System Innovation and Experimental Evaluation of Stressed-Timber Bridges

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Stressed decks are constructed by squeezing lumber laminations using galvanized steel bars with ultimate strengths of 155 ksi. Bridges of longer span lengths using stressed-deck concepts are feasible with two different methods: (a) increasing the number of layers of lumber laminations of the stressed deck; and (b) adding stringers and diaphragms to the stressed deck. The stressed-bridge systems developed and presented include (a) slab or solid stressed deck, (b) tee, (c) bulb-tee, and (d) box. Only tee, bulb-tee, and box systems were tested. The tee, bulb-tee, and box with laminated veneer lumber (LVL), glulam, and fiber-reinforced plastic stringers are tested for bending under three different load conditions and their responses are evaluated. The significant performance characteristics (such as lamination separation caused by transverse bending, vertical slip caused by direct vertical load, lamination rotational slip at butt joints caused by longitudinal bending, and the minimum transverse prestress levels in laminations) are checked. The tested systems (tee, bulb-tee, and box) are compared for their stiffness. The systems' composite action, diaphragm effects, and load sharing are evaluated. In addition, ultimate load characteristics are studied by taking the specimens to failure. GangaRao's analytical model with orthotropic material properties is verified with the experimental results.

In stressed decks, lumber laminations with a nominal thickness of 2 in. are squeezed by high-strength steel bars to make the resulting structure act like a plate. Frictional forces are created on the faces of lumber laminations caused by normal compression stresses created by prestressing forces. These frictional forces are responsible for preventing the lumber laminations from slipping vertically off their contact faces. When loads are applied perpendicular to the plane of the deck, laminations may separate from the contact faces at bottom fibers. If an adequate amount of compressive stresses are maintained on the contact faces of laminations, this problem can be prevented. The research conducted at the University of Wisconsin and at West Virginia University (WVU) indicates that a prestress level of 50 psi is adequate to prevent vertical slip and separation of laminations (*1–3*). Butt joints of lumber laminations can be provided in stressed decks because the frictional stresses on contact faces can transmit bending stresses from one laminate to another even at butt joint locations. A solid stressed deck can be modeled as an orthotropic plate with different properties in the longitudinal and transverse directions.

Stressed-slab decks are safe and economical for bridges of less than 30-ft span. (This result is based on the construction projects of 33 timber bridges in West Virginia during the years 1989 and 1990.) However, use of stressed-slab decks may be uneconomical for bridges with spans greater than 35 ft. Bridges of higher span lengths using stressed decks are possible with two different methods: (a) increasing the numbers of layers of lumber laminations of the stressed deck, and (b) adding stringers to the stressed deck. In addition to stringers, diaphragms could be used in between stringers for increasing the lateral stability of stringers, improving the load distribution between stringers, and increasing the bending and shear resistance of the overall systems. A variety of manufactured materials such as LVL, glulam, parallam, and fiber-reinforced plastic (FRP), including steel and aluminum, can be used for stringers and diaphragms. Therefore, stressed systems for timber bridges for longer spans (more than 35 ft) are possible by modifying the basic stressed-deck component. Also, other alternate systems can be configured by the geometries and materials of the components to choose the system to best suit the design requirements and site conditions.

STRESSED-TIMBER BRIDGE SYSTEMS

In a manner similar to concrete and steel bridges, stressed-timber bridge systems can be developed into structurally efficient and cost-competitive superstructures for primary and secondary highway applications. In the natural order of development for stressed-timber bridge systems, the solid deck system was developed first; then the design was modified to include stringers and diaphragms. Each stressed-timber bridge system is described. The dimensions that are shown in Figures 1–4 are the actual dimensions of the tested specimens.

Solid Stressed Deck

A solid stressed deck can be composed of single- or multiple-layer laminations through its depth. Figures 5 and 6 show the cross-sectional details of single- and multilayer stressed decks, respectively. In a multilayer solid stressed deck, different sizes of laminae are placed in such a way that an interlocking mechanism is created between them.

Tee Systems

The tee systems consist of stringers and flange components compressed together by the stressed rods as shown in Figure 1. The compressive force creates a composite action between the stringers and the flange by developing frictional forces between the contact faces of the components. Diaphragms are added (Figure 2) in between stringers for the tee systems

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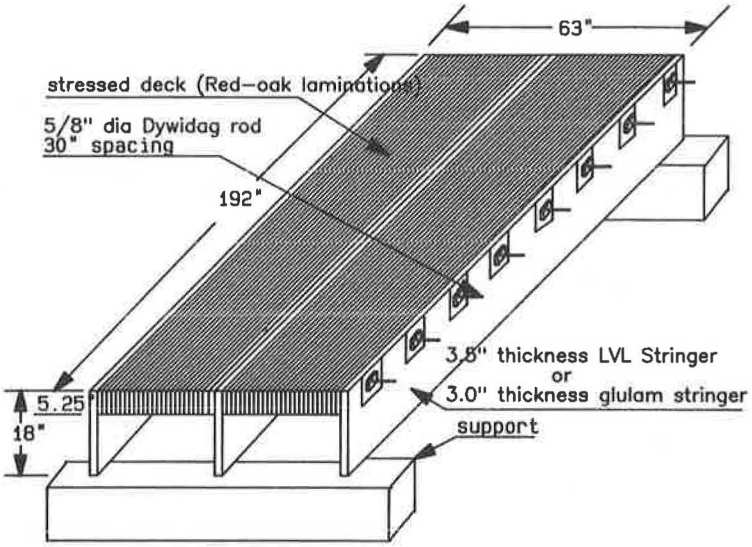
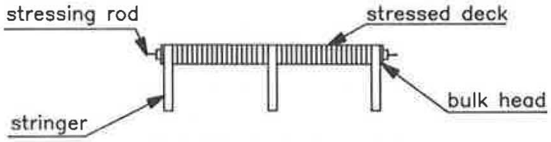
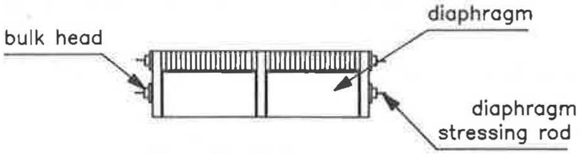


FIGURE 1 Tee system specimen.



