COMPARATIVE PERFORMANCE OF LONG-TERM LOADED WOOD COMPOSITE I-BEAMS AND SAWN LUMBER

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ABSTRACT

Solid sawn southern pine lumber $(2 \times 10 \text{ and } 2 \times 12)$ and wood composite I-beams having machine stress-rated southern pine flanges and composite panel webs (plywood, oriented strand board, and waferboard) were subjected to long-term loading in a stable hygrothermal environment and then destructively tested so that residual load-deflection characteristics could be measured. A 4-element viscoelastic model was fitted to the creep data on a specimen-by-specimen basis. Load history had a minor effect on the stiffness performance of I-beams, but did not influence load capacity or deflection at maximum load. Large variations in the lumber data obscured the subtle effects a load history might impose. Failure modes and locations in destructively tested specimens indicated that load history did not play a role in the ultimate failure mechanism.

Keywords: I-beams, lumber, load duration, creep, composite wood assemblies.

INTRODUCTION

At present, the literature contains little about the performance of wood composite I-beams under long-term loads. Service performance evaluations are the primary sources of information. Furthermore, the relative performance of wood composite I-beams and sawn lumber remains a matter of speculation. This paper features the results of a study in which we examined creep and load-deflection characteristics of wood composite I-beams and sawn lumber that had been longterm loaded to assess and compare the effects of load history on I-beam and lumber performance.

LITERATURE REVIEW

Discussion of long-term loads on wood and wood composites necessarily addresses the viscoelastic character of materials as well as load duration and damage because all three are intimately related.

The long-term load-deflection response of wood structural members is a viscoelastic event that can be described in three stages (Bodig and Jayne 1982). The

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primary stage, entered after initial loading, is defined by a decreasing rate of displacement and stress stabilization. The secondary stage is a transition period in which displacement rate is approximately zero. Finally, the tertiary phase is the stage in which deflection and deflection rate accelerate, usually signaling impending failure.

The viscoelastic behavior of wood and wood composites in tension, compression, and bending has been modeled with spring and dashpot models. Studying creep deformation of small, clear wood beams during drying, Leicester (1971) found that about 85% of total deflection was explained by a model consisting of an elastic element and a mechano-sorptive element; the mechano-sorptive element predicted deformation as a function of load and moisture content. A more refined 4-element model with Hookean springs and Newtonian dashpots (Szabo and Ifju 1970) adequately described creep displacement of wood beams under various sorptive conditions, even in changing environments. Comparing the 3- and 4-element models, each with Hookean springs and Newtonian dashpots, in compression tests with small, clear Sitka spruce [*Picea sitchensis* (Bong.) Carr.] specimens, Senft and Suddarth (1971) concluded that both model types were adequate, and that the 4-element model was the better choice for longer times and higher stresses.

Three and four-element models were evaluated by Pierce and Dinwoodie (1977), Pierce et al. (1979), and Dinwoodie et al. (1981, 1984) when studying creep in chipboard. One of these investigations (Pierce and Dinwoodie 1977) used nonlinear least-squares analysis to estimate model coefficients; multiple correlation coefficients were >0.96 for both model types. Senft and Suddarth (1971) used the maximum coefficient of multiple correlation as the criterion for goodness of fit, but this procedure gave dissimilar estimated values for replicated specimens. Furthermore, some values were negative, which satisfied the mathematical expression but made physical interpretation impossible.

Although the viscoelastic deflection of wood structural elements is not explicitly designed, the long-term effect of load on strength is adjusted with a deterministic factor in timber design. Duration of load was acknowledged as an important factor in early research on solid wood products. Wood (1951) conjectured that, at some threshold value of stress, duration is infinite. In Pearson's (1972) study, a damage threshold value (<50% of short-term strength) was suggested. Irreversible loading damage was shown to be the same for specimens intermittently loaded (repeatedly loaded and unloaded weekly) and matched specimens under constant load (Youngs and Hilbrand 1963).

More extensive studies on load duration attributes of structural hem-fir lumber in bending and tension perpendicular to the grain were reported by Madsen (1973, 1975). Madsen and Barrett (1976) concluded that the adjustment factors for duration of load do not apply to structural-size lumber subject to bending. The relationship between strength ratio and time to failure for dimension lumber differed considerably from that assumed.

