Stress-Laminated / Steel T-Beam Bridge System

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Abstract

The stress-laminated timber bridge deck has been successfully used for short span bridges. A design philosophy, procedure, and related equations have been developed for a timber-steel composite deck design which may offer improved economy and performance where longer spans are required. The design incorporates a series of inverted steel T-beams within the stress-laminated timber deck. A significant number of currently used design specifications and construction methods for stress-laminated bridges along with a design procedure familiar to most bridge engineers have been included in this design procedure. Large shear forces between the deck and steel beams require steel dowels. A grid system composed of the steel T-beams and wooden diaphragms provides additional load distribution, and may facilitate the construction process. Standard lumber sizes and relatively unskilled labor may be used to construct the bridge. It is anticipated that the design's lightweight nature may result in significant cost savings for the substructure and construction equipment required. Efficient use of labor, materials and existing design practices make this design advantageous for many applications in the 12.2m (40 ft) to 24.4m (80 ft) span ranges.

Keywords: Stress-laminated, timber bridges, prestressed timber, dowel, composite, T-beam.

Introduction

The timber-steel composite bridge deck is a new type of bridge superstructure being developed by the Civil, Agricultural and Geological Engineering Department at New Mexico State University. The system utilizes a stress-laminated timber deck with inverted steel T-beams for added stiffness (Figure 1). The added stiffness provided by the T-beams will allow longer spans than those possible with the conventional stress-laminated deck. The design process described in this report will utilized as much of the existing technology used to design stress-laminated decks as possible. The design methodology for concrete-steel composite bridge systems is familiar to most bridge designers. Therefore, the design of the steel T-beam and the method of shear transfer between the timber deck and the steel T-beam is similar to currently used design procedures.

This report describes the results for Phase I of this project. Phase I consisted of developing design procedures and relationships for a simple span bridge. Phase II & III, if funded, will involve testing a model bridge to verify and modify design parameters, and finally, a demonstration bridge will be built and monitored.

The philosophy used in developing this design procedure and related methodology centers on utilizing as much of the currently used bridge design practices as possible. This will insure that development costs are minimized and that bridge design engineers will be familiar with most of the concepts used in this design procedure, Additionally, the procedure developed will allow the bridge designer considerable latitude in adapting this type of bridge to a particular application. This will promote designs which are safe, reliable, and cost effective.

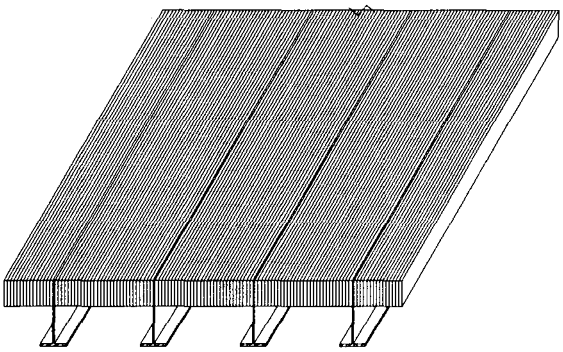

Figure 1—Timber-steel composite bridge deck.

Scope of Study

This study was limited to developing a bridge system for a simple span approximately 12.2m to 24.4m (40 - 80 ft) in length. T-beam spacing is in the range of 1.22m - 1.83m (4 - 6 ft) with deck thicknesses ranging between 203mm to 305mm (8 to 12 in.) nominal. These spacing and thickness ranges allow the designer sufficient latitude in developing an efficient design while restricting the design to predictable behavior.

Overview of Design Procedure

The design procedure will focus on designing an individual T-beam unit which consists of one steel "T" section and its associated deck section as, shown in Figure 2.

The recommended basic design procedure is as follows:

1. Specify initial parameters.
    a. Span length.
    b. Design vehicle.
    c. Wearing surface.
    d. Number of lanes.
    e. Clearance, if applicable.

2. Select material types and calculate allowable stresses.
    a. Wood species and grade.
    b. Steel.
        1) T-beam.
        2) Dowels.