Tee without diaphragms



Tee with diaphragms

FIGURE 2 Tee system with and without diaphragms.

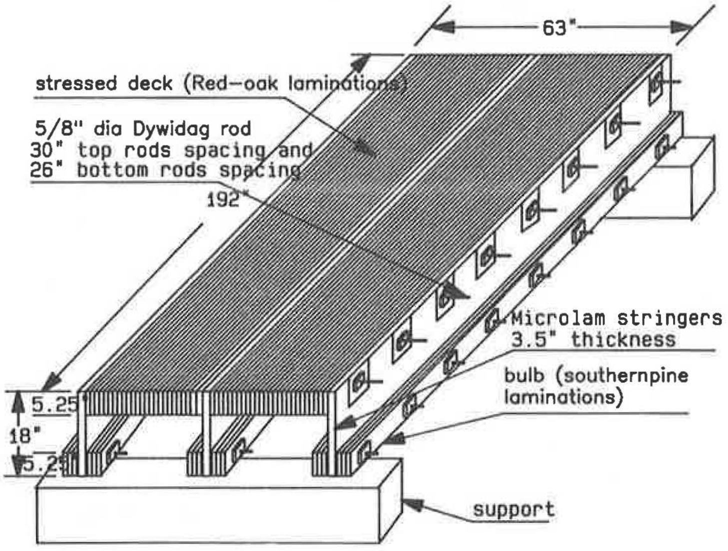


FIGURE 3 Bulb-tee system specimen.

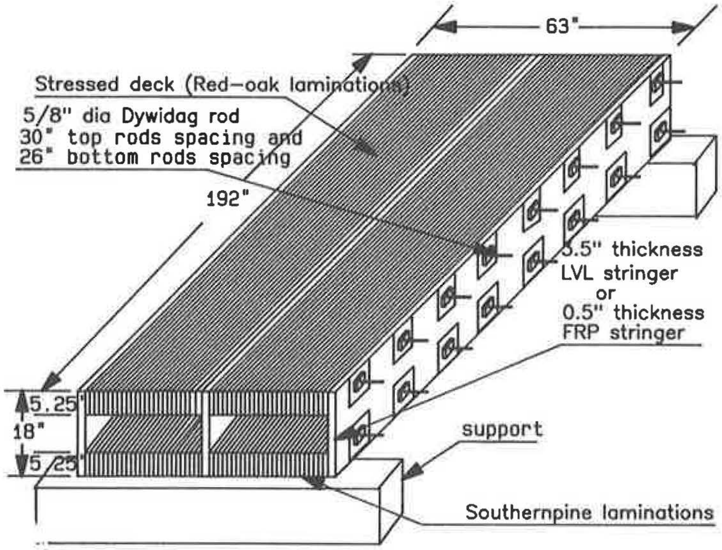


FIGURE 4 Box system specimen.

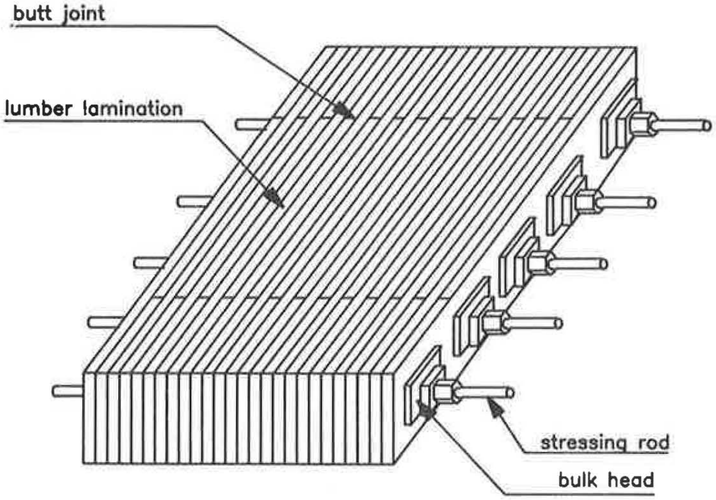


FIGURE 5 Solid stressed deck (single layer).

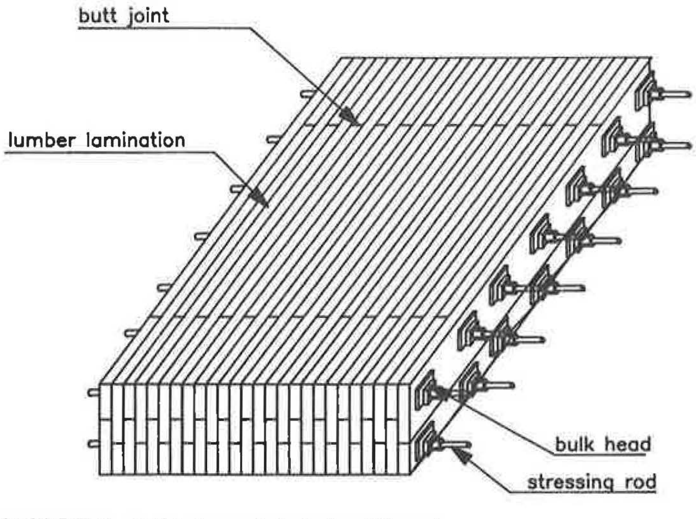


FIGURE 6 Solid stressed deck (multilayer).

to prevent lateral-torsional buckling of the stringers in case of large spans and for better transverse load distribution and improved stiffness.

