ANALYTICAL MODELING OF GLUED LAMINATED GIRDER BRIDGES USING ANSYS

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ABSTRACT

This paper aims at developing a finite element model of glued laminated girder bridges that can predict accurately the analytical behavior of the bridges. Two models have been developed to study the characteristics of this type of bridge. Two case studies have been considered to validate the accuracy of the models. The first case study is a long span single-lane bridge, the Tuscaloosa Bridge, in Alabama. The second case study is a medium span two-lane bridge, the Cow Gulch Bridge, in Montana. The models show good correlation with the experimental data and hence, the models can be used to find the maximum deflections in the bridge.

INTRODUCTION

The age of wood spans human history. As a building material, wood is abundant, versatile, and easily obtainable. Although in the 20th century, concrete and steel replaced wood as the major materials for bridge construction, wood is still widely used for short and medium span bridges. Of the bridges in the United States with spans longer than 20 feet, approximately 12 percent of them are made of timber. In the US Department of Agriculture (USDA) Forest Service alone, approximately 7,500 timber bridges are in use, and more are built each year. The railroads have more than 1,500 miles of timber bridges and trestles in service *(1)*. In addition, timber bridges recently have attracted the attention of foreign countries like Canada, England, Japan, and Australia.

Timber's strength, lightweight, and energy-absorbing properties furnish features desirable for bridge construction. Timber has the capability to support short-term overloads and contrary to popular belief, provides good fire resistance qualities that meet or exceed those of other materials *(1)*. Timber is not damaged by continuous freezing and thawing and resists harmful effects of de-icing agents and hence, can be constructed in any weather conditions. Timber bridges do not require high skilled labor for construction. They also present a natural and aesthetically pleasing appearance, particularly in natural surroundings. Some examples of major American timber bridges are the First Bridge across the Mississippi River at Rock Island, IL, and William Howe's Connecticut River Bridge, at Springfield, MA.

GLUED LAMINATED GIRDER BRIDGES

Description of Glued Laminated Girder Bridges

Glued laminated (glulam) girder bridges are the most common type of timber bridges. The spans of these bridges range from 20 to 100 feet. In this type of bridges, the deck panels are laid transverse to the girders that run between supports. The deck panels consist of a series of laminated lumbers that are placed on edge and glued together on their wide faces. The panels are not interconnected and are normally about 4 feet in width and 5 to 7 inches in thickness. The girders are also glued laminated and are usually 5 to 12 inches in width, with depth to width ratios of 2 to 1 or greater. Lag bolts are used to connect the girders to the deck panels and this is responsible for the composite action between the deck and the girder. The bridge railing system consists of treated timber posts and a glued laminated rail, faced with a galvanized steel w-beam. The approach guardrail system is usually treated timber posts with galvanized steel w-beam. A typical glued laminated girder bridge is illustrated in Fig. 1.

Properties of Wood

Wood is an orthotropic material with unique and independent properties in different directions. Because of the orientation of the wood fibers, and the manner in which tree increases in diameter as it grows, properties vary along three mutually perpendicular axes: longitudinal, radial and tangential (Fig. 2). Since the differences in wood properties between the radial and tangential directions is minor compared to their mutual differences in the longitudinal direction, most wood properties for structural applications are given only for directions parallel to the grain (longitudinal) and perpendicular to the grain (radial and tangential).

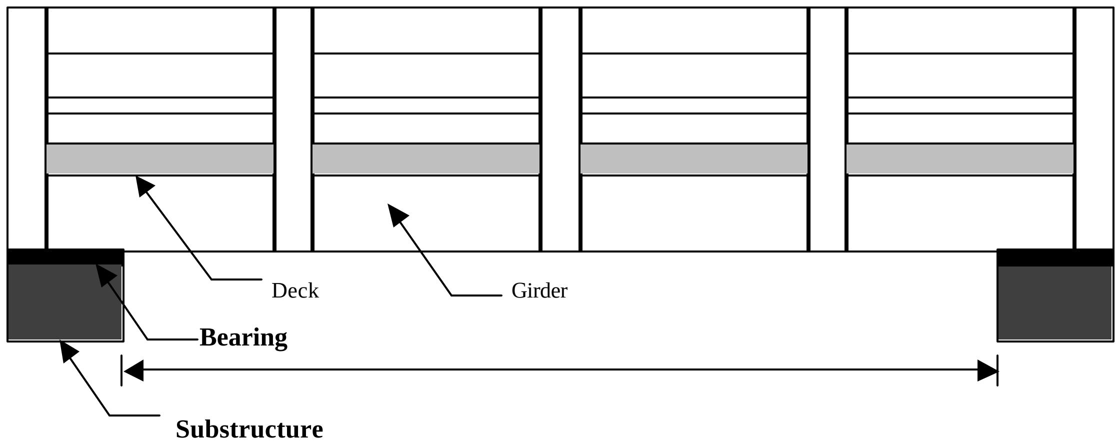
The ANSYS finite element software denotes these material properties by associating them with the corresponding material axes (Fig. 2), as shown below:

