HARDBOARD-WEBBED I-BEAMS SUBJECTED TO SHORT-TERM LOADING

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ABSTRACT

The performance of structural I-beams and box beams is highly dependent on the shear properties of the web materials. Some wood-base panel materials such as hardboard possess shear properties that indicate a good potential for such applications. Reports of the performance of hardboard-webbed I-beams are encouraging, although specific information necessary for design and for predicting their behavior is scarce. Also, the effects of two important factors, long-term loading and loading environment, have not been fully determined.

This research expanded previous work conducted at the Forest Products Laboratory by including the effect of other important factors, such as mode of failure (as affected by span length) and type of web material, and by providing additional data. In addition, data will serve as a base for judging the effects of long-term loading and loading environment on similar I-beams made from the same lot of material.

Results indicate that the behavior of hardboard-webbed I-beams subjected to short-term loading can be predicted reasonably well using fundamental engineering theory together with the properties determined from small specimen evaluations.

HARDBOARD-WEBBED I-BEAMS SUBJECTED TO SHORT-TERM LOADING[1 2]

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INTRODUCTION

The performance of structural I-beams and box beams is highly dependent on the shear properties of the web materials. Some wood-base panel materials, such as hardboard, possess shear properties that indicate a good potential for use as web materials in beams. These and other products are being investigated for use in composite structural members. Although basic data are available on the mechanical properties of both hardboard and particleboard, engineering design with these materials is now severely limited because design values have not been established for their properties. Also, because structural components made from wood-base panel products are coming to be accepted for commercial use, their performance under service conditions needs to be demonstrated.

Encouraging reports have described the use of hardboard-webbed I-beams in Europe *(4,5,7)*,[4] but specific information necessary for design of large structural components with wood-based materials is sparse. Also, the effects of long-term loading and of the loading environment have not been fully determined. An earlier study conducted at the Forest Products Laboratory indicated that the short-term behavior of three 34-foot I-beams with hardboard web material agreed with that predicted using standard design theory and properties obtained from small specimen tests *(11)*. This earlier study was limited to three identical beams subjected to short-term loading; therefore, the effect of other factors, such as span, type of web material, duration of load, and loading environment could not be determined.

The purpose of the research set forth in this paper has been to expand previous work conducted at the Forest Products Laboratory by considering other important factors, such as mode of failure (as affected by span length) and type of web material, and to provide such additional data as would be helpful in evaluating results. In addition, data from this study will serve as a basis for judging the effects of long-term loading and loading environment on similar I-beams made from the same lot of materials. The results of the long-term load study will be reported in the future.

[1] Condensation and revision of an advanced independent study, "Prediction of Shear Properties of Hardboard-Webbed I-Beams," by Terry J. Ramaker as a prerequisite for the Master of Science degree (Civil Engineering) at the University of Wisconsin, Madison, Wis., 1975. Research was conducted at the Forest Products Laboratory.

[2] Acknowledgement is made to H.M. Montrey, Engineer, for his assistance with theoretical analysis.

[3] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[4] Italicized numbers in parentheses refer to literature cited at the end of this report.

RESEARCH MATERIALS

Dimensions, rosette gage locations, and typical cross section of the hardboard-webbed I-beams used in this study are shown in figure 1.

The two commercial hardboards selected for web material were material A, a 1/4-inch-thick, dry-felted, dry-pressed, high-density tempered hardboard, and material B, a 1/4-inch-thick, wet-felted, wet-pressed, high-density tempered hardboard. These particular materials were selected because their shear properties indicate a good potential for use in structural I-beams and box beams. In addition, the mechanical properties of similar materials are known *(9)*, and it is believed that the results of this study can be extended to include other wood-base materials that behave similarly, such as randomly oriented flake particleboard.

The I-beam flanges were cut into the required size from parallel laminated Douglas-fir wood veneer panels 15 feet long, 25 inches wide, and 1-1/2 inches thick. Web stiffeners were cut from nominal 2-inch-thick construction grade lumber. A phenol-resorcinol adhesive was used to bond all materials. No nails or mechanical fasteners were used.