Bulb-Tee Systems

The bulb-tee system is similar to a tee system, except that timber planks are attached at the bottom of each stringer to create a bulb. Figure 3 shows the details of this design. Threaded rods are used to hold the bulb laminations. These rods are prestressed using a hydraulic jack. The bulb-tee stringers can also be constructed with diaphragms to prevent lateral buckling, as described earlier in this section.

Box Systems

Figure 4 shows the design of a cellular box system. This system is stiffer than girder sections described previously and requires shallower stringer depths than a tee system. However, a major disadvantage of a cellular box design is the difficulty of visual inspection. In addition, the closed environment of a box may trap moisture and lead to moisture condensation on the interior walls of the cells. In the case of large stringer depths, as with the tee and bulb-tee systems, diaphragms could be added to prevent buckling of stringers.

Alternate Systems

An optional design may require considering alternate timber components that best suit the site requirements. The alternate systems could be developed by simply altering the stringer materials and changing the diaphragm options. The possible stringer materials are steel, aluminum, LVL, glulam, parallam, and FRP. The diaphragms can be connected to the stringers with stressing rods. Holes have to be drilled all the way through the entire length of the diaphragms and the width of the stringers in order to run the stressing rods from one end to the other. The location and number of diaphragms are primarily controlled by design load requirements.

EXPERIMENTAL AND THEORETICAL ANALYSIS

Full-scale stressed-timber systems were tested in the WVU Major Units Laboratory. The test specimens include tee, bulb-tee, and box specimens with LVL, glulam, and FRP stringers, with options of diaphragms, and also individual LVL and glulam stringers. Theoretical analysis of stressed systems is mainly focused on the load-sharing capacity, deflections, and strains of the stringers. In the analysis, GangaRao's orthotropic plate equations are used (*4*). GangaRao's equations were basically derived from the analysis of bridge decks idealized as ribbed or grid-plate systems. Because the stressed timber systems are similar to ribbed systems, the formula for ribbed systems can be extended to the analysis of stressed-timber systems.

OBJECTIVES

The objectives of the experimental evaluation program were

1. To test tee, bulb-tee, and box systems (Figures 1–4) under different load conditions with the objective of establishing degree of composite action, influence of diaphragms, characteristics of load distribution, induced strains and stresses, and load deflection responses.
2. To check the stressed deck elements (hardwood planks) for possible adverse rotation of butt joints, vertical slip (incomplete shear transfer), and separation on the tension side of the deck under applied loads.
3. To test in bending the bridge components (LVL and glulam stringers) and the fully assembled systems (tee, bulb-tee, and box) in order to assess the failure mode and transverse load distribution characteristics of the systems.
4. To evaluate the magnitude of experimental responses, such as deflections and strains, of the three stressed systems under applied loads.
5. To obtain analytical results, such as transverse load distributions, stresses, and deflections, using GangaRao's orthotropic plate solutions, and correlate them with experimental results.

EXPERIMENTAL PROGRAMS

The test specimens for tee, bulb-tee, and box systems are shown in Figures 1, 3, and 4, respectively. These specimens consist of red oak top flanges and Southern pine bottom flanges (when required). The grade of the lumber used was No. 3. The systems were constructed with stringer components consisting of three distinct materials: LVL, glulam, and FRP. The FRP stringers had 50 percent of E-Glass fiber and 50 percent of vinylester matrix. The systems that were tested are presented in Table 1. Dywidag rods of ⅝ in. diameter were used to prestress the system, and a 100-psi prestress level in timber was maintained in the test specimens. The diaphragms are attached to the stringers by the compressive action of the prestressing rods. Three types of static load conditions were applied, referred to as load configurations *A*, *B*, and *C* as shown in Figures 7–9. The specimens were subjected to load conditions *A*, *B*, and *C*, and their load-deflection and load-strain responses were recorded. Strain gages and dial gages were used to measure strains and deflections. Loads were applied gradually and the loading range varied from 0 to 60 kips. The following systems were tested to failure: bulb-tee with diaphragms, glulam tee without diaphragms, and FRP box with diaphragms. For these tests, the load level was continuously increased even after the occurrence of the first failure of one or more of the stringers. Descriptions of the tests are presented in Table 1. In addition, the individual LVL and glulam stringers were tested in bending in accordance with the ASTM D198–84E standard. The specimens were simply supported and subjected to a concentrated load at the center. In order to prevent torsional buckling, lateral supports were

TABLE 1 LIST OF SPECIMENS TESTED UNDER DIFFERENT LOAD CONDITIONS

System	Tested Loading Conditions	Remarks
Tee with LVL Stringers with Partial diaphragms	A	-
Bulb-Tee with LVL Stringers w/o Diaphragms	A	-
Bulb-Tee with LVL Stringers with Diaphragms	A	The specimen was tested to failure.
Box with LVL Stringers w/o Diaphragms	A,B,C	-
Box with LVL Stringers with Diaphragms	A	-
Tee with Glulam Stringers w/o Diaphragms	B	-
Box with FRP Stringers w/o Diaphragms	A,B	The specimen was tested to failure.
Box with FRP Stringers with Diaphragms	A	The specimen was tested to failure.

(-) - Specimen was not tested to failure.

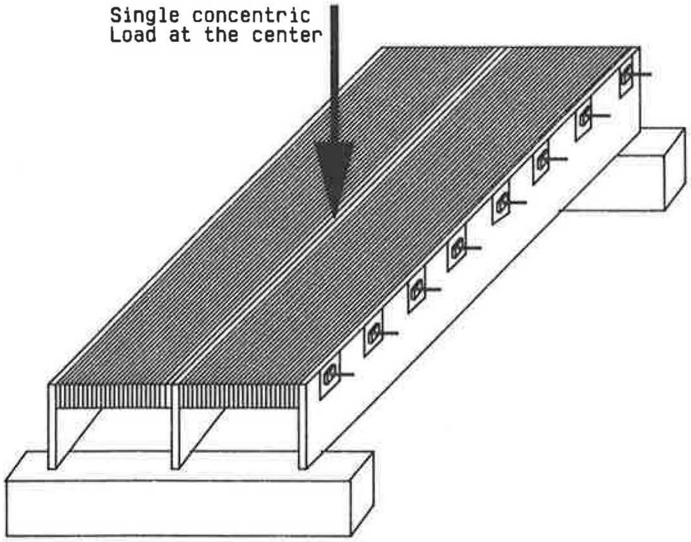


FIGURE 7 Load condition A.