Barrett and Foschi (1978a, b) included a threshold stress level below which no damage occurs. Subsequently, applying their probabilistic theory to structuralsize hem-fir lumber, Foschi and Barrett (1982) suggested, from empirical data, that 1 year should be a minimum long-term loading period. Furthermore, they estimated a damage stress threshold of 0.45 to 0.55 of maximum strength; a value of 0.50 yielded good agreement between model predictions and experimental results. Further analysis suggested that the effect of load duration was relatively species-independent.

For general laminates under constant loads, the stress state in the individual plies changes with time because of the different creep rates in each ply (Dillard and Brinson 1983). As stress is redistributed, load transfers from one ply to the next (Krus 1980; Boyle and Spence 1983; Dillard and Brinson 1983). A linear cumulative damage model has been used to account for the time-varying stress state between plies (Dillard and Brinson 1983).

Gerhards (1979, 1985) proposed a linear cumulative damage model for evaluating the time-related effects of loading on wood strength. The model assumed that residual fractional lifetime was the complement of the linear sum of fractional loading periods at various constant stress levels. Theoretical analysis suggested that loads not causing failure may have very little effect on strength.

The long-term load performance of hardboard- and plywood-webbed I-beams with Douglas-fir laminated veneer lumber flanges was investigated (Superfesky and Ramaker 1978; McNatt and Superfesky 1983). The I-beams, representing 12:1 (12 ft) and 6:1 (6 ft) span-to-depth ratios, were loaded under various environmental conditions. Lundgren (1957) had suggested 15% as a maximum longterm shear stress level, but Superfesky and Ramaker (1978) assumed 25% was the upper limit for design. Therefore, the I-beams were loaded at 15 and 25% of maximum shear strength. After long-term load and recovery, the beams were reconditioned and tested to ultimate capacity. For the 6-ft beams with hardboard webs, strength and stiffness were not affected by long-term loading at either stress level in the uncontrolled exterior environment, but were affected in the cyclic humidity environment. Strength values were slightly higher for 12-ft hardboardwebbed beams, and slightly lower for 12-ft plywood-webbed beams, than similar beams not long-term loaded; however, statistical significance was not determined. The effect of web material was evident in the time-deflection characteristics. For beams loaded at the same web shear-stress level, the hardboard-webbed specimens deflected less than did the plywood-webbed specimens of the same thickness. This effect was attributed to the shear modulus of the web material, which was much greater for hardboard than for plywood.

EXPERIMENTAL PROCEDURES

Materials

Full-scale tests were conducted with wood composite I-beams, 10 in. \times 16 ft (Fig. 1), and sawn lumber. The I-beam flanges were machine stress-rated southern pine lumber, minimum modulus of elasticity (MOE) of 2.2×10^6 psi, with finger joints at random intervals >72 in. Web materials were (1) ³/₈-in. 3-ply southern pine structural-1 plywood (PLY), (2) ³/₈-in. 5-layer oriented strand board (OSB), or (3) ³/₈-in. random waferboard (WB). The OSB and WB were primarily aspen. A phenol formaldehyde cold-setting adhesive was used in all beam joints.

I-beams of each web type were assembled with the minor axis of the web panel parallel to the beam span. As a result, butt joints in the web were at 48-in. intervals (Fig. 1). Web butt joints were recognized as a potential source of statistical variation, but the effect of butt joint location on the properties of interest was unknown.



FIG. 1. Location of web butt joints and loading points of wood composite I-beams. The crosssection is shown in section aa. P is load and R is reaction force.

Therefore, the location of the butt joints had to be either standardized or included in the experimental design; we chose standardization. One group of beams with the WB web was assembled with the major axis of the web panel parallel to the beam span; because WB panels were 20 ft long, these beams did not require web butt joints. The beams with butt-jointed WB webs are identified as WBJ, those without web butt joints as WBC.

The sawn lumber was no. 2 southern pine 2×10 s and 2×12 s purchased at local lumber retailers. No quality inspection was done at the time of purchase other than requiring that each piece was grade stamped.

The capacity of the long-term loading facilities influenced the number of replications possible for the study. So that the experiment might be completed in a reasonable time, 4 replications of each I-beam type and lumber size were used.

Specimen testing

Specimens were equilibrated at 75 F and 55% relative humidity for static and long-term load tests. For complete details on test methods and instrumentation, see Leichti (1986a, b).

