SPACEBOARD II PANELS: PRELIMINARY EVALUATION OF MECHANICAL PROPERTIES[1]

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ABSTRACT

This preliminary evaluation of the properties of Spaceboard II (SBII) was undertaken to establish the potential of a pulp-molded product in structural-use applications and to develop a basis upon which to optimize the Spaceboard pulp molding process. Various tests were implemented to characterize significant engineering properties, including static concentrated load, panel bending, panel shear, bearing strength, and coupon tension and compression strength. Although these tests were preliminary in nature, they were nonetheless adequate to show that SBII panels perform quite satisfactorily under "dry" conditions, relative to the current performance requirements established for structural-use panels. Our tests on SBII demonstrated that with proper formation and densification, a three-dimensional pulp molding process such as Spaceboard provides the opportunity to create structural products from fiber and to obtain the performance required of conventional products.

Keywords: Spaceboard, papier-mâche, sheathing panel.

INTRODUCTION

The development of new process technologies to produce products from cellulose pulps has been an active area of research at the USDA Forest Service, Forest Products Laboratory (FPL). A decade ago, Setterholm (1985) introduced the unique method of forming a three-dimensional, wafflelike structure from molded wood pulp. He called the board "Spaceboard" because of the presence of open cells or "space" between the ribs of the "board" (Fig. 1). At the time, Setterholm envisioned producing a Spaceboard panel that would have strength characteristics similar to that of corrugated boxboard but that could be produced in a one-step forming process. Additionally, the process could accommodate underutilized fiber sources such as mixed hardwoods and recycled papers. These two goals set the stage for several breakthroughs in molded pulp processing technology at FPL. Subsequent process improvements by other FPL researchers were developed to optimize the formation and densification of Spaceboard (Gleisner and Gunderson 1992; Gunderson 1988; Gunderson and Gleisner 1992, 1994; Setterholm and Hunt 1987). With these improvements, it became possible to produce Spaceboard in a variety of sizes, ranging from thin boxboard (Hunt and Scott 1988) to thick sheathing panels called Spaceboard II (SBII).

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FIG. 1. The Spaceboard pulp molding process is used to form a wafflelike, open-cell board. Two boards are then bonded rib-to-rib to produce a closed-cell panel. The panel shown has properties similar to that of corrugated boxboard.

The objective of this study was to characterize, under dry conditions, the basic mechanical properties of SBII. These evaluations will provide the basis for determining the potential of SBII as a structural-use panel. A variety of standard tests were conducted to measure various panel properties: bending stiffness and strength, concentrated load application, bearing strength, and interlaminar shear. In addition, coupons were extracted from specific facing locations to measure tensile and compression properties.

PHYSICAL CHARACTERISTICS

SBII is a sandwich panel, nominally 610 by 1,220 by 66 mm, made by bonding two open-cell boards rib-to-rib to form a closed-cell panel (Fig. 2). Both wet-formed and dry-formed boards are made in the same mold by similar processes. However, because of the nature of the fibers used and related internal bond development, the physical properties differ significantly (Table 1).

Wet-formed panels

With water as the forming medium, two basic mechanisms determine bond strength development: fiber flexibility (conformation) and hydrogen bonding. When the board is uniformly densified at elevated temperatures, the conformable fibers are pressed into intimate contact with each other. As the water vapor-