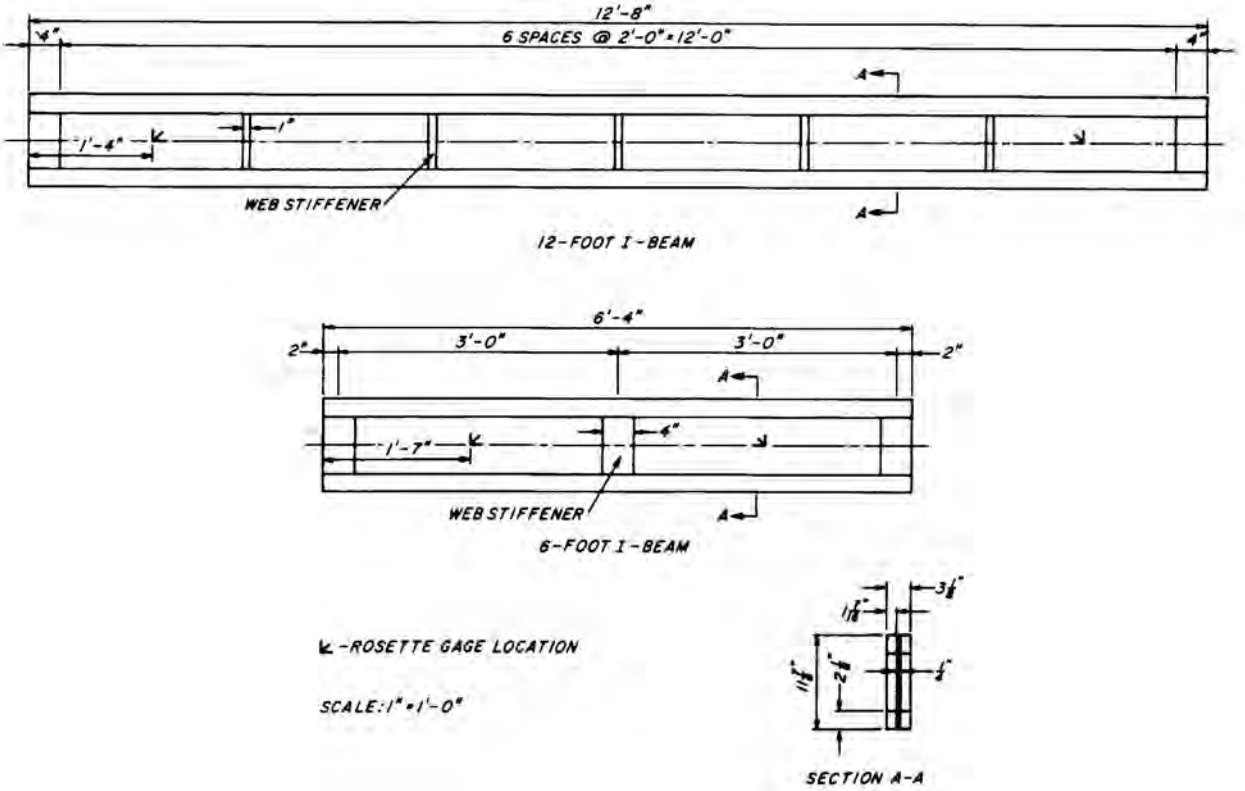

Figure 1.—Details of I-beams. (M 143 780)

RESEARCH METHODS

Evaluation of the Web and Flange Materials

The parallel—laminated veneer material was cut to size and conditioned to equilibrium moisture content at 68° F (20° C) and 50 percent relative humidity. Small hardboard specimens were cut to size, randomly selected, and tested in accordance with ASTM Standard D 1037-72 *(2)* and D 3044-72 *(3)*, except that conditioning was at 68Á F (20° C) and 50 percent relative humidity. The results of these evaluations are listed in table 1.

Table 1.-Basic strength and elastic properties of two types of 1/4-inch-thick, high-density tempered hardboard

Type of test[1]	Number of specimens	Strength				Elastic modulus	
		Average	Estimated standard deviation	Lowest observed value[2]	Adjusted value[3]	Average	Estimated standard deviation
		Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}
MATERIAL A, DRY-FELTED, DRY-PRESSED							
Compression parallel	10	4,640	600	3,550	1,140	762,000	54,000
Tension parallel	24	4,740	380	4,040	1,290	764,000	40,500
Rail shear	24	3,040	240	2,730	870	—	—
Plate shear	24	—	—	—	—	321,000	19,200
MATERIAL B, WET-FELTED, WET-PRESSED							
Compression parallel	10	5,700	540	4,720	1,510	864,000	59,000
Tension parallel	24	6,050	540	5,070	1,620	850,000	72,500
Rail shear	24	4,200	400	3,180	1,020	—	—
Plate shear	24	—	—	—	—	334,000	18,300

[1]Tests made in accordance with ASTM D 1037-72 except plate shear modulus (modulus of rigidity) was determined by the procedure used for plywood, ASTM D 3044-72.
[2]Estimate of "near minimum" values using a nonparametric or distribution-free technique.
[3]Lowest observed value multiplied by 0.48 for duration of load and divided by 1.5 for unforeseen conditions.

A nondestructive test method was used to determine the modulus of elasticity for each piece of the flange material. Each 1-1/2- by 2-1/8-inch by 12-foot-long piece with laminations (2-1/8-inch dimension) vertical was simply supported at the ends and vibrated transversely at its natural frequency. The elastic modulus was estimated using the measured vibration frequency, weight, and specimen dimensions. The pieces with the four closest values of elastic moduli were then matched in groups of four for use in the same beam. The average elastic modulus of each group of four was used to calculate the deflection of the beam in which they were used.

This approach enabled us to better evaluate the behavior of the hardboard web material, because additional variability or uncertainty would be introduced if one average value of elastic modulus were used for all flange material. To indicate the reliability of the data obtained by nondestructive tests, the modulus of elasticity of 11 pieces of flange material was determined using the nondestructive transverse vibration method, and then each piece was tested (destructively) as described by ASTM Standard D 198-67 *(1)*. The average elastic modulus determined using the nondestructive test method was 3 percent greater than that determined by standard test.

