Summary and Conclusions

The concept of stress laminating, which originated less than 25 years ago, is still one of the newer techniques used in modern timber bridge construction. In contrast to the traditional longitudinal glulam deck assemblies and nail-laminated assemblies, which achieve load transfer among laminations by structural adhesives or mechanical fasteners, the load transfer between laminations in stress-laminated bridges is developed through compression and interlaminar friction. The early stress-laminated deck bridge designs had simple rectangular cross sections composed of longitudinal sawn lumber laminations with transverse prestressing. These designs proved relatively successful in short span applications and they were relatively cost effective. However, to achieve longer spans with stress-laminating technology, new concepts were needed.

To meet this need for longer spans, researchers first developed a stress-laminated cellular or Box-beam type of superstructure. The system consisted of stress-laminated top and bottom flanges connected with continuous webs. Flange material was assumed to be sawn lumber while the webs could be constructed of glulam beams, LVL, PSL, or other non-wood structural products. A design similar to the box type is one that uses a stress-laminated T or ribbed cross section. In this design, deep beams using glulam, LVL, or PSL can be stress-laminated to a relatively thin sawn lumber deck or top flange.

Early testing and modeling research indicated that bridges built using this technology appeared to have promising structural behavior. However, during further field testing, questions arose about the performance and the cost of the bridge systems. Also, current American Association of State Highway and Transportation Officials (AASHTO) specifications do not include design guides for Box-beam and T-beam type stress-laminated bridges. Therefore, the research described in this report was conducted to clarify the design, performance, and cost effectiveness of both of these newer types of stress-laminated bridge systems: stress-laminated T-beam and Box-beam bridge superstructures. Also, the results from this research will provide input to the process for developing new timber bridge design procedures as well as provide recommendations on the applicability of this bridge system for U.S. highways.

Specific Conclusions

The following specific conclusions are stated on the experimental and analytical studies, and the design, performance, cost-effectiveness of the stress laminated T-Beam and Box-Beam bridge systems:

Evaluating Experimental and Analytical Studies

- Wheel load distribution factors developed using the finite element model, the WVU design procedures, and experimental data compared reasonably well for the limited number of bridges examined in this study. In each case, the FEM produced higher distribution factors than the proposed design equations. For the T-beam bridges, the differences in predicted distribution factors were minor. However, for the Box-beam bridge analyzed, there was a significant difference in the distribution factors predicted by the various methods. The proposed WVU design method resulted in distribution factors that were more liberal than those of the FEM.

- The location of the neutral axis was nearly the same as determined by both methods. This is an indication that the manner in which the effective flange width is calculated by the WVU design method is in agreement with the distribution of stress predicted by the FEM.

- There was fair agreement between the models in their prediction of the longitudinal bending stresses in the web. For the T-beam bridges, the proposed design method predicted higher stresses than the FEM, except for one case where the FEM gave a higher compression stress. In general, for the T-beam bridges, the proposed WVU design procedure gave conservative results when compared to the FEM results. However, this was not the case for the Box-beam bridges. For Box-beam bridges, the FEM gave significantly higher stresses under the inside load case, than those determined by the WVU design method. This was, in part, due to the lower distribution factor used in the design method.

- Predicted values of shear stresses through the web were in very close agreement for the different models. Likewise, the shear stresses calculated at the web-to-flange interface were nearly identical.

- The FEM model predicted that the highest compression stresses occur in the flange, usually beneath the wheel line. For the load case when the wheel lines were between the webs, the FEM gave stresses in the flange material which were slightly higher than those determined by the transformed section analysis. Further investigation may be warranted in this area. Because the wheel loads were applied as point loads and not distributed transversely over the width of the tire in the FEM, the results were likely high estimates of the flange compression stress. However, the proposed design criteria give little attention to this area.

- Overall, the WVU design method appears reasonably accurate provided that complete composite action is maintained in actual bridges. No attempt was made to predict behavior under partial composite action, which could exist in the field if the bar force in the stressing bars falls below minimum limits.