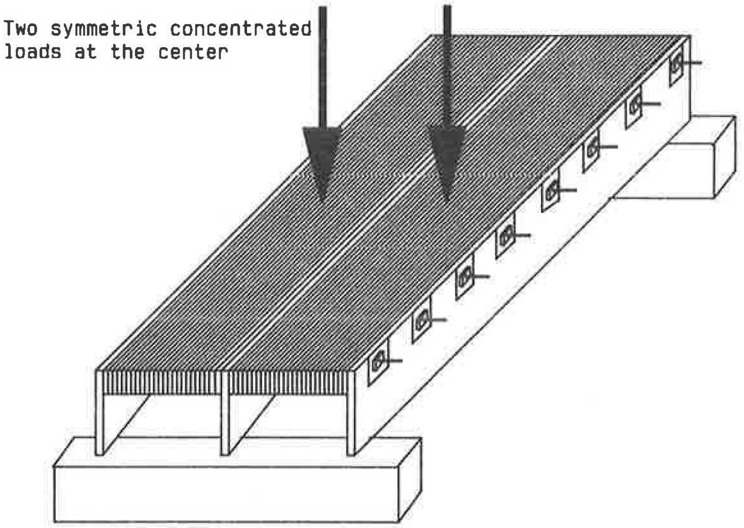


FIGURE 8 Load condition B.

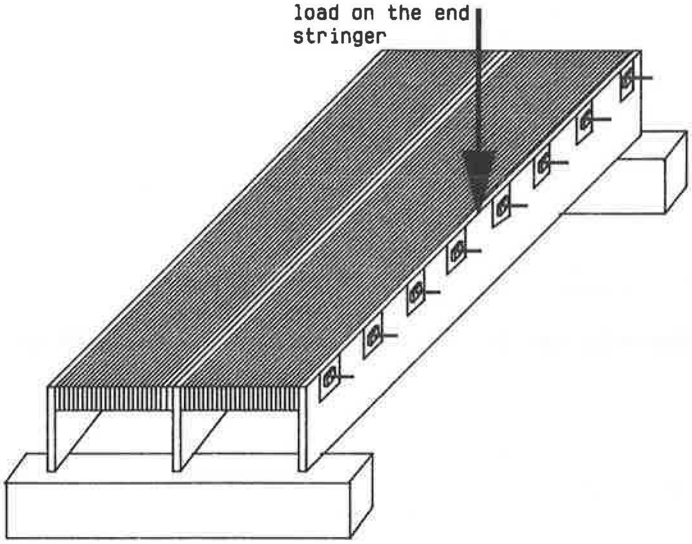


FIGURE 9 Load condition C.

provided for the specimens. The ultimate bending stresses were established by loading the stringer specimens to failure.

DISCUSSION OF RESULTS

Composite Action

Composite action of the stressed-timber systems considered in this report was verified by establishing the location of the neutral axis from top and bottom fiber readings in the longitudinal direction of stringers. Table 2 presents the shift of the neutral axis of the interior stringer from the geometric centroidal axis. For the tee and box systems, neutral axes were found to be 2.41 and 0.43 in., respectively, away from the geometric centroidal axis of their corresponding stringers. Computed shifts of the neutral axes of those sections on the basis of the classical static approach were close to the experimental values presented in Table 2. On the basis of the results, it can be concluded that nearly full composite action is developed for loads within the linear range. However, the composite action does not appear to be 100 percent for loads approaching failure. For example, when testing the tee section, the central stringer failed first; however, the adjacent deck laminations did not show any distress. Also, when the FRP box section was loaded to failure, the system underwent large deflections (over 6 in. at midspan) without any failure of the deck laminations occurring.

Load Deflection Characteristics of Stressed Systems

The load deflection curves demonstrate linear and nonlinear responses, which depend on the magnitudes and locations of the applied loads. For example, the tee with glulam stringers as tested to failure exhibited nonlinear behavior for load con-