Ex, y, z – Young's modulus in the longitudinal, tangential and radial directions respectively.

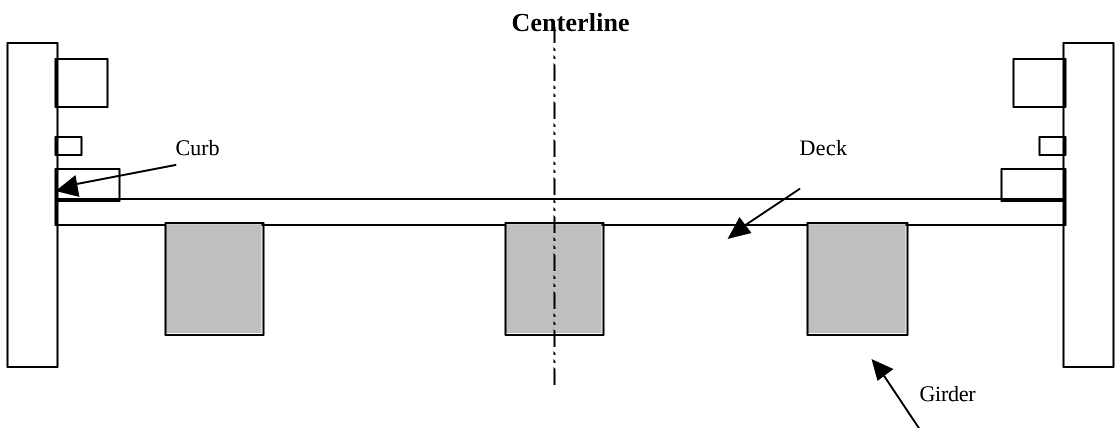
Gxy, yz, zx – Shear modulus in the x-y, y-z and z-x planes respectively.

νxy, yz, zx – Major Poisson's ratio in the x-y, y-z, and z-x planes respectively.

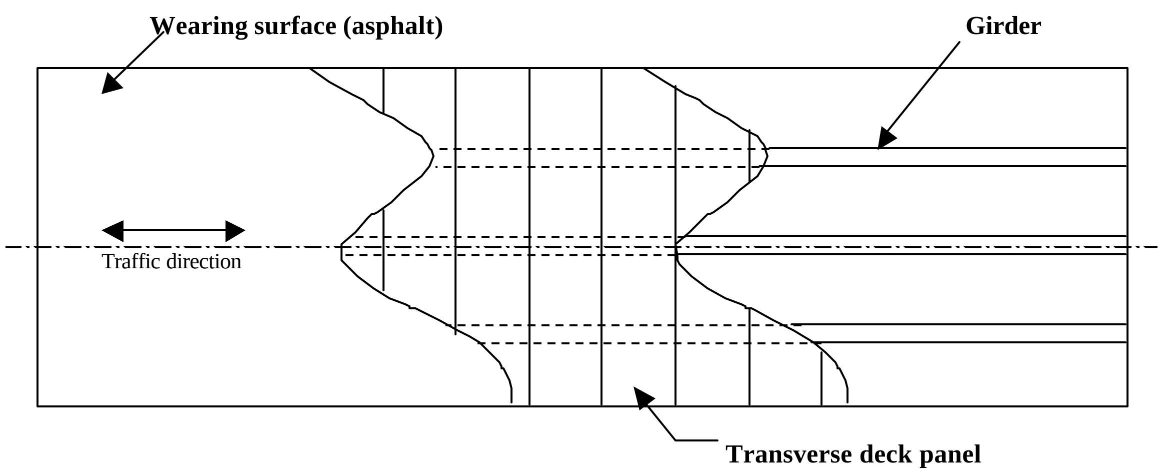
The ANSYS software relates the state of stress and strain in a body by the elasticity matrix, [D]. Fatal errors occur in the program if the inverse of the elasticity matrix [D]-1 is not positive definite. The [D]-1 matrix is also presumed to be symmetric. The use of Poisson's ratios for orthotropic materials causes confusion, so care should be taken in their use. To assure that the $[D]^{-1}$ matrix is positive definite and symmetric, the following relationship must be satisfied:



a. Side view of a longitudinal glued laminated girder bridge



b. Cross-section of a glued laminated girder bridge



c. Cutaway plan of glued laminated girder bridge

Fig. 1 – A typical glued laminated girder bridge

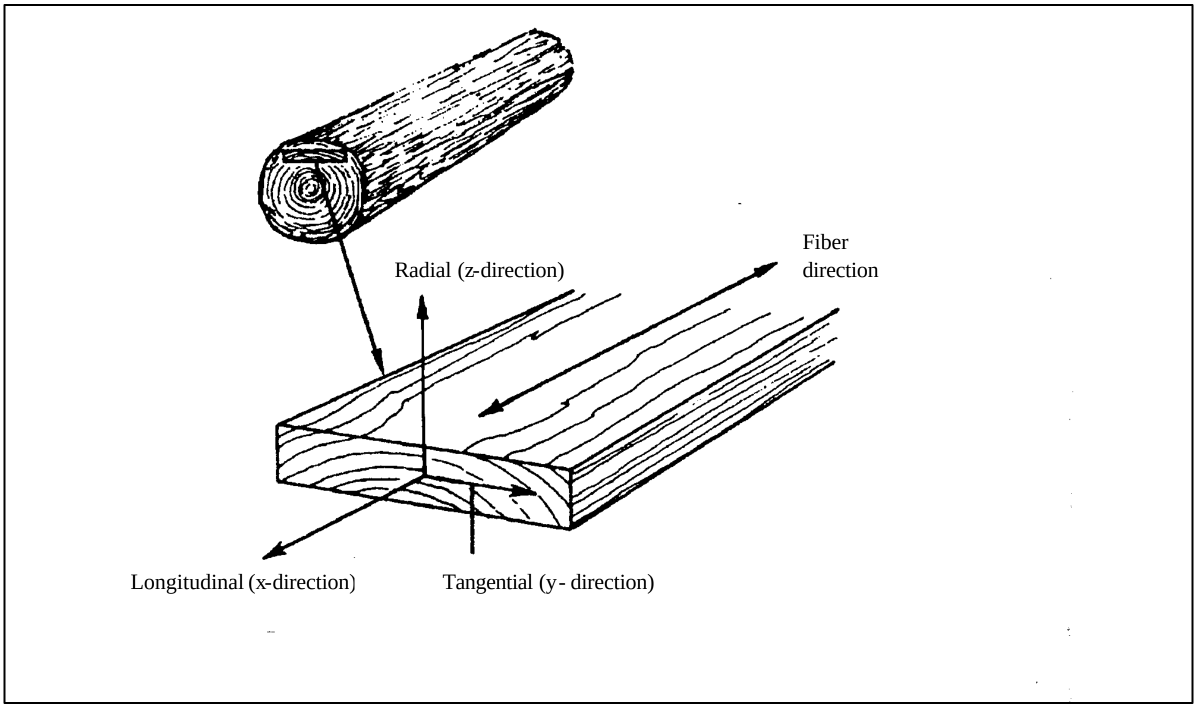


Fig. 2 – Three principal axes of wood with respect to grain direction and growth rings

$\nu_{ij} = \nu_{ji} E_i / E_j$

where,

i, j = x, y, z , and $i \neq j$

G_{xy} (default) = $E_x E_y / (E_x - (1+2\nu_{xy}) E_y)$

$$[D]^{-1} = \begin{pmatrix} 1/E_x & -\nu_{xy}/E_x & -\nu_{xy}/E_x & 0 & 0 & 0 \\ -\nu_{yx}/E_y & 1/E_y & -\nu_{yz}/E_y & 0 & 0 & 0 \\ -\nu_{zx}/E_z & -\nu_{xy}/E_z & 1/E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{xy} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{yz} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{xz} \end{pmatrix}$$

ANALYTICAL MODELS OFBRIDGE

The ANSYS software (2) was used to describe the bridge behavior analytically because of its vast element library and powerful analysis techniques. The model was assembled by modeling the deck panels, girders, and curbs, if present. The panels were modeled using quadrilateral, elastic, and orthotropic shell elements. While in Model 1 the girders were modeled with 3-D elastic beam elements, in model 2 the girders were modeled with quadrilateral, elastic, and orthotropic shell elements. The curbs were modeled with 3-D elastic beam elements connected to the deck by rigid links. All these elements are present in the ANSYS element library.