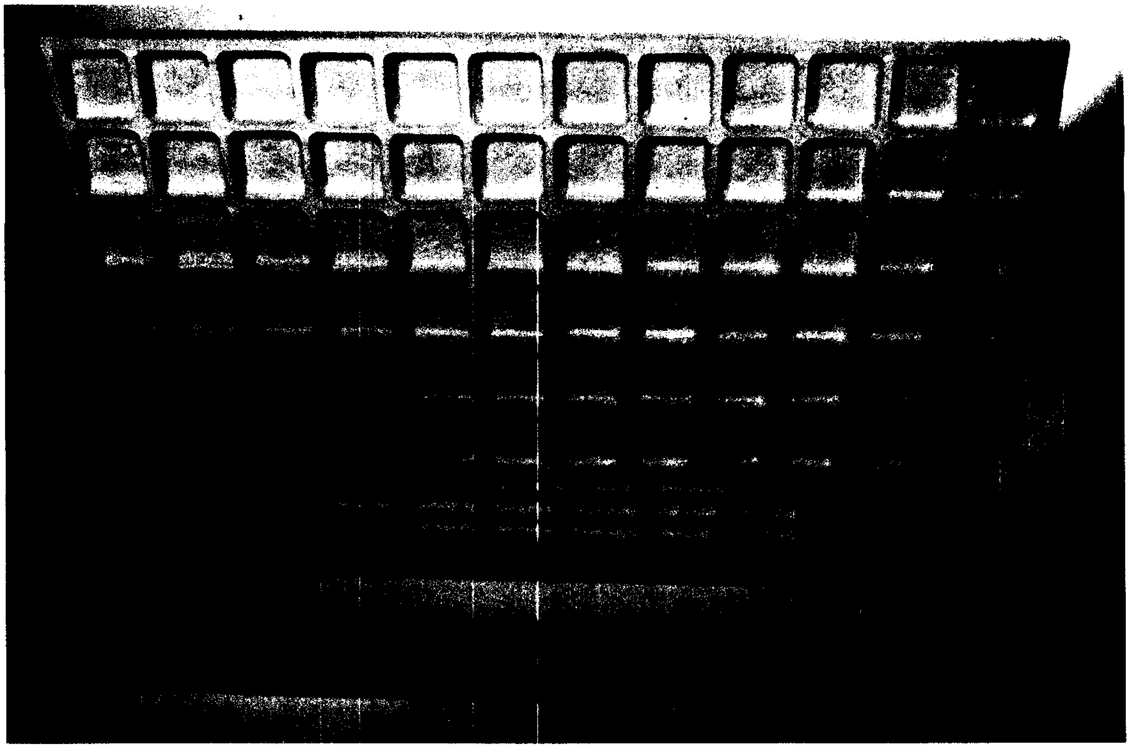

FIG. 2. Spaceboard II (SBII) sections showing rib structure and 100-mm-square open cells. The two panel sections below the board show closed-cell configuration when two boards are combined to make a panel.

izes, strong hydrogen bonds are produced, resulting in very high densities (specific gravity (SG) $\geq$ 1). A lightly refined kraft pulp (700 Canadian Standard Freeness) composed of 75% northern red oak and 25% loblolly pine was used to produce wet-formed SBII.

Dry-formed panels

With air as the forming medium, much lower densities are achieved (SG = 0.7). This is due, in part, to the lack of conformability of the dry-processed fiber, inhibiting densification. Thus, a high degree of intimate fiber contact is not achieved. Also, in the absence of water, bond strength can only be obtained through the addition of an adhesive (11% by weight phenolic). A commercially produced, pressure-refined aspen fiber was used to make dry-formed SBII.

A cross-sectional view of a typical SBII cell section is shown in Fig. 3 for both wet-formed and dry-formed panels. These views show an induced flair at the top and bottom of the ribs caused by the lateral deformation of the Spaceboard forming pads. These flaired regions (specifically the rib/face interface) are of somewhat lower density and, as will be shown later, strongly influence mechanical properties. For the purpose of simplifying the calculation of panel section properties for bending and shear calculations, the following assumptions were

TABLE 1. *Physical properties of Spaceboard II.*

Property	Wet-formed panel	Dry-formed panel
Panel thickness, mm	66.1 (3)	68.3 (1)
Facing thickness, mm	2.92 (3)	6.12 (2)
Basis weight, kg/m^2	15.9 (9)	17.6 (4)
Moment of inertia, $\times 10^4$ mm^4	407 (6)	816 (3)
Facing density, g/ml	1.05	0.67
Rib density, g/ml	0.85	0.69

Note: Coefficient of variation shown in parentheses (%).

