c increases. the probability increases that a strand will have a small θ. The ratio of strands with θ = 0° to strands with θ = 90° is approximately 3 to 1 when c equals 0.5, and the ratio is about 20 to 1 when c is 0.9.

TABLE 2. *Effect of heterogeneity in strand properties on composite properties.*

Type of heterogeneity	Mean composite properties[a] (MPa) Compr. strength	Tensile strength	MOE
None[b]	1.70 [24]	1.26 [22]	1,280 [19]
Wood dimensions[b]	1.69 [27]	1.23 [34]	1,260 [25]
Wood mechanical properties[b]	1.15 [28]	0.85 [38]	1,330 [15]

[a] Means of 20 simulations; percent COV is given in brackets.

[b] Strands in all networks have approximately random planar orientation.

Five groups of twenty simulations each were considered. The base group had orientation constant c in (1) equal to zero, for random orientation. Two groups were analyzed with c equal to 0.5; one was analyzed to determine composite properties in the direction of the preference and one ninety degrees away from it. This process was repeated with two more groups with c equal to 1.0. All input properties had the values given in Table 1, and volumes were generated with overall specific gravity conforming to a normal distribution with mean 0.50 and standard deviation 0.04, representing density measurements for specimens cut from a real panel. All simulation volumes were 50.8 × 25.4 × 12.7 mm.

RESULTS

Variability in strand properties

Results on strand property variability are shown in Table 2. Modulus of elasticity (MOE) is the initial modulus at low strain levels. First consider the results for the simula-

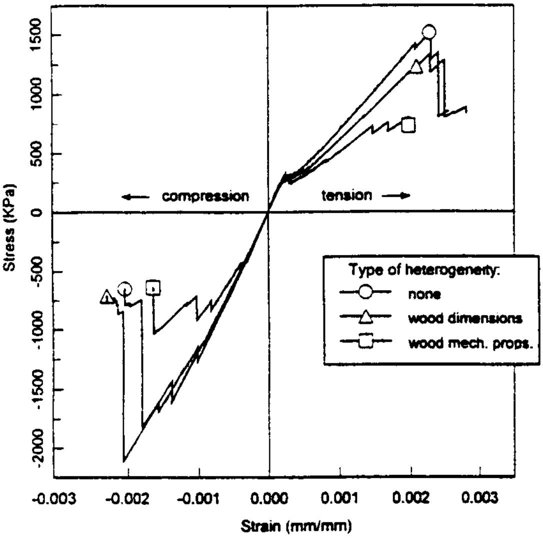

FIG. 4. Comparison of typical stress-strain curves in compression and tension for three levels of heterogeneity.

tions with no variability in strand properties; the composite mechanical properties all had coefficients of variation (COV) above 19%. This indicates that disorder in the arrangement of strands, the only source of heterogeneity in these simulations, had a significant effect on composite properties for specimens of this size. Variability in strand cross section dimensions had little additional effect on the composite's performance. The COVs for composite mechanical properties rose somewhat, but mean properties did not significantly change from the simulations with no heterogeneity.

Results for networks with variability in strand mechanical properties were different Although composite stiffness did not change significantly, composite tensile and compressive strengths decreased about 32% when the strand properties were variable. The strength differences between the simulations with no heterogeneity and those with strand mechanical property variability are significant at the 99.9% confidence level.

Sample stress-strain plots are shown in Fig. 4. These plots show the compressive and tensile response for one representative simulation from each of the three sets of simulations. The plot for the specimen with no variability and the plot for the specimen with strand dimension variability are similar, with little nonlinearity prior to the peak stress in compression. Both exhibit the obvious change in tensile stiffness that occurs when much of the cement coating on strands breaks, but beyond this major event, these two tension plots are almost linear to failure. The plot for the specimen with strand mechanical property variability has more pronounced nonlinearity prior to the peaks in both tension and compression. This behavior would be useful in applications where ductility, or energy dissipation prior to gross failure, is desired.

Variability in strand orientation

Results for the simulations with variations in strand orientation are presented in Table 3. Composite mechanical properties, except shear modulus, showed a strong and consistent dependence on the degree of orientation. The differences in mean strengths and MOE as orientation is changed were all significant to at

TABLE 3. *Mean mechanical properties in preferred (PD) and nonpreferred directions (ND).*[a]

Orientation constant (c)	Comp. strength (MPa)		Tens. strength (MPa)		MOE (MPa)		G (MPa)
	PD	ND	PD	ND	PD	ND	
0	2.07[b] [21]		1.10[b] [23]		1,240[b] [17]		586 [12]
0.5	2.48 [16]	1.31 [27]	1.31 [15]	0.69 [29]	1,650 [13]	758 [22]	483 [14]
1.0	3.17 [14]	0.59 [38]	1.63 [14]	0.37 [40]	2,140 [9]	352 [30]	552 [15]

[a] Means of 20 simulations; percent COV is given in brackets.
[b] Assumed isotropic when c = 0.

least the 97.5% confidence level. When c was changed from zero to 0.5, strength and stiffness gains in the preferred direction were not as large as losses in the non-preferred direction. When c was changed from 0.5 to 1.0, the gains were approximately equal to the losses. The 12% decrease in shear modulus when c was changed from 0 to 0.5 was significant at the 99% confidence level, but the difference between shear modulus at c equals 0 to c equals 1.0 was not significant.

Although the data do not indicate that a ceiling has been reached in the preferred direction properties, a practical limit may be imposed by declining properties in the nonpreferred direction. Note, in addition, that the decreasing COVs that accompany higher means could permit the use of a higher fraction of the mean as an *allowable* stress.

SUMMARY AND CONCLUSIONS

Many composite materials, especially those used in civil engineering applications, are made with fibers or other particles with variable properties and have highly disordered microstructure. Results presented in this paper show that these microstructural details can have an important effect on the engineering properties of the composite.

When strand mechanical properties were held constant, variability in strand cross-sectional dimensions did not have a significant effect on the composite's mean initial stiffness, stress-strain plots, or strength. When strand cross sections were held constant and strand mechanical properties varied, however, composite tensile and compressive strengths declined by about one third.

The investigation into strand alignment showed that relatively modest alignment (a 3 to 1 ratio of strands aligned with the preferred direction to strands oriented 90° away from it) led to approximately 25% increase in composite strength and a 33% increase in stiffness in the "preferred" direction. The micromechanical model could be used to identify the degree of alignment required to reach a desired ratio of strengths in the two panel directions.

The model and analysis procedures illustrated in this paper are proposed as a tool to aid in development and optimization of composite materials. While the procedure is computationally intensive and requires detailed input, it produces predictions that are simply not possible with other approaches. It can be used to simulate small volumes of material subjected to virtually any loading condition, so it could be used to explore multiaxial failure criteria. The model was developed specifically for CEB, but adapting it for other materials with network microstructure would be straightforward.

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