Modeling the Deck Panels

The deck panels are laid out transverse to the girders. The deck panels are not interconnected and the assumption made in this regard is that the asphalt-wearing surface and friction between the adjacent panels contribute insignificantly towards continuity and load distribution between panels.

The four-noded shell element (SHELL63) (3) was chosen to model the deck panel. The element chosen has six degrees of freedom at each node: translation in the nodal x, y, and z directions and rotations about the nodal x, y, and z directions. This element can be used to model the orthotropic properties of wood and is defined by thickness, longitudinal and transverse moduli of elasticity, shear modulus and major or minor Poisson's ratio.

The longitudinal modulus of elasticity (parallel to grain of fiber) of the panels is substantially higher than the transverse modulus of elasticity (perpendicular to grain of fiber) and the modulus of elasticity tangential to the grain of fiber. *Fig. 3* shows the SHELL63 element used to model the deck panels.

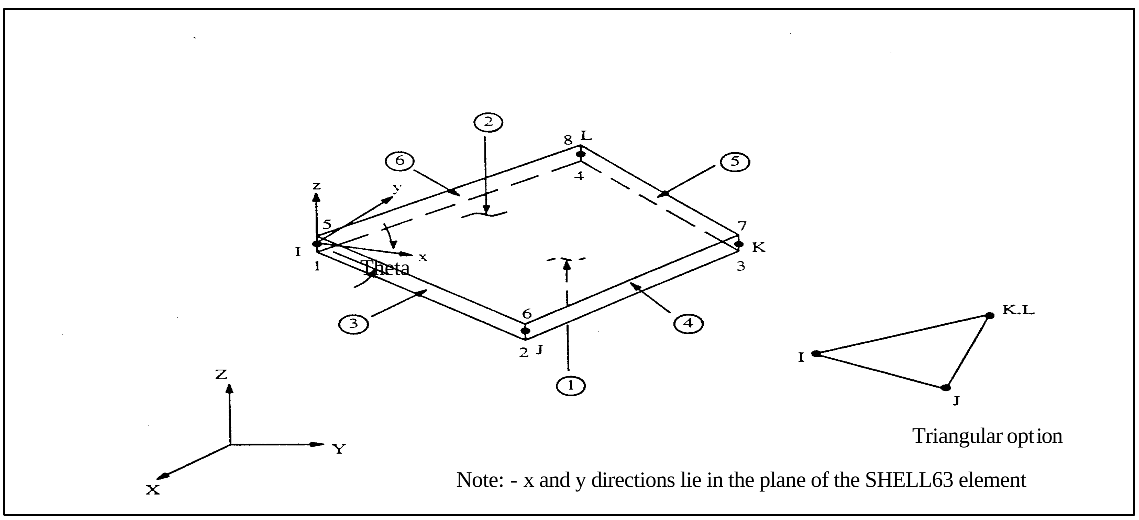


Fig. 3 – SHELL63 element used to model the deck panels

Modeling the Girders

In Model 1, the 3-D two-noded beam element (BEAM4) (3) was chosen to model the girders. The element has six degrees of freedom per node: translation about the x, y, and z directions and rotation about the x, y, and z directions. The element is defined by width, thickness, cross-sectional area, inertias about the x and y directions, longitudinal and transverse moduli of elasticity, shear modulus and major or minor Poisson's ratio. This however did not exactly represent the real situation on the field. The nodes of these beam elements are located halfway between the thicknesses of the girders. Hence, the abutment supports would have to be located at these nodes. In reality, however, the girder rests on the supports and hence, the supports should be located at the bottom of the girders. This led to the development of Model 2. Fig. 4 shows the BEAM4 element used to model the girders.