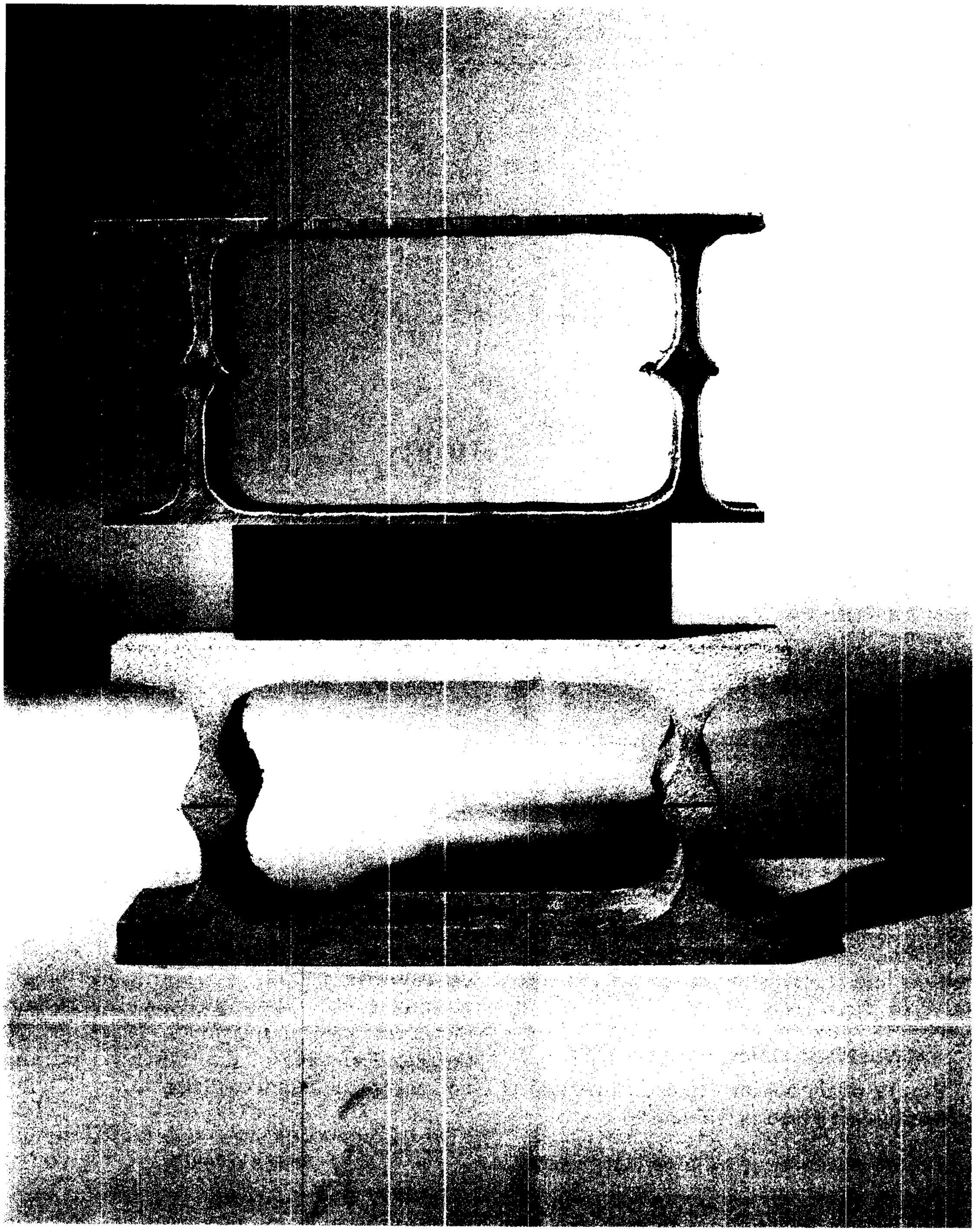

FIG. 3. Cross-sectional view of rib/cell structure for wet-formed (top) and dry-formed (bottom) SBII panels.