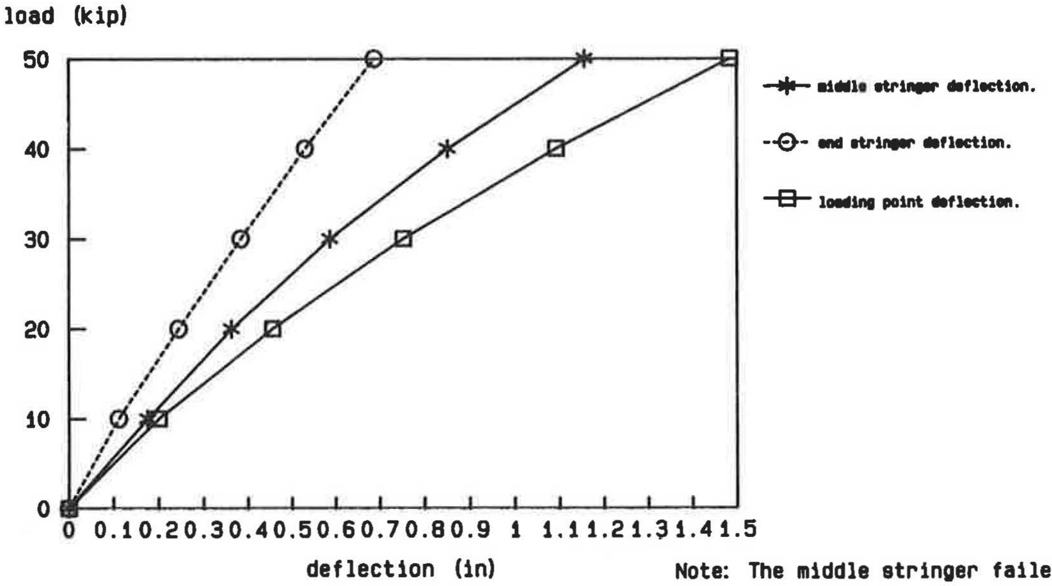
TABLE 2 SHIFTING OF NEUTRAL AXIS BECAUSE OF COMPOSITE ACTION

Type of System and Stringer Location	Strain on top of the stringer $(in/in)*10^{-6}$	Strain on bottom of the stringer $(in/in)*10^{-6}$	Shifting of the neutral axis from the geometric center of the stringer	
			Experiment	Analytical Approach
Tee with LVL Stringers (without diaphragms)-Interior Stringer	-1270	2200	2.41"	1.61"
Box with LVL Stringers (without diaphragms)-interior stringer	-465	510	0.43"	0.34"

dition B exceeding 30 kips (Figure 10). The bulb-tee with LVL stringers and diaphragms showed nonlinear behavior when loaded beyond 20 kips under load condition B (Figure 11). However, for load condition A, nonlinear behavior was not observed even at a load level of 30 kips (Figures 12–14). These observations imply that the lower transverse stiffness of the flanges causes them to undergo large local deflections when the load is applied directly on them. In contrast to the timber box section, the FRP box system showed nonlinear behavior both for load conditions A and B, which can be attributed to the low flexural stiffnesses of the FRP stringers (Figures 15 and 16); i.e., geometric nonlinearity of the members is probably the major cause of the nonlinear response of the system, which is magnified by the presence of butt joints and the opening of laminations for load levels above 20 kips. From the test results, it is evident that every stressed timber system will exhibit a degree of nonlinear response beyond a certain load range. In order to satisfy the serviceability limit states, design loads have to be within this load range.

Influence of Diaphragms

In Table 3, the addition of diaphragms to the bulb-tee system (with LVL stringers) reduced the maximum deflection from 0.895 to 0.593 in. for a 30-kip load, which represents an increase of 50 percent in the stiffness of the system. The box system (with LVL stringers) did not show any increase in stiffness



Note: The middle stringer failed at 51 kip load.

FIGURE 10 Load-deflection curves for the tee with glulam stringers (without diaphragms) for the Load Condition B.

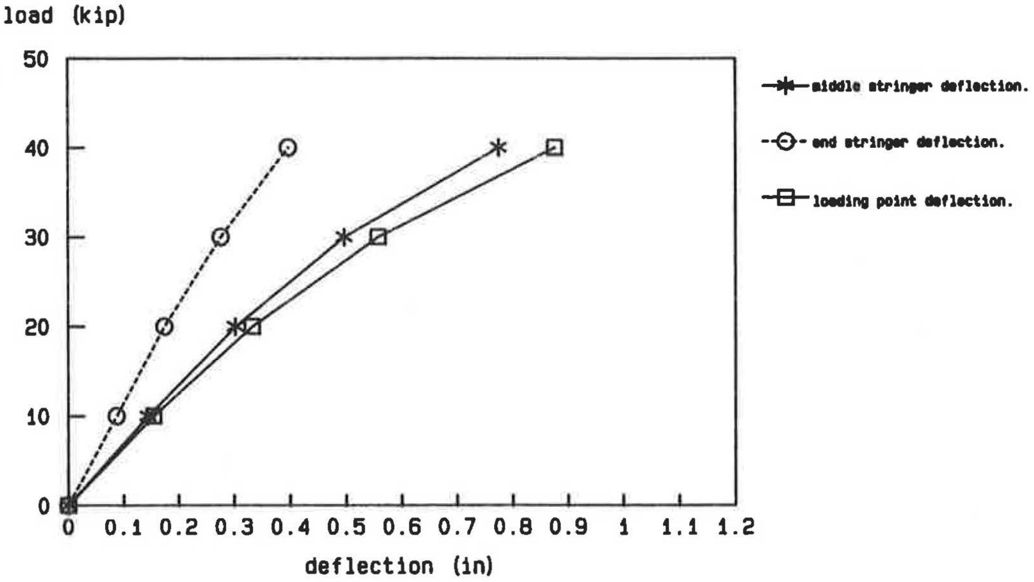


FIGURE 11 Load-deflection curves for the bulb-tee with LVL stringers (with diaphragms) after the failure of the middle stringer for Load Condition B.

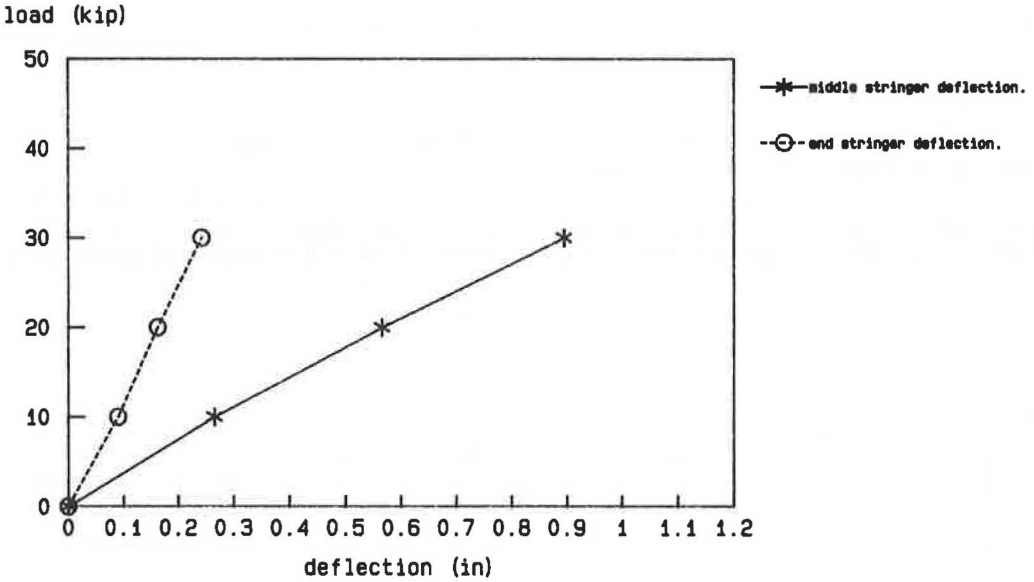


FIGURE 12 Load-deflection curves for the bulb-tee with LVL stringers (without diaphragms) for Load Condition A.