Field Performance

- The relatively frequent instances of cracked asphalt wearing surfaces indicates that slip may be occurring between the webs and the flanges. In one instance, visible slip between the web and flange was observed during a truck crossing. The occurrence of slip, even with what appear to be adequate levels of bar forces, would result in bridge stiffnesses and strengths at levels lower than that intended at the design stage. Consequently, these occurrences of slip would also result in levels of structural safety for the bridges lower than what has been assumed by the designer.

- The presence of cracks or checks in the exterior webs of many of the bridges is cause for concern and may be indicative of excessive levels of transverse bending stresses in the glulam beams. Since this phenomenon has apparently manifested itself during the years since the bridges were erected, the cracks may continue to grow. This issue warrants further monitoring to determine if the cracks are changing in size with length of bridge service.

- The frequency of crushed wood under bearing plates indicates that design procedures for bearings need to be re-evaluated.

- The presence of low bar forces indicates that the bridges require more periodic maintenance than is currently being provided by the WVDOH or other local municipalities. In cases where stressing bars were cut off after construction was completed, there is little question that the interlaminar stresses will be lower than the minimum levels and the bridges will therefore need restressing. However, to accomplish the restressing operation, the bars will need to be replaced or some other significant modification will be needed for the stressing system.

- The elevated levels of moisture indicate that the wearing surfaces are not providing dry conditions for the interior webs. Also, the elevated moisture levels indicate that, eventually, there may be premature decay problems with the wood components. More importantly, as moisture levels change, there will be corresponding fluctuations in interlaminar stress. These fluctuations in interlaminar stress will necessitate further restressing operations.

Bridge Cost

- The mean superstructure costs of the T-beam and Box-beam bridge systems were higher than the overall mean superstructure costs of all traditional timber bridge systems constructed in the U.S, such as longitudinal glulam girder bridges, longitudinal glulam deck bridges, and longitudinal stress-laminated deck bridges.

- Even if an alternative lumber species grouping, such as southern pine, was used for the flanges, the resulting average costs of the T-beam and Box-beam bridges would still have been greater than the costs of typical glued-laminated and stress-laminated bridge systems.

- There were no apparent span ranges where the T-beam or Box-beam bridges showed a particular cost advantage.

- When their relatively high cost is combined with some of the other maintenance and field performance issues and possible design changes noted in this report, it appears that the true life-cycle costs of the bridges will be even less cost effective.

Research Needs

- Additional laboratory research is needed to accurately characterize the performance of full-scale bridge systems up to their ultimate load capacity. Also, if any further testing programs are conducted, material properties of the wood components must be fully characterized to accurately model the bridge behavior.

- Alternative levels of interlaminar stresses need to be examined. To prevent slip between the flanges and webs, researchers in Australia are recommending higher interlaminar stress levels than those in the U.S. These higher stress levels need additional consideration before finalizing design procedures in the U.S.

- Additional modeling and laboratory research is needed to focus on the shear transfer between two glulam webs placed side by side. Also, current finite element models may need to be modified to include this used of two webs side by side and to account for differences in friction coefficients across the width of the bridge.

- Reliability-based design procedures for T-beam and Box-beam bridges are needed. Current methods use ASD principles; however, parallel LRFD design methods are needed for the AASHTO LRFD bridge design specifications.

- Stressing bar anchorage design procedures need additional examination to determine if current design stresses and design methods are adequate. Field observations indicated that webs on several bridges had crushing under the anchorage plates. Examination of design values for compression-perpendicular-to-grain indicates that revisions in design procedures for anchorages may be necessary.

- While not directly related to design procedures, additional research is needed to document life-cycle costs of T-beam and Box-beam bridges. Also, further research is needed to examine the potential for alternative flange and web materials so that the bridge systems can become more cost effective. Finally, research is needed to determine if diaphragms are necessary for proper function of these bridge designs and if their additional cost is warranted.

In summary, while the bridges are carrying vehicle traffic, there are several potentially serious issues that will affect their long-term ability to safely carry vehicle loads. In some cases, these are maintenance issues, while in other cases, there are fundamental design issues (such as appropriate levels of bar force) that need to be resolved in order to insure the highest levels of bridge safety. Finally, the high cost of these bridge systems is not competitive with other traditional timber bridge systems or with other bridge materials. Given all of these factors, it appears that using other, more traditional timber bridge superstructure designs should be recommended over using the stress-laminated T-beam and Box-beam bridges.