An average value of 92,000 pounds per square inch (lb/in.^{2}) for the modulus of rigidity (plate shear modulus) of the flange material was determined in accordance with ASTM Standard D 3044-72 *(3)*. Five 24- by 24-inch specimens were sawn from one nominal 1-1/2- by 25-inch by 15-foot panel. The specimens were planed to 3/4-inch thickness and conditioned at 50 percent relative humidity and 68° F (20° C) prior to testing.

Design and Construction of I-Beams

Beams for a 12-foot span were designed to carry 100 pounds per lineal foot without exceeding an allowable web shear stress of 250 lb/in.^{2}, which is the allowable value for plywood for shear perpendicular to the plane of the plies. The 100-pound-per-lineal-foot load is based on a 50-pound-per-square-foot floor load and a 24-inch joist spacing. The purpose of fabricating the shorter, 6-foot beams was to include specimens having a high probability of web shear failure.

Twelve 12-foot-long and sixteen 6-foot-long beams were fabricated using material A as the web material and an equal number using material B. After conditioning to equilibrium moisture content at 50 percent rela-

tive humidity and 68° F (20° C), the flanges, the web, and the web stiffeners were bonded using a phenol-resorcinol adhesive. After fabrication, the beams were returned to the 50 percent relative humidity and 68° F (20° C) conditioning room for 2 weeks. Eight 12-foot-long and eight &foot-long beams were then tested to failure and the remainder saved for long-term load evaluations. The results of the long-term study will be included in a subsequent report.

Experimental Procedure and Loading Method

A pulley and cable system was used to load the simply supported 12-foot I-beams (fig. 2). Tensioning of the cable that passed over the pulleys applied load at five equally spaced points. The loads were transmitted from the pulleys to the top flange via flat 3-1/2- by 3-1/4-inch wooden blocks. Total load was measured with a 10,000-pound-

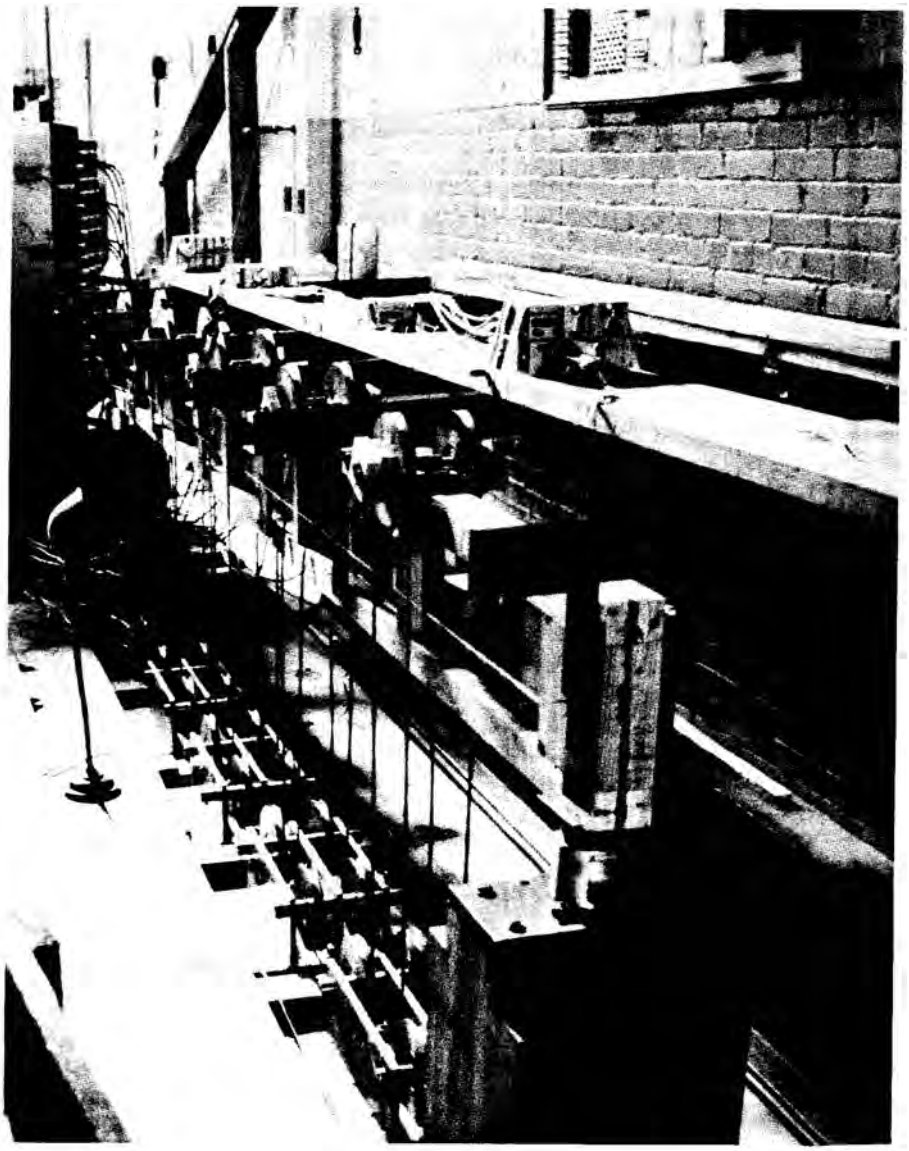

Figure 2. —Pulley loading system for 72-foot I-beams.