TABLE 2. *Mechanical properties of Spaceboard II.*

Property	Wet-formed panel	Dry-formed panel
Coupon tensile strength		
Number of tests	8	9
Fail stress, MPa	36.6 (10)	10.5 (20)
Fail strain %	0.54 (13)	0.51 (9)
Modulus of elasticity, GPa	6.91 (15)	2.07 (12)
Coupon compression strength	rib/facing	composite
Number of tests	6/12	12
Fail stress, MPa	33.3/41	8.9
Modulus of elasticity, GPa	5.9/7.2	1.6
Interlaminar shear		
	5	
Number of tests	5	
Shear fail stress-rib, MPa	3.11	3.98
Shear modulus-rib, MPa	208	205
Center-point bending—Edge		
Number of tests	10	10
Modulus of elasticity, GPa	6.48 (14)	1.99 (19)
Center-point bending—Face		
Number of tests	5	5
Modulus of elasticity, GPa	6.37 (22)	2.05 (18)
Fail load, N	1,250–2,570	1,520–2,280
Modulus of rupture, MPa	17.6–30.2	10.1–14.3
Rib shear at failure, MPa	2.10–3.48	1.06–1.48
Bearing strength—Flat		
Number of tests	5	4
Gross fail stress, kPa	500	830
Bearing strength—Edge		
Number of test	5	4
Gross fail stress, kPa	4,310	3,450

Note: Coefficient of variation shown in parentheses (%).

made: (1) all ribs are thin rectangular columns of uniform density, (2) rib and face elements have the same density, and (3) rib thickness equals facing thickness for wet-formed panels, and rib thickness equals one-half facing thickness for dry-formed panels. Coupon tests for tension and compression properties were used to verify these assumptions.

MECHANICAL PROPERTY EVALUATIONS

Results of the various tests on mechanical properties are given in Table 2.

Tensile properties of SBII facing coupons

Tensile specimens were extracted from SBII board facings for both wet-formed and dry-formed panels. To achieve the required specimen dimensions as specified in ASTM D1037, (1991a) the facings were first bandsawn to rough dimension, then machined with a router, and thickness-sanded to remove the ribs. As was mentioned previously, the facing section just above the rib was of lower density and thus produced a "weak link" in the specimen. It was necessary to place this section in the middle of the necked-down region inside the extensometer. (As was anticipated, all failures did in fact occur in the rib interfacial area.) A crosshead speed of 0.2 mm/min was used, and no specimens were tested wet.

Compression properties of SBII facing coupons

Initially, 25- by 102-mm compression specimens were prepared in a manner similar to the tension specimens. Each specimen was then placed in a lateral restraint device to prevent slip and buckling while a compressive load was