Static load tests.—Sets of I-beams and lumber were destructively tested at a constant loading rate of 0.20 in./min in a hydraulic testing machine modified to accommodate full-size structural members. The tests conformed as nearly as possible to ASTM methods (1974). Load and deflection data were recorded by a computer-controlled data acquisition system (Leichti 1986b).

Long-term load tests. – Sets of I-beams and lumber matched to those statically tested were subjected to a stress level representing $\frac{1}{3}$ of the average short-term load capacities for I-beams and lumber combined. This level was selected because it was not expected to cause creep rupture. Yet the long-term load exceeded allowable design stresses for sawn single members (visual, $F_b = 1,200$ psi) and approximated the allowed design stress for I-beam tension flanges (MSR, $F_t =$



FIG. 2. Loading mechanism for long-term load tests of wood composite I-beams and sawn lumber.

2,150 psi) (National Forest Products Association 1986). In addition, web shear stresses were expected to approach 25% of static edgewise shear strength.

Loads for each type of member were calculated as follows from elementary bending theory, allowing for the elastic properties of the constituent materials and using the assigned stress level of 2,070 psi as the tension flange stress (σ_{tf}):

$$P = 6\sigma_{tf} EI/LcE_{tf}$$
(1)

where

P = load (lb)

EI = composite flexural rigidity (lb in.²)

L = span length (in.)

c = distance from neutral axis to outermost fiber (in.)

 $E_{tf} = MOE$ of tension flange (psi).

To date, standard methods and apparatus for testing full-size structural members in long-term bending are not available. Therefore, a loading frame that can accommodate up to 14 full-scale structural members was designed and erected. I-beams were set in the frame with the best flange in tension, lumber with the best edge in tension. This orientation was preserved for subsequent residual strength tests. Separate dead loads, as calculated with Eq. (1), for each specimen were rapidly imposed and held constant with a lever and cable system (Fig. 2). Displacements were measured with yoke-mounted, precision rotary potentiometers through a computer-controlled data acquisition system (Leichti 1986b).

The long-term load tests were conducted in two sets, the first for 2,644 h (111 days), the second for 2,742 h (114 days). The time difference between the two sets was assumed to be insignificant. The load period was selected because it nearly corresponded with the duration of load adjustment for snow (National



FIG. 3. Four-element model describing viscoelastic displacement, used for evaluating creep of wood composite I-beams and sawn lumber under long-term load. α_1 and α_2 are Hookean springs, and α_3 and α_4 are Newtonian dashpots.

Forest Products Association 1986). At the end of the long-term loading period, the loads were quickly removed. However, the test specimens were otherwise undisturbed for at least 14 days, which allowed recovery of the delayed elastic response.

Residual strength tests. — The specimens were removed from the test frame after the recovery period and placed on the testing room floor. So that the influence of load history on load-deflection characteristics of I-beams and lumber could be identified, the specimens were destructively tested within 3 weeks of final deflection readings in the recovery period. Procedures were the same as those for the initial static loading.

Analysis

Creep.—Linear viscoelastic theory treats total deformation as the sum of three components: initial elastic displacement, delayed elastic displacement, and displacement from viscous flow. A 4-element model comprising Kelvin and Maxwell bodies in series (Fig. 3) can effectively describe the viscoelastic behavior of a specific point on wood and wood composite I-beams (Szabo and Ifju 1970; Pierce and Dinwoodie 1977; Pierce et al. 1979; Bodig and Jayne 1982; Dinwoodie et al. 1984; Leichti and Tang 1986). Mathematically, the 4-element model expresses displacement, δ (in.), as (Pierce and Dinwoodie 1977; Bodig and Jayne 1982):

$$\delta = \beta_1 + \beta_2 \{ 1 - [\exp(-t/\beta_3)] \} + \beta_4 t$$
(2)

where

$$\beta_i$$
 = model parameters, i = 1, 2, 3, 4
t = time (h).

The elastic component of the Maxwell body, $\beta_1 = P/\alpha_1$, was the displacement measured when the long-term load was applied. The viscous component of the Maxwell body, $\beta_4 = P/\alpha_4$, was the residual displacement measured after the recovery period. However, the delayed elastic components, $\beta_2 = P/\alpha_2$ and $\beta_3 = \alpha_2/\alpha_3$, could not be directly measured and instead were estimated with regression methods.