(M 142 288)

capacity load cell located at each support. Comparison of the measured load at each reaction indicates that the loads distributed to each load point were essentially equal. The same procedure was used for loading the shorter beams spanning 6 feet except load was directly applied at the midspan with an 18-inch radius load block by methods described in ASTM D 198-67 *(1)*. Maximum load for each specimen was attained in less than 15 minutes.

Center-span deflection of each 6-foot beam was measured relative to the supports with a linear variable differential transformer (LVDT) and a yoke. Center-span deflection of each 12-foot beam was measured relative to the supports with a wire deflectometer.

SR-4 rectangular rosette gages were used to measure strain in the hardboard webs. The gages were mounted on one side of the web at locations shown in figure 1. Signals from each transducer were monitored with a 100-channel recorder. The output from each transducer was observed on a digital voltmeter which had an accuracy of ±3 microvolts on a 100-millivolt range. A coupler-controller switched the voltage values to a calculator where they were converted into engineering units. The coupler-controller also directed the calculator output to teletype and punch paper tape recording systems for immediate observation of data and for later computer analysis.

THEORETICAL ANALYSIS

Strength and Elastic Values Used in this Study

Strength and elastic values were estimated to determine load levels for long-term loading and to compare the behavior of the I-beams with that predicted by theory. The determination of the elastic moduli of the flange material using nondestructive test methods and 24- by 24-inch plate shear tests has been previously discussed. The elastic moduli values of the hardboard-web material listed in table 1 are the average of the values obtained from 24 small specimen tests. All calculations for this study were made using these values.

Determination of Stresses and Deflections

Built-up structural components, made by rigidly gluing pieces with different engineering properties together, can be analyzed using the transformed area method. Such a procedure for plywood-webbed I-beams is presented in the Wood Handbook *(12)*. Using this procedure for hardboard-webbed I-beams, the area of wood in the flanges was transformed to an equivalent area of hardboard. This was accomplished by multiplying the area of wood (A_W) by the ratio of the average modulus of elasticity of the four pieces of wood flange material (E_W) to the average modulus of elasticity of hardboard (E_H).

$$A_{transformed} = NA_W$$

where N is $\dfrac{2E_W}{E_{HC} + E_{HT}}$,

E_{HC} is average modulus of elasticity of hardboard in compression, and E_{HT} is average modulus of elasticity of hardboard in tension.

The section properties of the transformed section were then calculated and incorporated into the elastic beam theory to determine stresses and deflections. The modulus of rigidity and the breadth of the I-beam flanges differed substantially from that of the web; therefore, it was necessary to calculate a shear deflection coefficient for each I-beam. The procedure used for estimating the shear deflection coefficient is similar to that described in Research Note FPL-0210 *(10)*.

ANALYSIS OF RESULTS

Twelve-Foot I-Beams

The results of the static bending tests of the 12-foot I-beams are presented in table 2. The first two loads listed for each beam are the loads that would cause theoretical shear stresses of approximately 15 and 25 percent of the shear strength of the web material. The lower stress level was selected based on the work of Lundgren *(7)*, who suggested a 15 percent stress level as a maximum for beams exposed to the elements for extended time periods. A stress level of approximately 25 percent would be an upper limit for design. The actual design stress level will in-

Table 2—Comparison of behavior of 12-foot long hardboard-webbed I-beams with behavior predicted using elastic beam theory

I-beam no.	Total load[1]	Shear stress			Difference $\frac{(3)-(4)}{(3)} \times 100$	Deflection		Difference $\frac{(6)-(7)}{(6)} \times 100$
		Ratio[2]	Theo-retical[3]	"Measured"[4]		Theo-retical[5]	Measured	
	(1) Lb	(2)	(3) Lb/in.²	(4) Lb/in.²	(5) Pct	(6) In.	(7) In.	(8) Pct
A-31	2,110	0.18	533	451	15.4	0.217	0.217	0
	3,230	.27	816	703	13.9	.330	.333	- .9
	12,400	—	—	—	—	—	1.297	—
A-37	2,240	.20	597	496	16.9	.218	.182	16.5
	3,300	.29	882	737	16.4	.319	.274	14.1
	10,500	—	—	—	—	—	.946	—
A-41	2,230	.17	531	434	18.3	.213	.217	-1.9
	3,340	.26	796	658	17.3	.317	.324	-2.2
	11,700	—	—	—	—	—	1.165	—
A-43	1,990	.15	471	390	17.2	.188	.180	4.3
	3,100	.24	734	620	15.5	.291	.282	3.1
	13,900	—	—	—	—	—	1.344	—
B-29	3,140	.16	678	595	12.2	.296	.250	15.5
	5,540	.29	1,198	1,059	11.6	.518	.456	12.0
	16,900	—	—	—	—	—	1.608	—
B-32	3,380	.17	727	656	9.8	.315	.311	1.3
	5,690	.23	984	887	9.9	.526	.533	-1.3
	13,200	—	—	—	—	—	1.203	—
B-35	3,210	.17	699	645	7.7	.296	.272	8.1
	4,360	.23	949	880	7.3	.401	.377	6.0
	16,600	—	—	—	—	—	1.718	—
B-44	3,300	.17	710	647	8.9	.298	.288	3.4
	5,120	.26	1,101	1,026	6.8	.459	.450	2.0
	16,400	—	—	—	—	—	2.017	—