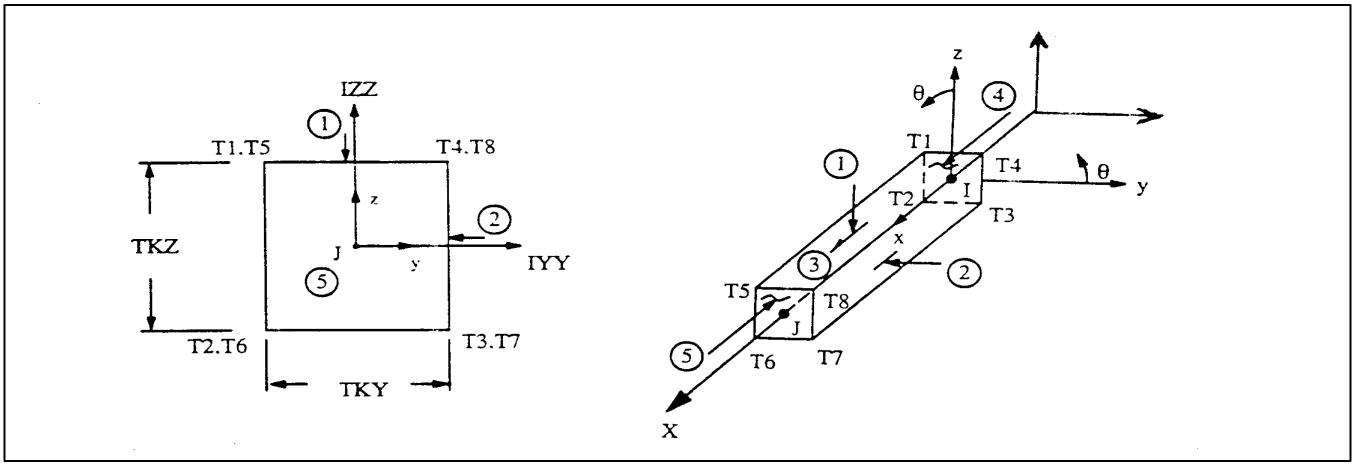


Fig. 4 – BEAM4 element used to model the girders

In Model 2, the girders were modeled with SHELL63 elements. This helped solve the problem of location of supports explained earlier. The girder was modeled as shell elements and the thickness of the shell elements was the width of the girder. Nodes were located at the bottom of the girders for addition of supports.

Bhari's research (4) showed that the assumption of full composite action between the girder and the deck was valid. Hence, in both the models explained above, full composite action was assumed. In Model 1, the composite action was idealized by rigid links (BEAM4 elements with very high flexural and axial stiffness) while in Model 2, the composite action was idealized by making the connecting nodes, between the deck panels and the girders, common nodes.

Modeling the Loads and Abutment Supports

The bridge was assumed to be simply supported since this assumption would be closer to the real situation and deflections would be conservative. The live load applied was truck wheel loads. The wheel contact areas were assumed to be small relative to the bridge and hence, were applied as concentrated point loads. Since the ANSYS software requires concentrated loads at nodes, the concentrated wheel loads were distributed to the nodes in the form of equivalent loads, since very rarely did the location of a wheel load correspond to the location of the panel node. Interpolation functions for rectangular elements (5) were used to distribute the concentrated wheel load to the four nodes of the shell element upon which the wheel load was located.

Note should be taken that the dead load or the permanent weight of all the structural and non-structural components of the bridges, including the roadway, sidewalks, railing, and wearing surface were not included in the load. Normally, girder bridges have curbs along their edges. These curbs stiffened the edges but have little or no contribution to the maximum deflections and stresses of the girders as we move away from the edge. The curbs (if present) were modeled as 3-D beams running along the edges of the bridge, connected to the deck by rigid links. This idealization was shown to be sufficient in the case studies explained later in the paper. Models of a typical glued laminated girder bridge are shown in Figs. 5 and 6.