when the diaphragms were added, which can be attributed to the fact that the deck itself acts as a diaphragm for shallow stringer depths. The addition of diaphragms to box system (with FRP stringers) increased the deflection from 0.780 to 0.974 in., which is attributed to readjustment of the butt joints of lumber laminations and FRP stringers when diaphragms were present.

Failure Modes of Systems and Individual Components

The bulb-tee with LVL stringers and diaphragms was tested to failure by applying a concentrated load (load condition A) to the middle stringer. A tensile bending failure to the middle stringer was observed at a load of 60 kips (corresponding to 4,350-psi flexural stress). The tee with glulam stringers was tested to failure under load condition B. The middle stringer failed in bending at a load level of 51 kips (4,800-psi tensile bending stress). The failure was sudden and was originated at a knot located at the outer bottom fiber. The box with FRP stringers and timber diaphragms was tested to failure under load condition B. The specimen did not show any failure or vertical slippage of the elements up to a load level of 50 kips. For a sustained load of 58 kips, the specimen failed because of buckling failure of the compression flanges of the FRP stringers. In the tested systems, no shear failure of the string-

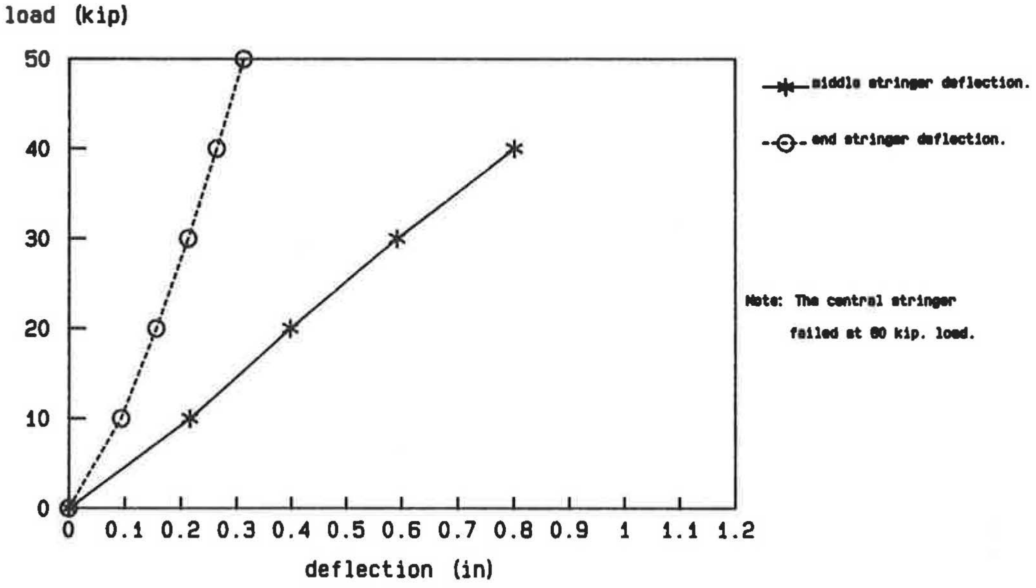


FIGURE 13 Load-deflection curves for the bulb-tee with LVL stringers (with diaphragms) for Load Condition A.

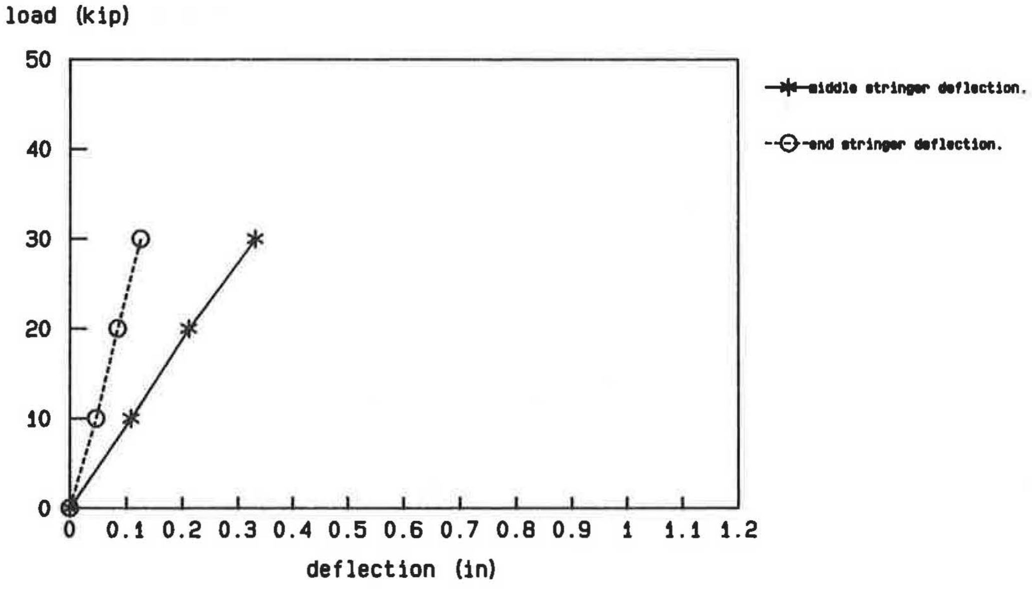


FIGURE 14 Load-deflection curves for the box with LVL stringers (without diaphragms) for Load Condition A.

ers and no failure or vertical slippage of the laminations was observed. Testing of individual LVL and glulam stringers showed bending failure at the bottom-most fiber at midspan. The LVL and glulam stringers failed at 25.00 kips (4,350-psi tensile bending stress) and 25.60 kips (4,800-psi tensile bending stress), respectively.