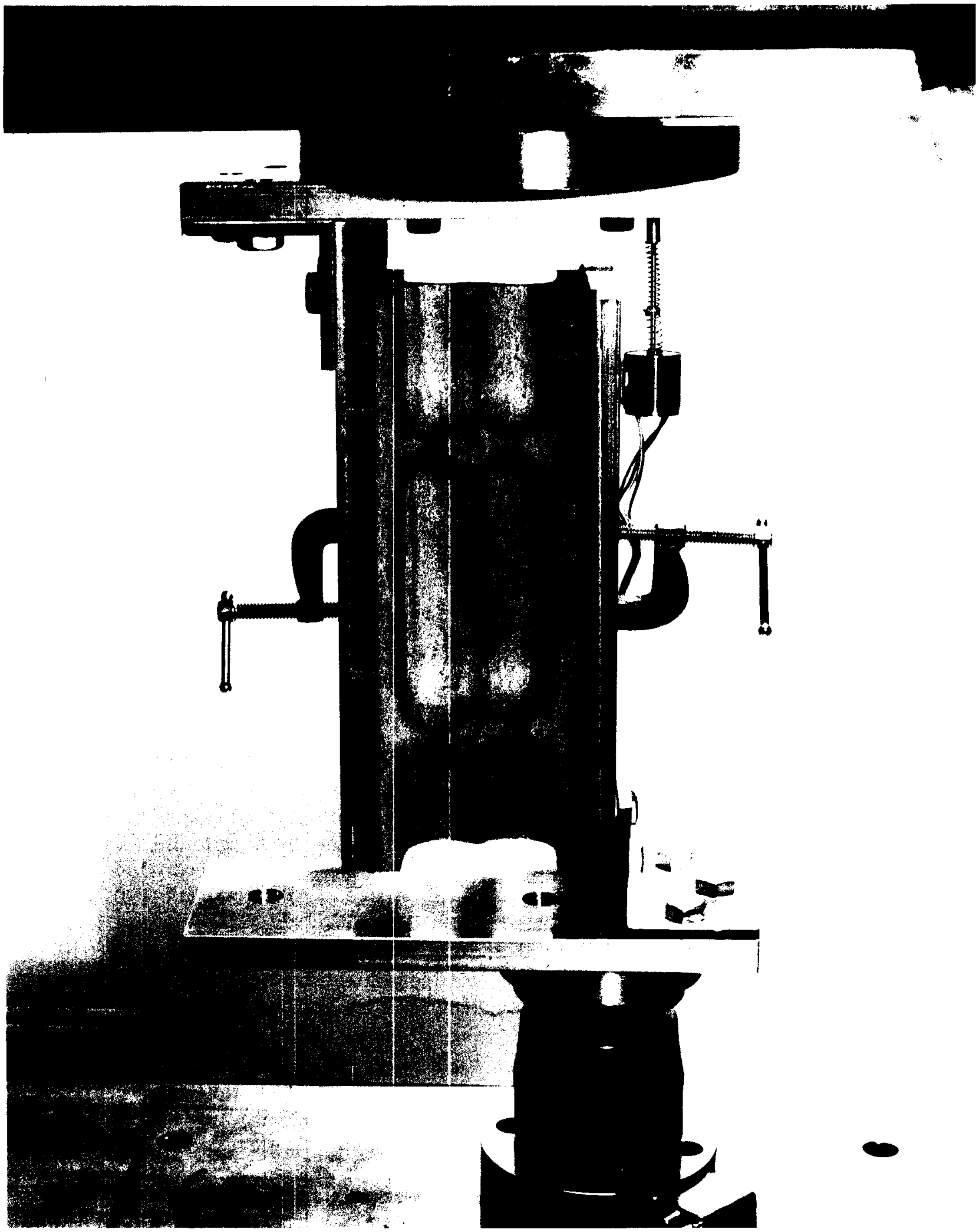

FIG. 4. Interlaminar shear test configuration used to induce shear stresses on a single SBII rib section.

applied. A crosshead speed of 0.1 mm/min was used. Analysis of the data obtained from the wet-formed coupons showed that although the failure load averaged about 1,780 N, the modulus of elasticity (MOE) values were only 70% of the corresponding tensile MOE values. We determined that the specimen buckled despite the induced lateral restraint. Given an average facing thickness of 3 mm for a typical wet-formed board, the "worst case" column buckling load would be around 267 N. Clearly, buckling did indeed occur, reducing the compression properties.

To eliminate buckling, short and wide specimens (25 by 38 mm) were prepared. By producing these short specimens, it was possible to isolate and test the lower density interfacial region. Subsequent compression tests confirmed that the interfacial area is a region of lower strength. However, since this area comprises only about 16% of the facing area, a composite compression MOE of 6.98 GPa could be approximated with transformed section analysis.

Compression property values of dry-formed SBII are based on the standard 25- by 102-mm specimens since the thickness of the dry-formed boards was sufficient to prevent buckling.

Interlaminar (rolling) shear properties

Due to the inherent thickness of SBII panels, a nonstandard test was devised to measure interlaminar shear properties. The test configuration (Fig. 4) was developed to minimize additional stresses that would otherwise occur in standard shear tests for these thick panels. Specimens were prepared by cutting 76- by 203-mm rib sections from the panels. This shape was chosen to preserve symmetry and to induce shear stresses on a single rib. For each test, a specimen was clamped to the adherends, which were displaced at a rate of 6 mm/min.

Center-point bending tests

Narrow panel strips of one-cell width were subjected to a center-point bending load to determine MOE, modulus of rupture (MOR), failure load, and mode of failure. Two beam orientations of the same strip were evaluated, as shown in Fig. 5. An attempt was made to implement these tests in accordance with the requirements of ASTM D1037 (1991a). However, because of the thickness and length of SBII, it was not possible to comply with the span length and reaction radius requirements. Instead, a 1,220-mm span was used with a 51-mm-diameter pipe as the midspan reaction load (l/d = 18). A displacement rate of 2.4 mm/min was imposed on this pipe.