[1]Total load applied to each beam via 5 3-1/2- by 3-1/4-in. flat loading blocks spaced 2 ft on center. The third load listed for each beam is the maximum load.

[2]Ratio of theoretical shear stress to average ultimate rail shear strength obtained from small specimen tests.

[3]Calculated at horizontal centroidal axis using elastic beam theory and transformed section properties.

[4]Shear stress calculated using strains measured at horizontal centroidal axis and average values of elastic moduli obtained from small specimen and nondestructive tests.

[5]Calculated using elastic beam theory, methods described in USDA For. Serv. Res. Note FPL-0210, and average values of elastic moduli obtained from small specimen and nondestructive tests.

clude consideration of factor of safety, loading environment, and long-term load behavior. The effects of these factors are currently being investigated as an extension of this study; the results will be reported later.

The third load listed for each beam is the maximum load that each beam did sustain. The 12-foot beams with web material A failed at an average load of 12,100 pounds and the beams with web material B at an average load of 15,800 pounds. Load-deflection and load-strain curves for the hardboard-webbed I-beams were essentially linear below a load level equivalent to 60 percent of the rail shear strength determined from small specimen tests. Final failure of each beam occurred in the tension flange with essentially no inelastic deformation prior to failure. Buckling of the web material did not occur prior to failure of the beam flange. A typical load-deflection curve for the 12-foot I-beams is presented in figure 3.

Comparisons of measured and theoretical values of shear stress and deflection are also presented in table 2. The theoretical values calculated using elastic beam theory compare reasonably well with the measured values. The difference between shear stress calculated using simple beam theory (parabolic shear stress distribution) and shear stress obtained from rosette analysis ranged from 6.8 to 18.3 percent, with an average of 12.8 percent. The theoretical shear stress was greater for each of the eight beams. The percent difference between theoretical and measured deflection ranged from -2.2 to 16.5, with an average of 5.0. The theoretical value for deflection was greater than that measured for all beams except two.

The difference between measured and theoretical values for the 12-foot beam is probably due in part to the variation of approximately 7 percent in the elastic properties of the web material. (Average values of the elastic properties obtained from small specimen evaluations had been used for converting stresses to strains and for deflection calculations.)

Six-Foot I-Beams

The results of the static tests of the 6-foot I-beams are presented in table 3. The method for establishing the load levels used for comparing stresses and deflections is the same as that described for the 12-foot beams. As with the 12-foot beams, load-deflection and load-strain curves for the 6-foot beams were essentially linear below a load level equiva-