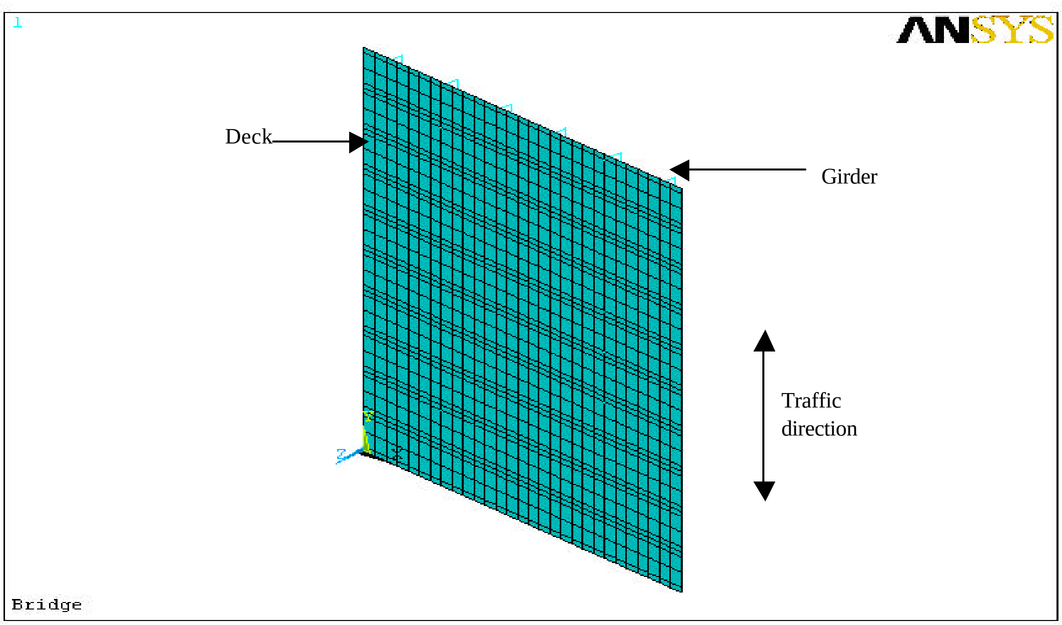


Fig. 5 – Model 1 of a typical glulam girder bridge

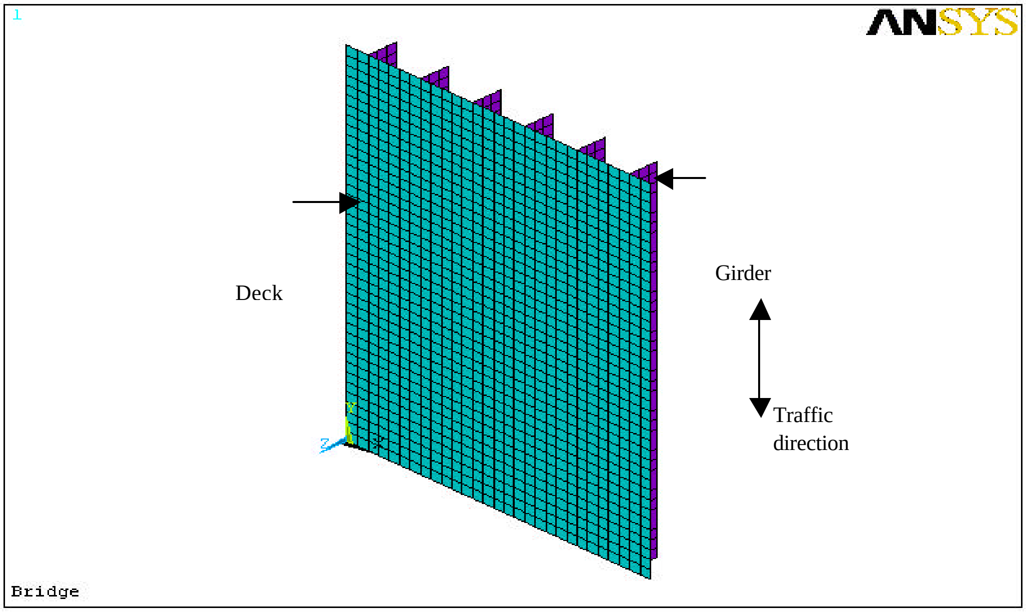


Fig. 6 – Model 2 for a typical glulam girder bridge

CASE STUDIES

Two case studies were undertaken to test the model developed. The first case study was a medium span field bridge, the Cow Gulch Bridge, owned by Yellowstone County, Montana. This bridge was built from a grant received by the county from the Wood In Transportation program in 1996. The focus of the grant was to construct economical timber bridges, and to encourage involvement by a local timber laminating facility. The second case study was a long span, single lane field bridge, the Tuscaloosa County Bridge, in Alabama. This bridge consists of four simple spans but only the third span is analyzed in this paper. The material properties and field-test data for this bridge was obtained from Dlabola (5).