The edge bending test was implemented first and only loaded elastically to determine MOE. The strip was then rotated to the face bending position and loaded to failure.

Of the 20 strips tested in the face bending orientation, only 10 were loaded to failure (5 wet-formed and 5 dry-formed). A variety of failure modes were observed, ranging from

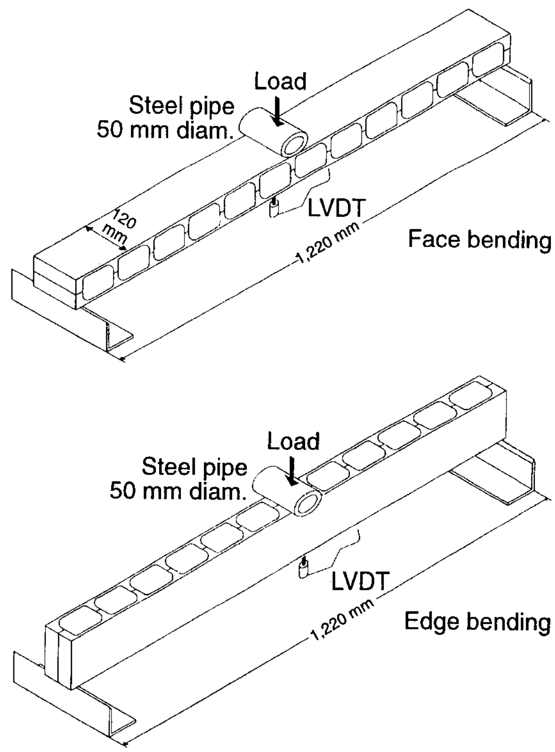

FIG. 5. Load application for center-point bending tests in face bending and edge bending orientations.

shear failure of the ribs or glueline, to tensile or compressive failure of the facings. Of the five wet-formed beams tested to failure, four failed in shear and one in compression. Of the five dry-formed beams tested, two failed in compression and one in tension, and two were glueline shear failures. For nonshear failures, the MOR values can be compared to the tension and compression fail stress values.

The center-point bending test has an inherent shear component that is constant over the length of the beam equal to one-half the applied load at midspan. Typically, for solid-section beams, this component is small relative to the shear capacity of the beam and can be neglected. However, for I-beam and box-beam sections with thin webbing, the shear component may contribute to overall beam deflection and may even become the principal mode of failure. Indeed, this was the case in four of five wet-formed strips.

Consider the cross-sectional area of a face bending strip (Fig. 3). Through the panel facing, the shear stress is quite small. However, at the rib interface, the shear load is transferred to the thin ribs, resulting in a substantial increase in shear stress. From here, it parabolically increases to a maximum at the neutral axis. For the beams tested to failure, this maximum shear stress was calculated from the failure loads.

Bearing strength tests

Bearing strength properties were evaluated to determine the compression strength of panel subelements. These subelements were square panel blocks encompassing one complete cell. Two block orientations were evaluated. A flat crush test with a uniform compressive force applied normal to the facing was implemented to determine the crush strength of the ribs. A crosshead speed of 1 mm/min was used for these tests. For the edge crush tests, a block was placed on end and loaded parallel to the facing. This orientation was intended to characterize panel strength for bearing wall applications. A crosshead speed of 0.5 mm/min was used for these tests.

Concentrated load application

In an effort to determine the viability of using SBII as a sheathing-type product, full-size panels were tested for their deflection resistance due to concentrated load application. Panels were tested in accordance with the guidelines set forth in APA Test Method S-1 (ASTM E661—1991b). Three basic panel support systems were evaluated that represent joist spacings typical of construction practices (410-, 610-, and 1,220-mm spans). One of these systems is shown in Fig. 6. Load is applied at midspan via a 76-mm-diameter disk (simulating foot traffic) with deflection measured directly under the load. A constant deflection rate of 2.5 mm/min was induced on the disk as a continuous sampling of load, and deflection was made. Table 3 lists the deflections measured for all span conditions tested. Also listed in Table 3 are the APA maximum allowable deflection criteria at each span for STURD-I-FLOOR, floor sheathing, and roof sheathing (APA PRP-108, 1991). In addition to the deflection criteria, APA also specifies a minimum ultimate load for this procedure.