The 4-element model, Eq. (2), was used as a regression function that was fit to 98 data points with nonlinear least-squares techniques. The multivariant secant method of solution was employed, wherein the derivatives of the model equation

are estimated from the history of iterations rather than being explicitly stated. The solution method iterated until convergence criteria were met.

Creep displacement rates were computed with Eq. (3), obtained by differentiating Eq. (2) with respect to time:

$$\frac{\partial \delta}{\partial t} = (P/\alpha_3)[\exp(-t/\beta_3)] + \beta_4$$
(3)

Residual strength.—Data were subjected to analysis of variance (ANOVA). Previously (Leichti and Tang 1983), variability in load capacity and deflection at maximum load differed for I-beams and lumber. Hence, a 2-part design was used. The I-beam data were assembled in a factorial completely randomized design (CRD), with I-beam type and load history as the factorialized sources of variation in the ANOVA. The lumber data were assembled in a separate factorial CRD, with lumber size and load history as the sources of variation in the ANOVA. If significant differences were identified by ANOVA, then a Duncan's Multiple Range Test was invoked.

I-beam and lumber means were statistically compared with Student's *t*. Because the comparisons represented the condition of unpaired observations and unequal variances, each statistical test required the appropriate estimated standard deviation between the two means and a weighted critical *t*-value (Steel and Torrie 1960).

RESULTS AND DISCUSSION

Creep

Measured (Fig. 4) and modeled creep displacements generally deviated <3% over the period studied. Displacement tended to be overestimated at the time of unloading.

Parameter estimates for the 4-element model are summarized in Table 1. Meaningful statistical analyses were precluded by the extremely large standard deviations. No clear trend was evident among the four I-beam types or between the I-beams as a group and the lumber. Others (McNatt and Superfesky 1983; Chen et al. 1987) have suggested that web shear strength and shear modulus play a leading role in creep performance.

Creep rate was computed for 3,060 h [Eq. (3)], and selected results up to 2,000 h are shown (Fig. 5). In our study, after an initial, rapid decrease (primary creep), the creep rate stabilized for two-thirds of the specimens within the computational time (secondary creep). The remaining one-third had continuously decreasing rates, but no specimens entered the tertiary stage. Stable creep rates were reached as early as 240 h (OSB) and as late as 2,340 h (2×10). Yet no definite trends could be established with respect to creep rates and member type.

Ongoing studies (Chen et al. 1987) clearly indicate that wood composite I-beams tested in a cyclic relative humidity environment will yield a much different load-deflection response. Changes in moisture content are known to cause creep curves to shift in small-specimen tests, and similar shifting occurs in tests of full-scale structural members.

Residual strength

I-beams. – Average maximum load capacities of the four I-beam types ranged from 4,954 (PLY) to 6,224 (OSB), coefficients of variation (CVs) from 3.3% (WBC)



FIG. 4. Long-term load-deflection responses of the six member types, two specimens per type. PLY, I-beam with plywood web; WBC, I-beam with waferboard web, no butt joints; WBJ, I-beam with butt-jointed waferboard web; OSB, I-beam with oriented strand board web; 2×10 and 2×12 , southern pine lumber sizes.

to 7.8% (WBJ) (Table 2). Data from the initial static and residual strength tests were combined for the ANOVA, and sources of variation partitioned by beam type, load history, and beam type-load history interaction. Beam type was significant at $\alpha = 0.05$; the OSB I-beams had a significantly greater load capacity than the other three beam types, which did not differ from each other as revealed by Duncan's Multiple Range Test (Table 3).

Load history was not significant. But the beam type-history interaction was significant at $\alpha = 0.10$, due largely to the WB-webbed members. Average load capacity of WBC members, 5,529 lb in the initial static tests, was only 5,163 lb in the residual strength tests; that of WBJ members, initially 4,971 lb, was 5,730 lb in residual tests. However, average load capacities of PLY and OSB members differed by <110 lb for initial and residual tests. Evidence from photographs of failures, lab notes, and broken test specimens indicated that minor differences in flange quality probably caused the changes observed in the performances of the two WB member types. Additional replications might have eliminated this effect.