3. Calculate maximum shear and moment acting on bridge.

4, Design composite T-beam unit for maximum moment.

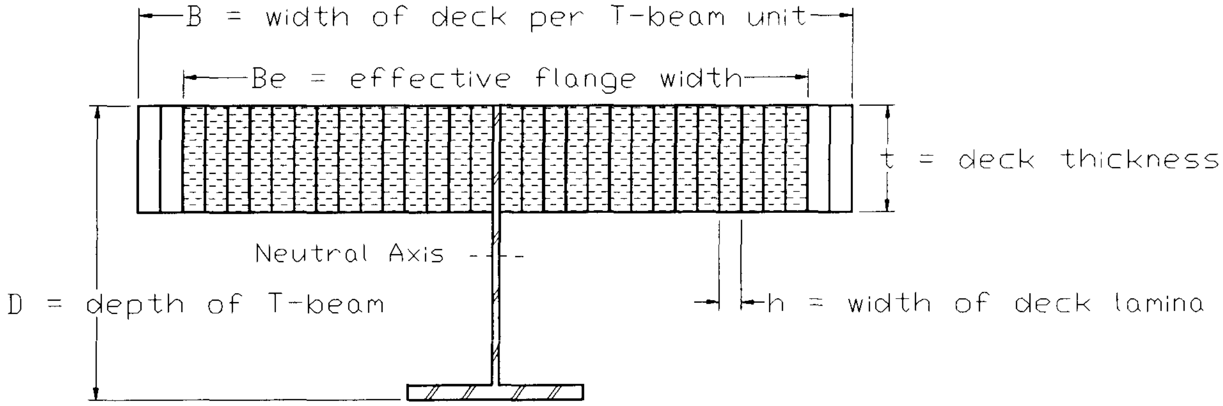

Figure 2— T-beam design unit.

a. Choose deck thickness.
b. Choose T-beam spacing.
c. Determine distribution factor.
d. Determine effective flange width.
e. Select trial size for steel T-beam.
f. Determine non-composite stresses due to dead load.
g. Determine composite stresses due to live load.
h. Repeat steps d-g for outer T-beam units.
i. Check diaphragm spacing.
j. Check web shear.
k. Revise as necessary.

5. Check global deflection at midspan.

6. Check local effects.
   a. Deck.
      1) Transverse deflection.
      2) Transverse bending stress.
      3) Punching shear.

7. Design dowels for horizontal shear.
   a. Check bearing stress on the web.

8. Design diaphragms.
   a. Check longer spacings.
   b. Size the diaphragm.

9. Design prestressing system and guard rails.

10. Check camber.

Development of Design Equations

Previously developed equations for predicting the effective flange width and distribution factor for other types of prestressed timber deck systems were found to be inadequate for the timber-steel deck system. Therefore, design equations of effective flange width and transverse distribution factor were developed for this system. A butt joint factor of 1 in 4 is recommended for all designs. Butt joint factors higher than this are probably not economical since deck forces usually do not control the design.

Effective Flange Width

A number of finite element models were generated and evaluated to determine the effective flange width. These models were evaluated for decks of 203mm, 254mm, and 305mm (8", 10", and 12") nominal thickness, and T-beam spacings of 1.22m, 1.53m, and 1.83m (48", 60", and 72"). Two layers of solid elements were used to model the deck. The appropriate orthotropic elastic constants for Douglas-fir were used in the solid element models. Frame elements were used to model the steel T-beam.

Results of the finite element studies indicated that effective flange width varied between 0.79 and 0.86 of the T-beam spacing. In the design process, the effective flange width will be transformed into an equivalent steel width so that stresses may be calculated. In most cases a modular ratio corresponding to a butt joint frequency of 1 in 4 would be used to calculate the transformed effective flange width, B_e. The slight variation in effective flange width from 0.79 to 0.86 will become insignificant after transformation using the modular ratio. Thus, to simplify calculations, an effective flange width of 0.80 is recommended for all deck thicknesses and T-beam spacings.