Although all SBII panels were loaded only in the linear range to preserve the panels for further tests, the 410- and 610-mm-span tests were loaded well past the minimum acceptable load levels (>2700-N) while maintaining a linear load/deflection relationship. It should be noted, however, that the SBII panels were not preconditioned as prescribed in ASTM E661—(1991b) (20 C, 65% relative humidity (RH) but were allowed to equilibrate to test conditions of 23 C and 50% RH for a minimum of 2 weeks. Also, no wet exposure or impact tests were implemented.

In a similar experiment, a 25-mm-diameter disk was used to determine "puncture" resistance (simulating an appliance load). A 610-mm span was evaluated and three distinct facing locations were chosen for load application, which correspond to the unique features of SBII panels, i.e., centered on a single rib, centered over an open cell, and centered on a rib/rib intersection (see Fig. 6).

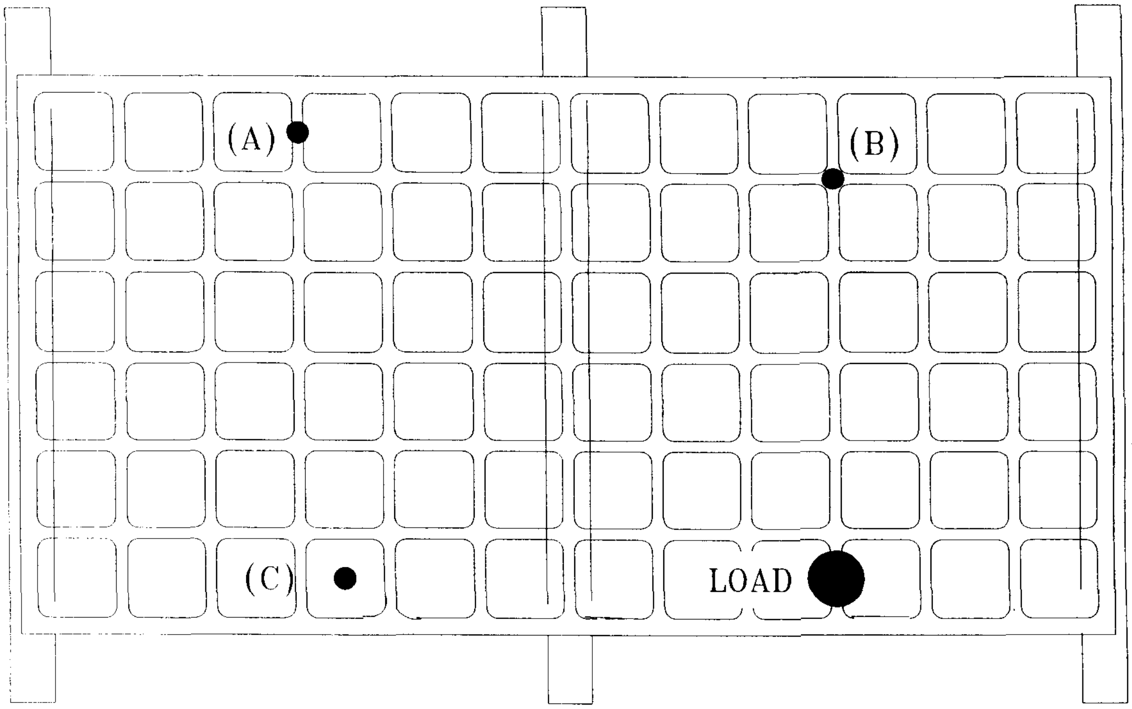

FIG. 6. 610-mm span location for static concentration load test on SBII. The large black dot indicates the position of the 76-mm loading disk. The small dots indicate puncture positions of the 25-mm disk. (A) rib, (B) rib/rib intersection, (C) face.