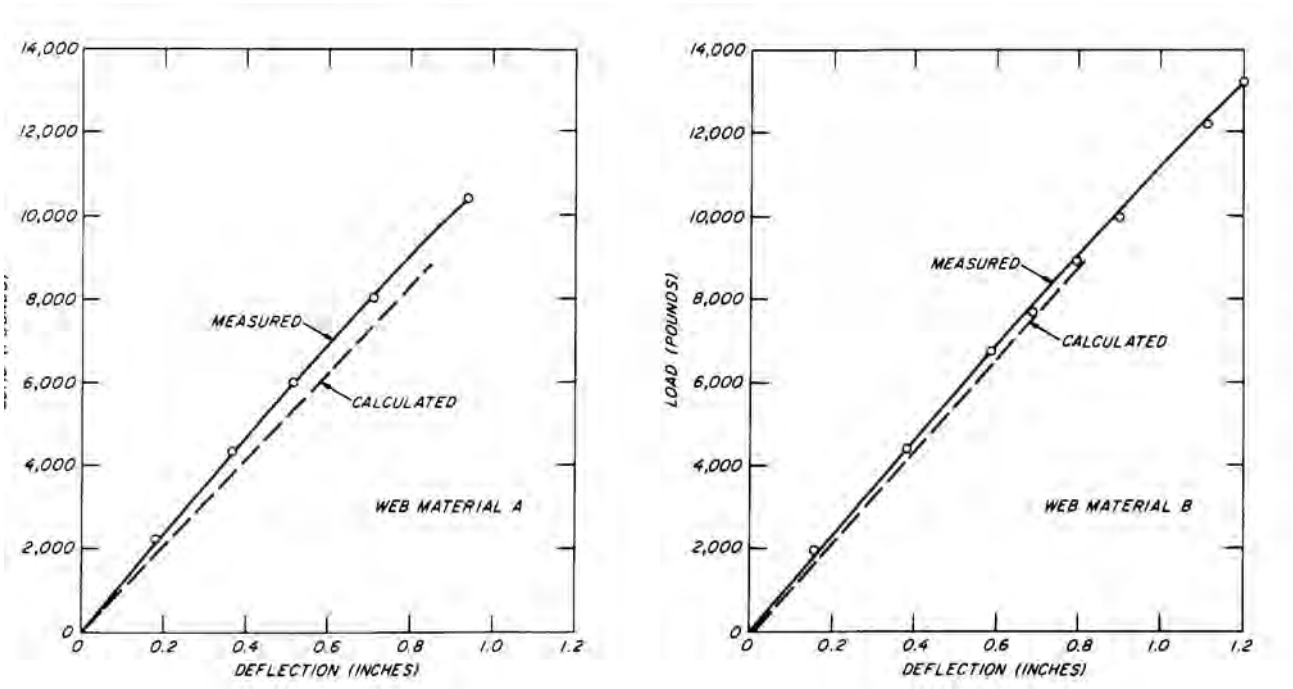

Figure 3.—Comparison of measured and calculated midspan deflection for typical 72-foot hardboard-webbed I-beams.

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lent to 60 percent of the rail shear strength determined by small specimen tests. The failure mode for all of the 6-foot beams was web shear. A typical shear failure in a web is shown in figure 4. A typical load-deflection curve for the 6-foot I-beams is presented in figure 5.

The 6-foot beams with web material A failed at an average load of 11,800 pounds and the beams with web material B at an average load of 15,400 pounds. Of interest here is the safety factor for a design shear stress of 25 percent of the ultimate shear strength determined by small specimen tests.

Table 3—Comparison of behavior of 6-foot long hardboard-webbed I-Beams with behavior predicted using elastic beam theory

I-beam no.	Total load[1]	Shear stress			Difference $\frac{(3)-(4)}{(3)} \times 100$	Deflection		Difference $\frac{(6)-(7)}{(6)} \times 100$
		Ratio[2]	Theoretical[3]	"Measured"[4]		Theoretical[5]	Measured	
	(1) Lb	(2)	(3) Lb/in.²	(4) Lb/in.²	(5) Pct	(6) In.	(7) In.	(8) Pct
A-23A	1,900	0.14	423	418	1.2	0.060	0.050	16.7
	3,300	.24	734	729	.7	.104	.089	14.4
	12,800	—	—	—	—	—	.405	—
A-23B	1,920	.14	436	352	19.3	.061	.041	32.8
	3,300	.25	749	618	17.5	.105	.076	27.6
	14,300	—	—	—	—	—	.394	—
A-49A	1,500	.13	406	331	18.5	.052	.036	30.8
	2,970	.26	803	665	17.2	.103	.075	27.2
	9,870	—	—	—	—	—	.293	—
A-49B	1,970	.17	531	485	8.7	.068	.057	16.2
	2,960	.26	804	733	8.8	.103	.088	14.7
	10,400	—	—	—	—	—	.350	—
A-50A	1,960	.16	490	455	7.1	.064	.053	17.2
	2,950	.24	737	685	7.1	.097	.082	15.5
	12,200	—	—	—	—	—	.395	—
A-50B	1,960	.18	538	468	13.0	.068	.055	19.1
	2,970	.27	811	708	12.7	.104	.088	15.4
	11,000	—	—	—	—	—	.366	—
B-53A	2,840	.15	609	549	9.9	.082	.071	13.4
	4,720	.24	1,011	919	9.1	.136	.119	12.5
	15,300	—	—	—	—	—	.387	—
B-53B	2,970	.15	638	613	3.9	.086	.093	-8.1
	4,970	.25	1,067	1,023	4.1	.144	.154	-6.9
	15,500	—	—	—	—	—	.448	—

[1]Total load applied at midspan via 18-in. radius loading block. The third load listed for each beam is the maximum load.

[2]Ratio of theoretical shear stress to average ultimate rail shear strength obtained from small specimen tests.

[3]Calculated at horizontal centroidal axis using elastic beam theory and transformed section properties.

[4]Shear stress calculated using strains measured at horizontal centroidal axis and average values at elastic moduli obtained from small specimen and nondestructive tests.

[5]Calculated using elastic beam theory, methods described in USDA For. Serv. Res. Note FPL-C210, and average values of elastic moduli obtained from small specimen and nondestructive tests.