Distribution Factor

When a vehicle is placed on a bridge, there is a lateral distribution of its weight. This lateral distribution depends in part on the stiffness of the deck and girder system. In the bridge design process, a single T-beam unit is designed and loaded with a single wheel line. The distribution factor is intended to account for the lateral load distribution when using the single T-beam as the design unit.

Finite element models were constructed for complete composite T-beam bridges and for the corresponding single T-beam design unit. The model for the entire two lane bridge was loaded with two design vehicles so that the maximum moment was produced in an interior girder. Similarly, the single T-beam design unit was loaded with a wheel line of the design vehicle such that the maximum moment was produced. The ratio of these maximum moments is the distribution factor.

Table 1—Recommended distribution factors.

T-beam Spacing	Deck Thickness	Distribution Factor
1.22m (48")	203mm - 305mm (8 - 12 in.)	0.8
1.53m (60")	254mm - 305mm (10 -12 in.)	1.0
1.83m (72")	254 mm - 305mm (10-12 in.)	1.1

Finite element studies using nominal deck thickness of 203mm, 254mm, and 305mm (8", 10", and 12") with T-beam spacings of 1.22m, 1.53m, and 1.83m (48", 60", and 72") and loaded as described above were conducted to determine the distribution factor. The 203mm (8 in.) deck was found to be unsatisfactory for a T-beam spacing of

1.83m (72 in.) due to excessive transverse bending deflection and other local effects and was, therefore, not considered further. Table 1 below summarizes the findings. A linear interpolation is recommended for T-beam spacings between those listed in the table.

Horizontal Shear

A large horizontal shear force exists between the steel T-beam and the wood deck. The friction resistance which results from the prestressing force is of insufficient magnitude to resist this force. Steel dowels were selected to carry the additional shear force not carried by friction. The design for these dowels is similar to that used to design the shear studs for a concrete-steel composite section. Following AASHTO (AASHTO, 1993) procedures, the total shear to be resisted by the dowels and the friction force is the compression force in the flange when loaded for maximum moment. This shear force is distributed from the point of maximum moment to the point of zero moment. Since the maximum moment occurs near the centerline of a simple span bridge, one-half the span length may be used. An appropriate number of dowels are selected and spaced uniformly within this portion of the span. The same number of dowels are used in the remaining half-span.

The design of the dowels utilizes current yield limit theory for bolted connections (NDS, 1991). A nut and washer may or may not be used on the ends of the dowels depending on the construction methods used. However, the design strength used for these dowels assumes that a nut is placed on each end of the dowel since the prestressing force will serve as the clamping force for those cases where nuts are not used.

The design of the dowels assumes a double shear type connection with a steel center member. With this conjuration only NDS equations 8.3-2, 8.3-3, and 8.3-4 cm-responding to modes I_s, III_s, and IV apply (Breyer, 1993, NDS, 1991). Pending experimental studies, the thickness of the side member may be taken as one-half the effective flange width, B_e, since data is not available for prestressed layered side members. The larger side member thickness effectively eliminates all failure modes except mode IV. Thus, NDS equation 8.3-4 is used for dowel design:

$$Z = \frac{D^2}{1.6\,K_\theta}\sqrt{\frac{2\,F_{em}F_{yb}}{3\,(1 + R_e)}} \tag{1}$$

where Z is the nominal bolt design value(lbs); D is the nominal bolt diameter (inches); $K_\Theta = 1 + (\Theta_{max} / 360°)$; Θ is the maximum angle of load to grain; F_{em} is the dowel bearing strength of main member (psi); F_{yb} is the bending yield strength of bolt (psi); $R_e = F_{em} / F_{es}$; and F_{es} is the dowel bearing strength of side members (psi).

Steel "T" Section

Preliminary studies have indicated that standard WT sections may not be economical in many cases. This is due to the relatively shallow depth of the web, thereby requiring the use of sections with large web and flange thicknesses to obtain an adequate stiffness. Although cost studies are not part of this project, it appears that a built-up "T" sections may be the most economical for most cases, A standard WT section with a web extension is an alternative, but it appears to be more costly than the built-up section. A final possibility which was not investigated is a standard W section with the top flange removed and welded to the bottom flange creating a "T" section with a relatively large bottom flange. In any case, these decisions should be left to designer so that he/she may take advantage of the local material supply.