The Cow Gulch Bridge, Montana

The Cow Gulch Bridge is a glulam girder bridge made of Coast Douglas Fir, with six girders supporting the deck panels. The deck panels were about 4 feet in width, 28 feet in length, and 5.125 inches in thickness and were laid transversely on the girders. They were connected to the girders by lag bolts at 6 inches in from each edge of the panel. The bridge measured 38.5 feet in span, measured center-to-center of bearings. The girders had a nominal width of 8.75 inches, and a nominal thickness of 28.5 inches. Curbs with cross-section dimension 8 inches by 8 inches were present along the edges of the bridge. The deck panels had a longitudinal and transverse modulus of elasticity of 1800 kips-per-square inch (ksi) and 130 ksi respectively. The shear modulus of the deck panels was about 100 ksi. The girders had a longitudinal and transverse modulus of elasticity of 2000 ksi and 240 ksi respectively. The shear modulus of the girders was about 106 ksi (1).

Loading

The load case considered was a three-axle, fully loaded gravel truck with a gross vehicle weight of 54,000 pounds. The truck was located longitudinally on the bridge so that the rear axles were centered about the midspan of the bridge. It should be noted that the experimental deflections measured were only due to the live truckload. Since the load was placed such that the maximum deflections occurred at the midspan, the experimental deflections were measured at the midspan of each girder. The plan layout along with the loading case considered is shown in Fig. 7.

Results and Discussion

A comparison between experimental data and analytical results for the Cow Gulch Bridge is shown in Fig. 8. The graph shows the midspan deflections at each girder. The analytical results compare very well with the experimental values. The deflections of the girders based on the analytical model are on the average about 8% larger than the experimentally measured deflections. For a timber bridge with properties that vary in each direction, this is a very good correlation. The differences between the analytical results and the experimental values can be attributed to the assumed material properties.