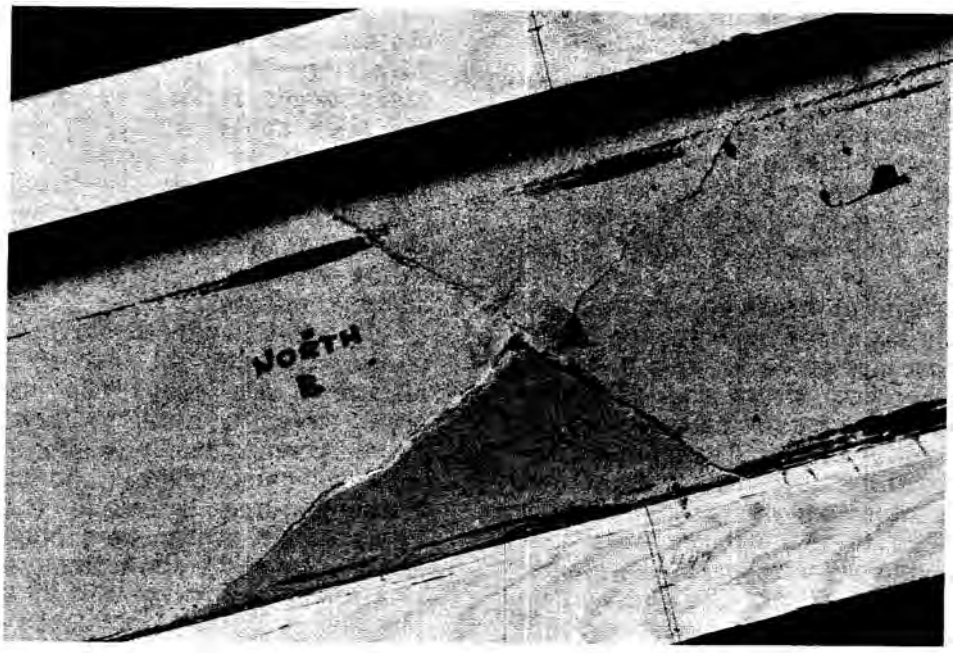

Figure 4. —Shear failure in 6-foot hardboard- webbed I-beams. (M 141 032)

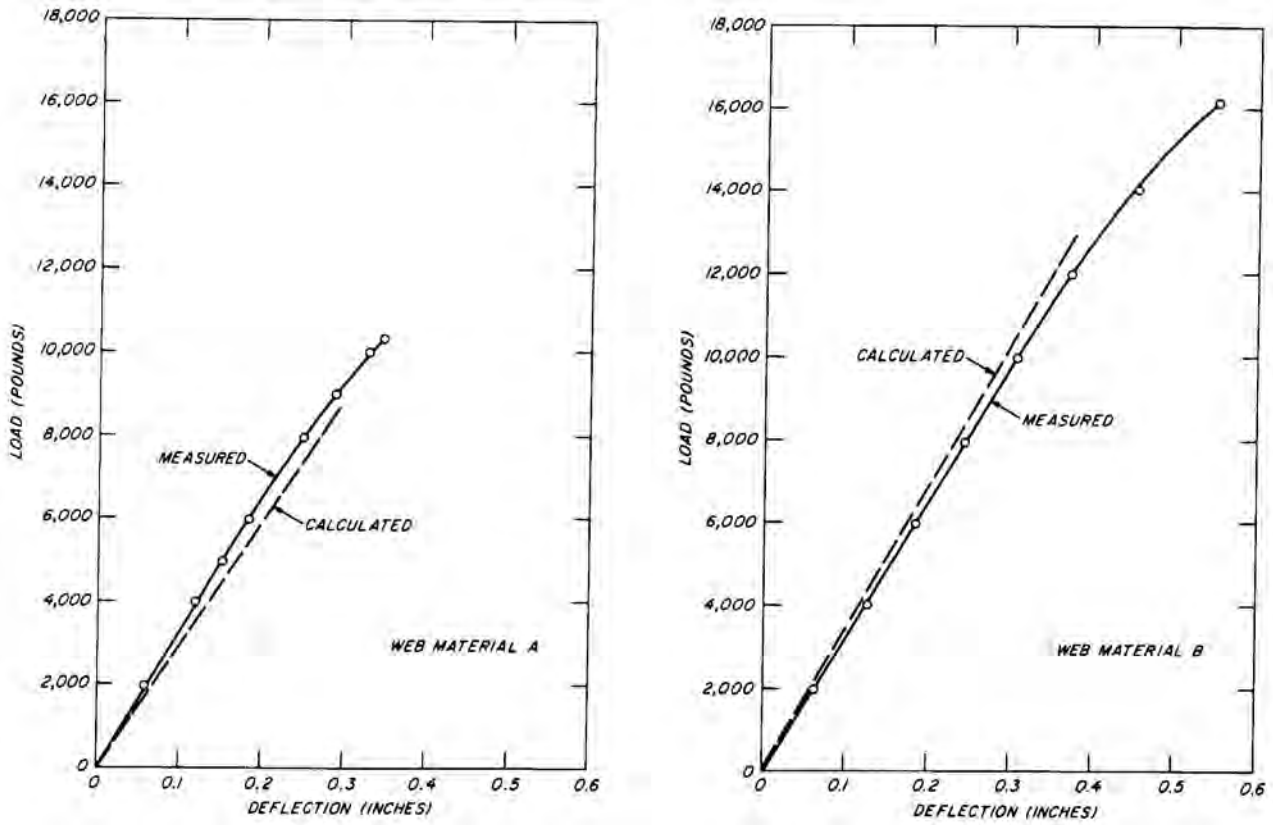

Figure 5. —Comparison of measured and calculated midspan deflection for typical 6-foot hardboard-webbed I-beams.