Diaphragms

Diaphragms are recommended for the design for three reasons. First, sidesway web buckling (Summers, 1982) is a possible failure mechanism for the T-beams. To prevent the possibility of this type of failure, diaphragms should be used at spacings equal to or less than those given by the AISC-ASD formula C-K1-1 (AISC, 1989):

$$\frac{d_c / t_w}{l / b_f} > 2.3 \tag{2}$$

where d_c is the clear unsupported distance between flanges (inches); t_w is the web thickness (inches); l is the largest laterally unbraced length along either flange at the point of load (inches); and b_f is the width of bottom flange of the steel T-beam (inches).

Second, diaphragms are useful for increasing the lateral distribution of loads. Finite element studies indicate that this lateral distribution increase may be substantial in some cases. Finally, diaphragms are useful in the construction process as discussed later in this paper.

Wood diaphragms were chosen for use in this design for two reasons. First, the possibility of fatigue cracks developing at the web-diaphragm connection when wood is used for diaphragms is substantially reduced compared to steel. The fatigue cracks which often form when steel diaphragms are used result from out-of-plane bending of the girder web and from metallurgical changes caused during the field welding process. This out-of-plane bending is the result of differential vertical movement of adjacent girders, Wood diaphragms avoid both of these problems since no welding is required, and because the connection will be semi-rigid in nature, out-of-plane bending in the steel T-beam web is minimized (Fisher and Mertz, 1985).

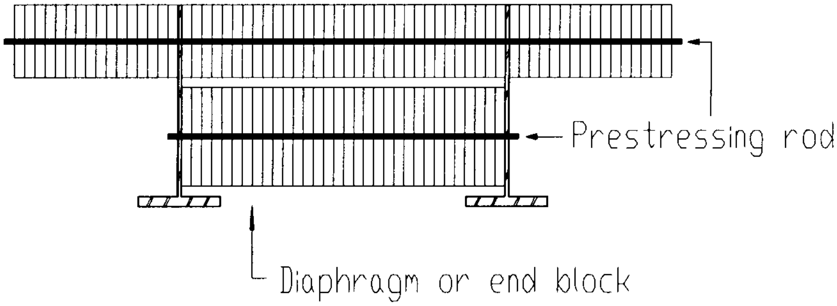

Figure 3—Diaphragm or end block assembly.

Second, wood diaphragms have the same coefficient of thermal expansion as well as the same rate of shrinkage and swelling with moisture content changes as the wood deck has. Thus, there are no transverse differential dimensional changes induced in the bridge due to moisture or thermal changes.

The wood diaphragms should be connected by one prestressing rod of the same size as those used in the deck (Figure 3). They should also have one dowel in them to carry the excess shear not carried by the friction force. Wood diaphragms connected in this manner are semi-rigid in nature and minimize out-of-plane bending in the T-beam web.

Transverse Deflection

Pending experimental studies, the transverse deflection may be calculated using the equation developed by West Virginia University for the stress-laminated T-system timber bridges (Davalos and Salim, 1993):

$$\delta_{\max} = \frac{PS^3}{4K_\delta E_t t^4} \qquad (3)$$

$$K_\delta = -10.9 + 7.8\frac{S}{t} + 0.27\frac{E_L'}{E_t} \qquad (4)$$

where $\delta_{\max}$ is the maximum local transverse deflection (inches); P is the rear axle wheel load (lbs); S is the T-beam spacing (inches); E_t is the transverse modulus of elasticity of the deck (psi); $E_L' = E'$ is the allowable longitudinal modulus of elasticity of the deck (psi); and t is the deck thickness (inches).

Maximum transverse deflection of the deck between the steel T-beams should be limited to approximately 0.1 to 0.2 inches (Davalos and Salim, 1993).