Average deflection at maximum load ranged from 2.450 in. (PLY) to 1.890 in. (WBC), and CVs were <10.4% (Table 2). Data from the initial static and long-

Mambar	Statiatia?	Model parameter				
type ¹	(n = 4)	β_1 (in.)	β_2 (in.)	β ₃ (h)	β ₄ (10 ⁻⁴ in./h)	
I-beam						
PLY	Mean	0.7026	0.1187	164.92289	0.9516	
	SD	0.0725	0.0467	181.36825	0.7543	
	CV (%)	10.3	39.3	110.0	79.3	
WBJ	Mean	0.6551	0.0902	137.37623 ³	0.4674	
	SD	0.0455	0.0059	35.34720	0.3899	
	CV (%)	6.9	6.5	25.7	83.4	
WBC	Mean	0.6390	0.1256	141.74928	0.4608	
	SD	0.1400	0.0356	157.49013	0.2646	
	CV (%)	21.9	28.3	111.1	57.4	
OSB	Mean	0.6207	0.0766	138.91201	0.5074	
	SD	0.0269	0.0336	121.71274	0.2631	
	CV (%)	4.3	43.9	87.6	51.8	
Lumber						
2 × 10	Mean	0.8510	0.1394	235.45528	0.5550	
	SD	0.1714	0.0521	106.86256	0.2408	
	CV (%)	20.1	37.4	45.4	43.4	
2 × 12	Mean	0.9101	0.1686	179.31834	0.7632	
	SD	0.2555	0.0912	113.64935	0.4324	
	CV (%)	28.1	54.1	63.4	56.6	

TABLE 1. Summary statistics for the parameters of the 4-element displacement model.

¹ PLY, I-beam with plywood web; WBJ, I-beam with butt-jointed waferboard web; WBC, I-beam with waferboard web, no butt joints; OSB. 1-beam with oriented strand board web; 2×10 and 2×12 , southern pine lumber sizes. ² SD = standard deviation; CV = coefficient of variation.

 3 n = 3, WBJ7 data censored.

term load tests were pooled for the ANOVA. Beam type was significant at α = 0.05, but neither load history nor beam type-history interaction was significant. Deflection at maximum load of the PLY and OSB beams was significantly different $(\alpha = 0.05)$ from that of the WB beams (Table 3).



FIG. 5. Creep rates of representative wood composite I-beams and sawn lumber under constant long-term load. See Fig. 4 caption for definitions of abbreviations.

Member type	Statistic (n = 4)	Dependent variable				
		Maximum load (lb)	Load-deflection ratio ² (lb/in.)	Deflection at maximum load (in.)	Moisture content ³ (%)	
I-beam						
PLY	Mean	4,954	2,318	2.450	9.8	
	SD	241	32	0.200	0.2	
	CV (%)	4.9	1.4	8.2	1.8	
WBJ	Mean	5,730	2,774	2.095	9.1	
	SD	447	167	0.158	0.1	
	CV (%)	7.8	6.0	7.5	0.8	
WBC	Mean	5,163	2,750	1.890	9.6	
	SD	171	295	0.196	1.4	
	CV (%)	3.3	10.7	10.4	14.6	
OSB	Mean	6,224	2,894	2.130	9.1	
	SD	320	180	0.088	0.5	
	CV (%)	5.2	6.2	4.1	5.4	
Lumber						
2 × 10	Mean	5,406	1,690	3.258	9.1	
	SD	2,366	355	1.528	1.7	
	CV (%)	43.8	21.0	46.9	19.0	
2 × 12	Mean	6,381	2,414	2.949	10.3	
	SD	960	545	0.630	1.2	
	CV (%)	15.0	22.6	21.4	12.2	

TABLE 2. Statistics from residual strength tests after long-term loading for the wood composite *I*-beams and sawn lumber.¹

¹ See Table 1 footnotes for definitions of abbreviations.

² Load at 1.0 in. of deflection. ³ Oven-dry basis.