(M 143 782)

To calculate this safety factor, the ultimate load for each beam was multiplied by 0.48 to account for a 10-year load duration *(8).* This quantity was then divided by the load that would theoretically produce a shear stress in the web equal to 25 percent of the shear strength of the small specimens. This resulted in an average factor of safety in shear of 1.87 for material A and 1.51 for material B.

A comparison of measured and theoretical deflection and shear stress for the 6-foot I-beams is also presented in table 3. Measured and theoretical stress and deflection for the 6-foot beams did not compare as well as for the 12-foot beams. The percent difference between theoretical shear stress and shear stress obtained via rosette analysis ranged from 0.7 to 19.3 with an average of 9.9. The theoretical shear stress was greater for each of the eight beams. The average percent difference between theoretical and measured deflections was 16.2. Theoretical deflections were greater than measured for all of the 6-foot beams except one, and differed from the measured deflections of two of the 6-foot beams by as much as 33 percent.

Part of this difference can be attributed to variation in elastic properties. In addition, Mohr's circle analysis of the state of stress near center span at the point where the flange and web materials join indicates that the maximum principal stress and maximum shear stress are approximately equal. Short deep beams do not behave in accord with the dictates of simple bending theory. Also, the magnitude of the deflection of the 6-foot beams is such that the inherent or experimental error would affect the comparison more.

Possible Design Approaches

Results of this study indicate that the stresses and deflections calculated using elastic beam theory are usually larger than the measured values, i.e., elastic beam theory tends to be slightly conservative for this particular investigation. But if the elastic moduli are normally distributed and the average value is used for design, at least 50 percent of the structural components can be expected to exceed the deflection requirements when subjected to design loadings. For design it may be necessary to reduce the probability of exceeding the allowable deflection; therefore, a lower design value for elastic moduli would be required. One such approach described by the Nordic Committee on Building Regulations[5] recommends a characteristic stiffness for use in calculating the deformation of wood-base material. The characteristic stiffness value is defined as the value above which 70 percent of the stiffness values are found. If the stiffness values are normally distributed, the characteristic value, as defined by the Nordic Committee, would be approximately equal to the average minus one-half the sample standard deviation.

In order to investigate possible design stress levels and to establish stress levels for use in this study, "near minimum" rail shear strengths of 2,730 lb/in.^{2} for hardboard A and 3,180 lb/in.^{2} for hardboard B were estimated using a nonparametric or distribution-free technique (table 1) *(6).* These values, which were obtained from a sample size of 24, are at the lower end point of a tolerance interval with 95 percent content and 72 percent confidence. "Near minimum" values of compression and tension parallel to the surface, also listed in table 1, were estimated using the same technique. The sample size for these values was 10; therefore, the confidence is very low. Structural applications will require a higher confidence which would necessitate increasing the sample size.

The "near minimum" strength values were then multiplied by 0.48 to account for a 10-year duration of load and divided by 15/10, a factor of safety to account for unknown or unforeseen conditions *(11).* The 0.48 duration of load factor is based on the following formula for 1/4-inch-thick tempered hardboard by McNatt *(8).*

$$\frac{121}{T^{0.047}}$$

where S is the stress level expressed as a percent of the static strength determined using ASTM Standard D 1037-72, and T is the duration of stress to failure in seconds.

Strength values adjusted for duration of load and unforeseen conditions are presented in table 1. These values were derived to illustrate a possible method for determining design stresses. Establishment of general design stresses would require additional testing.

[5] Nordic Committee on Building Regulations, Recommendations for Strength and Rigidity of Flooring and Roof Sheathing. (Preliminary report for proposed publication.) Copenhagen. 1972.

SUMMARY

1. The behavior of hardboard-webbed I-beams subjected to short-term loading can be reasonably predicted using elastic beam theory, the method of transformed areas, and basic strength and elastic properties determined from small specimen evaluations. The behavior of 6-foot I-beams does not adhere as well to simple bending theory as does that of the 12-foot I-beams.

2. How environment and long-term loading affect the performance of built-up members of wood-base panel materials is not known. These important factors are currently being evaluated and the results will be reported.

3. For a design shear stress of 25 percent of the shear strength determined by small specimen tests, the average factor of safety in shear for the hardboard-web material was 1.87 for material A, a 1/4-inch-thick, dry-felted, dry-pressed, high-density tempered hardboard, and 1.51 for material B, a 1/4-inch-thick, wet-felted, wet-pressed, high-density tempered hardboard. These factors of safety were calculated by multiplying the average ultimate load for the 6-foot I-beam by 0.48 to account for duration of load, then dividing by the load that would produce a shear stress in the web approximately equal to 25 percent of the shear strength.

4. Load-deflection and load-strain curves for the hardboard-webbed I-beams were essentially linear below a load level equivalent to 60 percent of the rail shear strength determined from small specimen tests. Failure of the 12-foot I-beams occurred in the tension flange; there was very little inelastic deformation in the flanges to warn of failure prior to attaining the ultimate load.

5. Buckling of the 1/4-inch tempered hardboard web was negligible with stiffeners spaced 3 feet on center.

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