RESULTS AND DISCUSSION

With an elastic modulus (MOE) of about 7 GPa and tensile strength >35 MPa, we were able to show that Spaceboard process technology is capable of producing a three-dimensional structural product from pulped fiber. However, as shown in this report, it is extremely important to optimize fiber distribution and densification. For example, the rib structure of SBII (if formed and aligned properly) can sustain considerable bearing forces. However, these thin ribs are susceptible to shear stresses in bending, particularly if discontinuities are present as a result of poor formation. Therefore, to prevent shear failures, more fiber can be added to the ribs and/or rib spacing decreased. Perhaps, even a different rib geometry can be used.

In the case of static concentrated load application (Table 3), both the wet-formed and dry-formed SBII panels had acceptable deflections. However, in making this evaluation, we are comparing a SBII panel that is 66 mm thick to a standard 19-mm plywood panel. Herein lies a dilemma. How can these vastly different panel products be compared on an equivalent basis?

Two approaches are possible. First, based on measured mechanical properties, we can predict the deflection of a 19-mm SBII panel by center-point bending analysis. For example, assume we can produce a SBII panel that is as thick as plywood and has the same basis weight. This SBII panel would have a facing thickness of 2.5 mm and a rib spacing of 51 mm. With this geometry, a deflection of 0.41 mm will be observed for a 890-N load at a 410-mm span. Applying this analogy to a 19-mm plywood panel with MOE = 6.9 Gpa and I = 33.3 cm^4 (APA Plywood Design Specification) will result in a deflection of 0.53 mm for the same 890-N load and 410-mm span.

TABLE 3. *Spaceboard II—Static concentrated load tests.*

Panel type	Deflection (mm) under 890 N with 76-mm disk @ span (mm)				Puncture load (kN) 25-mm disk		
	1,220	610	610 clamped	410	Rib	Face	Rib/rib
Wet-formed	2.11	0.84	0.66	0.48	4.63	2.00	6.36
	1.80	0.86	0.71	0.69			
	1.91	0.76	0.58	0.48			
Average	1.94	0.82	0.65	0.55			
Dry-formed	2.77	0.86	0.76	0.53	4.65	1.56	5.83
	2.77	0.97	0.76	0.58			
	2.69	0.94	0.58	0.48			
Average	2.74	0.92	0.70	0.53			
	APA maximum allowable deflections						
STURD-I-FLOOR	3.38	2.74	2.74	1.98	2.45	2.45	2.45
Subfloor	7.95	6.35	6.35	4.78			
Roof	12.7	12.7	12.7	11.1			

A second approach would be to accommodate the use of thicker panels as is. Consider the 1.93-mm deflection of the wet-formed SBII panels at the 1,220-mm span length. This is equivalent to the deflection of STURD-I-FLOOR at a 410-mm span. If this is an acceptable deflection, would it then be possible to eliminate half the floor joists if SBII panels were used? In any event, there is an obvious need to develop performance criteria to accommodate these new and vastly different panels.

CONCLUSIONS

As with any material property evaluation, some assumptions must be made to simplify experimental procedures and analysis. These assumptions were discussed where appropriate and seem to be practical in light of our results. Also, variability in measured properties was quite high as a result of the selection of panels tested. We attempted to look at a variety of panels, good or bad, and not focus on those of uniform size to determine the effect of process variables on fiber distribution, densification, and resultant mechanical properties. This preliminary evaluation demonstrated the structural potential of a pulp-molded panel such as SBII. However, additional tests must be implemented to fully characterize SBII panels for structural-use applications. These include uniform loads, impact loads, racking shear, duration of load and creep, wet/redry durability, fire resistance, and fastening. Of utmost importance, however, is the issue of durability. Due to the nature of hydroxyl bonding, the wet-formed, pulp-molded panels are inherently susceptible to moisture. Consequently, these bonds must be protected or enhanced to produce a durable panel. These additional tests are the basis for continued FPL research on Spaceboard process technology.

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