Assessment of Load Sharing of Stringers

The percentage of load sharing of the stringers was evaluated by comparing the test results of the ultimate loads of the stressed systems and the individual stringers. Table 4 indicates that the load shared by the stringers without diaphragms is 50 percent of the total load carried by the system, and when diaphragms are included, the percentage is 58 percent.

Stiffness Comparison of Stressed System

The maximum deflections of the system considered in this study, for a 30-kip load and load condition A, are presented in Table 5. The relative stiffnesses for the bulb-tee systems with and without diaphragms, the box systems, and all of the

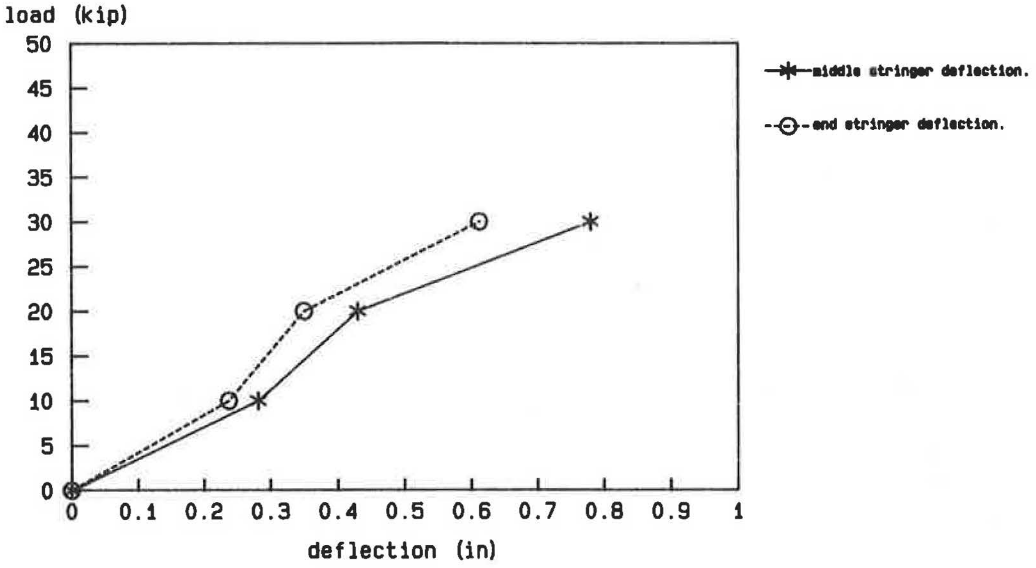


FIGURE 15 Load-deflection curves for the box with FRP stringers (without diaphragms) for Load Condition A.

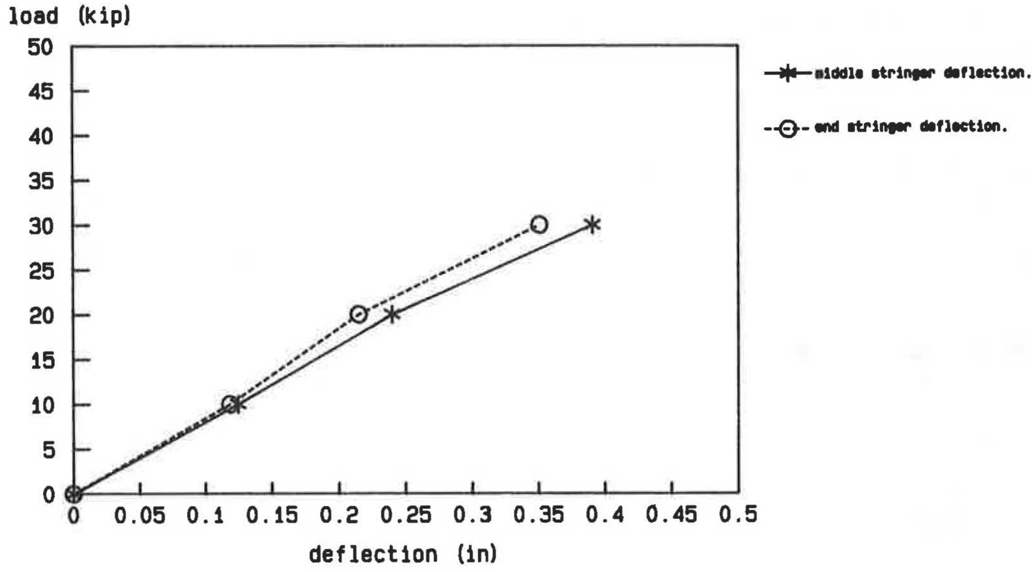


FIGURE 16 Load-deflection curves for the box with FRP stringers (without diaphragms) for Load Condition B.