Load-deflection ratio was also examined. Beam type was significant at $\alpha = 0.05$, load history at $\alpha = 0.10$. Load history apparently was significant because average load-deflection ratio of the long-term loaded I-beams was greater than that of each beam type before loading. Similarly, McNatt and Superfesky (1983) observed that hardboard-webbed I-beams were stiffer after long-term load. Despite the suggested significance of load history on load-deflection ratio, the beams with and without load histories were treated as a group for Duncan's Multiple Range Test. The load-deflection ratio for I-beams webbed with OSB and WB was greater (α = 0.05) than that of those webbed with PLY (Table 3). Differences in measured load-deflection ratio can be attributed to the shear modulus of the web material

TABLE 3. Duncan's Multiple Range Test—effect of I-beam type on load-deflection characteristics; pooled results of initial static and residual strength tests.

	Dependent variable ²				
$\begin{array}{l} \text{I-beam type}^{t} \\ (n = 8) \end{array}$	Maximum load (lb)	Deflection at maximum load (in.)	Load-deflection ratio ³ (lb/in.)		
OSB	6,213a	2.287a	2,777a		
WBJ	5,350b	2.029Ъ	3,683a		
WBC	5,346b	1.982b	2,740a		
PLY	5,008b	2.534a	2,286b		

See Table 1 footnotes for definitions of abbreviations.

² Within columns, means followed by the same lowercase letter do not significantly differ ($\alpha = 0.05$).

³ Load at 1 in. of deflection.

and are consistent with the shear moduli reported by Leichti (1986a). The actual deflection components due to bending and shear can be calculated (Leichti and Tang 1983).

So that the overall effect of web butt joint on beam performance could be determined, performance of WBJ and WBC members was compared. WBC and WBJ members were not significantly different from one another with respect to maximum load, deflection at maximum load, load-deflection ratio, or variability.

The physical failure characteristics of the I-beams were qualitatively compared for specimens from initial static and residual strength tests. Finite element analyses coupled with strength theory (Leichti 1986a) predicted that long-term load levels may have produced localized failures in the web panels at the tips of the web butt joints. However, the residual strength data and failure patterns did not reveal any evidence of damage from loading.

Lumber. – Data from the initial static and residual strength tests were combined for the ANOVA. The large variations and relatively low number of degrees of freedom contributed to the lack of significance of lumber size, load history, and the size-history interaction for maximum load and deflection at maximum load. However, the two lumber sizes differed significantly ($\alpha = 0.10$) for load-deflection ratio. A qualitative examination of static test data from initial and residual strength tests showed that load-deflection and failure patterns were similar.

I-beam and lumber comparison.—Initial static and residual strength data for I-beams (n = 32) and lumber (n = 16) were pooled. Then maximum load, deflection at maximum load, and load-deflection ratio for I-beams and lumber were statistically compared with a 2-tail *t*-test ($\alpha = 0.10$). The maximum load capacities of I-beams and lumber did not differ. However, the mean deflections at maximum load and the load-deflection ratios differed significantly for I-beams and lumber. These results imply that although the I-beams and lumber carried equivalent loads, the I-beams were probably stiffer than the lumber. These results should be interpreted carefully, though, because the variables, maximum load, load-deflection ratio, and deflection at maximum load, are not normalized for cross-section geometry.

SUMMARY

Four different wood composite I-beam types and two sizes of sawn southern pine lumber were subjected to long-term loading in a stable environment, and later the full-size structural members were destructively tested. The long-term load level for I-beams approached the design stress for the flanges and exceeded the expected damage threshold for panel products. A 4-element model was used to evaluate creep of each member type. Analysis of variance was used to examine the effects of beam type, load history, and beam type-load history interaction with respect to maximum load capacity, deflection at maximum load, and load-deflection ratio.

Large variations in creep model parameters precluded meaningful statistical analyses. However, two-thirds of the members actually measured moved from primary to secondary creep between 240 and 2,340 h, whereas creep rates continuously decreased (typical of primary creep) for the remaining one-third. Creep performance of I-beams and lumber could not be distinguished.

Web material of the I-beams was the basis for significant differences in maxi-

mum load capacities, deflection at maximum load, and load-deflection ratio. Load history apparently played a minor role in I-beam stiffness. Data from lumber tests varied widely, obscuring the subtle effects that might have developed from the imposed load history.

Statistical tests with pooled data from destructive load tests suggested that I-beams and lumber had the same maximum load capacities, that lumber probably deflected further than I-beams at maximum load, and that I-beams were probably stiffer than lumber.

Wood composite I-beams are not generic; there is a wide range of materials and geometries in use. Therefore, extrapolation beyond the conditions presented is cautioned.

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