Transverse Bending Stress

The transverse bending stress may be calculated using (Davalos and Salim, 1993):

$$\sigma_{\max} = \frac{3PS}{2K_\sigma t^3} + f_p \qquad (5)$$

$$K_\sigma = 3.0 + 3.1\frac{S}{t} + 0.15\frac{E_L'}{E_t} \qquad (6)$$

where $\sigma_{\max}$ is the maximum transverse bending stress (psi); and f_p is the operational prestress level (psi).

Punching Shear

The punching shear for the deck is calculated by the following equation (AASHTO, 1993, AASHTO 1991, and Davalos and Salim, 1993):

$$V = \frac{Ph}{(b_f + 2t)\,C_{bj}} \qquad (7)$$

$$C_{bj} = \frac{j}{j+1} \qquad (8)$$

where V is the calculated punching shear force (lbs); h is the thickness of the deck lamina (inches); and b_f is the tire contact length perpendicular to span (inches).

Bearing Stiffeners

Steel bearing stiffeners are required for welded girders (AASHTO 10.34.6.1) and for rolled girders when the shear stress in the web adjacent to the bearing exceeds 75 percent of the allowable shear stress (AASHTO 10.33.2), These stiffeners serve to prevent failure in the web due to local web yielding and web crippling, which is a form of web buckling (Salmon and Johnson, 1990). The stiffeners are required to extend from the bottom flange to the top flange and to be welded to the web and to each flange, Since the wood deck serves as the top flange in this design it would be very difficult for the designer to design a functional connection between the deck and the bearing stiffener. For this reason, wood end blocks are recommended for this application. These end blocks should be constructed of the same material as the deck and should fit tightly between the bottom of the deck and the top of the bottom flange of the "T" section. They should extend from one "T" section to the adjacent one (Figure 3). A prestressing rod of the same size and with the same applied force as that used for the diaphragms should be used.

The wood end blocks serve to prevent local web buckling by supplying lateral support to the web of the T-beam at the reactions. This lateral support of the web in effect creates the equivalent of a column on an elastic foundation, thereby substantially increasing the buckling resistance of the web. Representative calculations of the stress at which buckling would occur for a typical T-beam, 762mm (30 in.) deep with a 12.7mm (½ in.) web indicated that the buckling stress would be approximately 6 times higher than the allowable compression stress for the section. Thus, buckling is not possible and need not be considered further.

Local web yielding may be prevented by following ASSHTO 10.33.2 which limits the shear stress in the bearing area to 75 percent of the allowable. In the unlikely event that the applied shear stress exceeds 75 percent of the allowable the tightly fitting wood end blocks will serve to carry part of the bearing load making failure unlikely. Other remedies are available to the designer if needed or desired. First, the thickness of the web could be increased, lowering the applied stress in the web for a given loading. Secondly, a flat plate could be welded to the web to increase the web thickness in the bearing area with the end result of lowering the stress in the web. If used, this steel plate should be shop welded in lieu of field welding, to minimize the possibility of fatigue cracking in the area of the weld.

Construction Methods

Construction of this bridge system may be accomplished using methods similar to those used for the concrete deck-steel girder bridge. With this type of construction the T-beams are placed on the abutments first and the deck is added later. Here diaphragms are used to stabilize the steel beams while the deck is being installed. This process may prove difficult since the diaphragm connections must be left "loose" so that the wood deck and dowels may be placed between the T-beam webs.

The construction of the bridge may be more efficiently carried out by preassembling a single T-beam unit before it is placed on the abutments. In this case a nut and washer may placed on the ends of the dowels to hold the unit together while it is being set on the abutments. After setting preassembled units, prestressing rods may the be placed in the deck and tensioned.

Conclusion

The stress-laminated / steel T-beam bridge system described in this paper utilizes a procedure familiar to most bridge engineers. The design addresses the effective flange width, transverse load distribution, horizontal shear, diaphragms, and local effects in accordance with many existing and proposed AASHTO procedures. Lightweight and efficient steel sections may be incorporated within the stress-laminated timber deck to allow for longer spans, and a cost effective alternative to current designs.

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Acknowledgments

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