TABLE 3 STIFFNESS COMPARISON WITH ADDITION OF DIAPHRAGMS

System	Deflection Without Diaphragms (in)	Deflection With Diaphragms (in)	% Increase in Stiffness
Bulb-Tee with LVL Stringers	.895	.593	50%
Box with LVL Stringer	.332	.350	00%
Box with FRP Stringer	.780	.974	00%

TABLE 4 PERCENTAGE LOAD SHARING OF MIDDLE EXTERIOR STRINGER

System	Type of Stringer	Ultimate Load of the Stringer	Load Condition of the System	Ultimate Load of the System	% Load Carried by the Middle Stringer	% Load carried by the Exterior Stringers
Bulb-tee with LVL Stringer with Diaphragms	LVL	25 kip	A	60 kip	42%	58%
Tee with Glulam Stringer without diaphragms	glulam	25.6 kip	B	51 kip	50%	50%

TABLE 5 MAXIMUM DEFLECTION OF THE STRESSED SYSTEMS FOR A 30-KIP LOAD

System	Deflection (inch)		
	Load Condition A	Load Condition B	Load Condition C
Tee with LVL Stringers with partial diaphragms	.816 (A_2)	-	-
Bulb tee with LVL-Stringers without diaphragms	.895 (A_2)	-	-
Bulb Tee with LVL-Stringers with Diaphragms	.593 (A_2)	-	-
Box with LVL-Stringers without diaphragms	.332 (A_2)	.249 (b_2)	.501 (b_2)
Box with LVL-Stringers with Diaphragms	.350 (A_2)	-	-
Tee with Glulam Stringers without diaphragms	.753 (Interpolated Value) (A_2)	.737 (C_2)	-
Box with FRP Stringers without diaphragms	.780 (A_2)	-	-
Box with FRP Stringers with Diaphragms	.974 (A_2)	-	-

A_2 - Center point at the top of the middle stringer.

b_2 - Center point at the top of the exterior stringer.

C_2 - Bottom of the loading point of the load condition B.

(-) - Test was not conducted

other systems considered in this study are consistent with expected results. The inclusion of diaphragms in the bulb-tee system reduced the maximum deflection from 0.895 to 0.593 in. The maximum deflections of the box system are 0.243 and 0.486 less than those of the tee and bulb-tee systems, respectively. The deflection values for the box with LVL stringers and no diaphragms (0.332 in.) and the box with LVL stringers and diaphragms (0.335 in.) are nearly identical, which implies that the diaphragm action in the box system with shallow stringer depths is negligible. The deflection of the box with FRP stringers with diaphragms (0.974 in.) is more than the maximum deflection of the same box without diaphragms (0.780 in.), which was attributed to readjustment of butt joints of the laminations and the FRP stringers when diaphragms were present.

Discussion of Special Topics

Stressed-timber systems have to be stressed at least three times to stabilize prestressing forces acting on timber and to minimize the time-dependent prestress losses. Research in Ontario (*5,6*) showed that when a constant transverse compressive stress is applied to a mechanically laminated timber deck system, it slowly deforms with time. If the deck system is stressed only once, a prestress loss of 80 percent or more would take place in a relatively short period of time before stabilization of prestressing forces on timber lamination. Subsequent stressing of the deck two or more times can reduce the long-term losses to a minimum, and a compressive prestress level of 50 lb/in^2 can be maintained. However, additional investigations have to be made regarding the effects of cyclic or fatigue loads on potential loss of prestress. The stressed systems that were tested in this study consisted of red oak (hardwood) and southern pine (softwood) decks. However, the findings provide a basis for the design of stressed systems with other hardwood and softwood combinations.

Theoretical Analysis of Stressed Systems

Table 6 presents a comparison between theoretical and experimental results. The differences between the theoretical and experimental results may be the result of using approximate values for the elastic constants in the computations. All test specimens had only three stringers (one interior and two exterior stringers). GangaRao's formulas more precisely represent systems with more than one interior stringer. Thus, the discrepancies in the results can also be partially attributed to the use of the equations for systems with just one interior stringer.

CONCLUSIONS

The following conclusions were drawn on the basis of limited data. More data are needed to substantiate the results.

TABLE 6 COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS BETWEEN A TEE AND A BOX SYSTEM

Analysis Type	Deflection		Strain			
	Exterior Stringer	Interior Stringer	Top of ext. stringer	Bot. of ext. stringer	Top of int. stringer	Bot. of int. stringer
Tee System						
Orthotropic Plate Theory-WVU	0.233	0.691	503	775	1271	2518
WVU Method	0.174	0.485	455	703	1084	2147
Experimental Results	0.185	0.816	*	*	1348	2670
Box System						
Orthotropic Plate Theory-WVU	0.088	0.270	235	247	716	765
WVU Method	0.097	0.270	314	329	854	913
Experimental Results	0.123	0.330	237	165	465	570

* - Not measured

1. The flange component of the bulb-tee and box systems showed nearly full composite action with the stringers. However, there was no full composite action at load levels closer to failure.

2. Even under a 40-psi precompression stress, the lumber laminations of the flange components did not exhibit any vertical slip. Also, no opening or separation of the laminations in the transverse direction was observed. The butt joints showed no rotational slip, and no shear failure was observed in the flange elements or the individual stringers.

3. Depending on the load location, the stressed systems showed both linear and nonlinear load deflection responses. The nonlinear behavior was more pronounced at the locations of the concentrated loads and at the center of the interior stringer at very high loads, i.e., close to the failure loads. However, when the load was applied directly on the stringers, a linear behavior was observed. Also, the stressed systems demonstrated linear and nonlinear behavior depending on the overall stiffness of the systems.

4. The addition of diaphragms proved to be effective in improving the response of tee systems.

5. The percentage of load shared by the stringers of the tee system is approximately 50 percent, which increases to 58 percent when diaphragms are added. These percentages of load sharing could be higher for actual systems, which usually have more than three stringers.

6. When a system is loaded for the first time, it does not completely recover its deflection after removing the load. However, no such permanent deflection is noted during the second and third cycle of loading. This may be because of readjustment of the butt joints in the systems.

7. As expected, box systems showed higher stiffness value and lower stresses than tee and bulb-tee systems for a 30-kip load corresponding to load condition A.

8. The theoretical analysis based on GangaRao's plate solutions (*2*) demonstrated a good overall correlation with experimental results for the deflections and strains for the exterior and interior stringers of tee and box systems under load condition A.

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