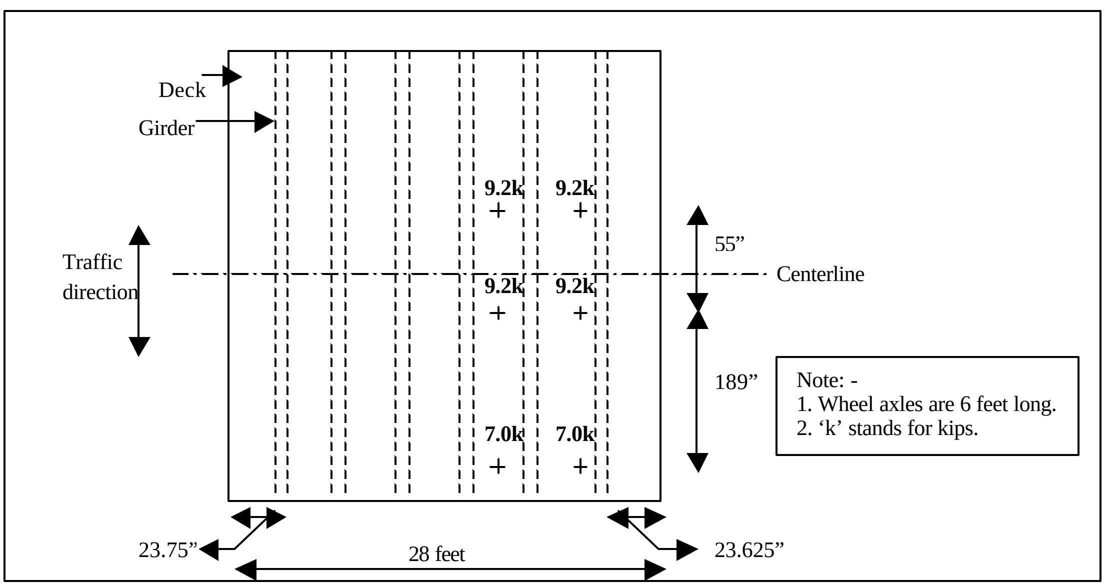


Fig. 7 – Plan layout of the Cow Gulch Bridge, Montana

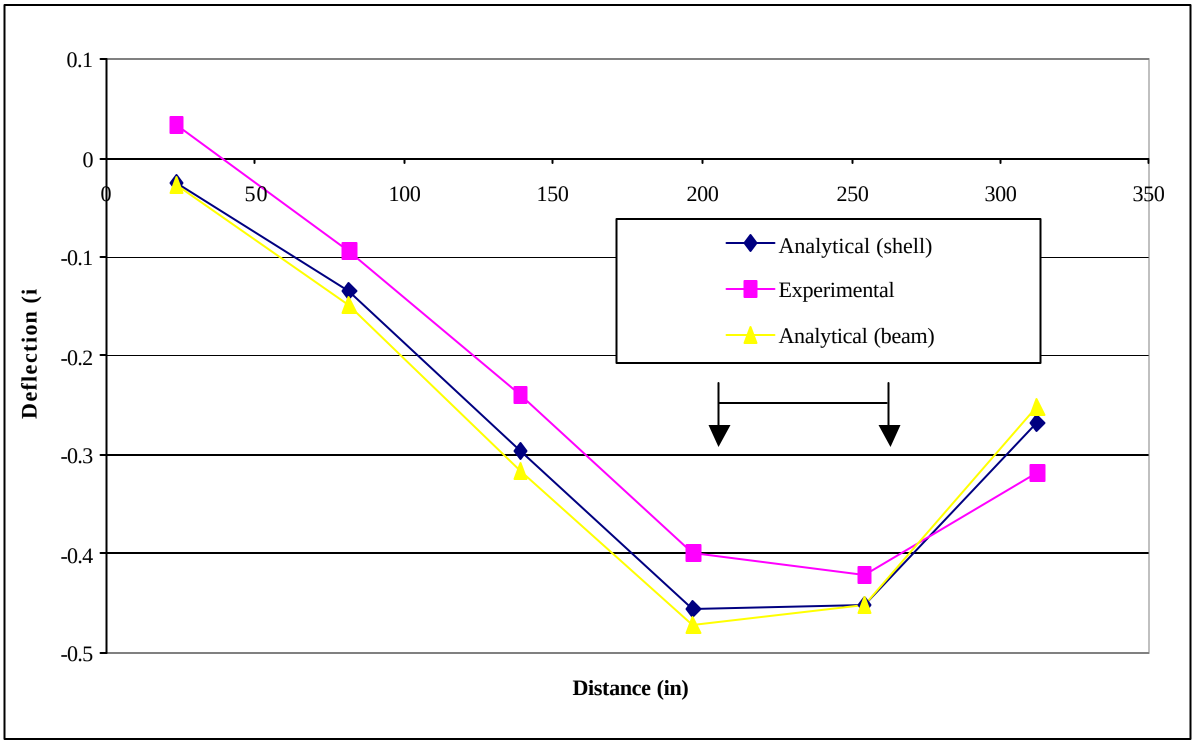


Fig. 8 – Panel deflections at midspan of girders – Cow Gulch Bridge

Model 1 and Model 2 compare very well with each other. There is more composite action between the deck and the girder in Model 2 and hence the deflections obtained from Model 2 are slightly lesser than the deflections from Model 1. The author also mentioned earlier about the problem of location of supports in Model 1. This did not seem to have any effect on Model 1. However, since Model 2 represented the real situation better, the author recommends Model 2 though Model 1 can be used as a good approximation.

A mesh sensitivity analysis on the analytical model showed that differences in deflections and bending stresses in the girders were smaller than 2% when the mesh size was 12 inches by 12 inches. The results discussed in the preceding paragraphs were obtained with a mesh size of 12 inches by 12 inches.

The Tuscaloosa Bridge, Alabama

The third span of the Tuscaloosa Bridge is a glulam girder bridge made of Southern Yellow Pine, with four girders supporting the deck panels. The deck panels were about 4 feet in width, 15.1 feet in length, and 5.125 inches in thickness and were laid transversely on the girders. They were connected to the girders by lag bolts at 6 inches in from the edge of each panel. The bridge measured 102.1 feet in span (center-to-center of bearings). The girders had a nominal width of 10.625 inches and a nominal thickness of 63.125 inches. The Tuscaloosa Bridge is a long span, single lane bridge with bigger girders than the Cow Gulch Bridge. The material properties for the analytical model were obtained from the National Design Supplement (7) for the particular combination of lumbers and grade of lamination. The deck panels had a longitudinal and transverse modulus of elasticity of 1930 ksi and 240 ksi respectively. The shear modulus of the deck panels was about106 ksi. The girders had a longitudinal and transverse modulus of elasticity of 1930 ksi and 240 ksi respectively. The shear modulus of the girders was about 106 ksi.

Loading

The load case considered was a three-axle dump truck with a gross vehicle weight of 55400 pounds. The wheel load in the front and the two rear axles was 16,860 pounds and 19,270 pounds respectively. To obtain maximum deflection caused by the truck, the centerline of the three axles of the vehicle was placed to coincide with the transverse centerline of the bridge. The longitudinal centerline of the truck was also placed to coincide with the longitudinal centerline of the bridge. The experimental deflections were measured at the midspan of each girder. The plan layout along with the loading case considered is shown in Fig. 9.

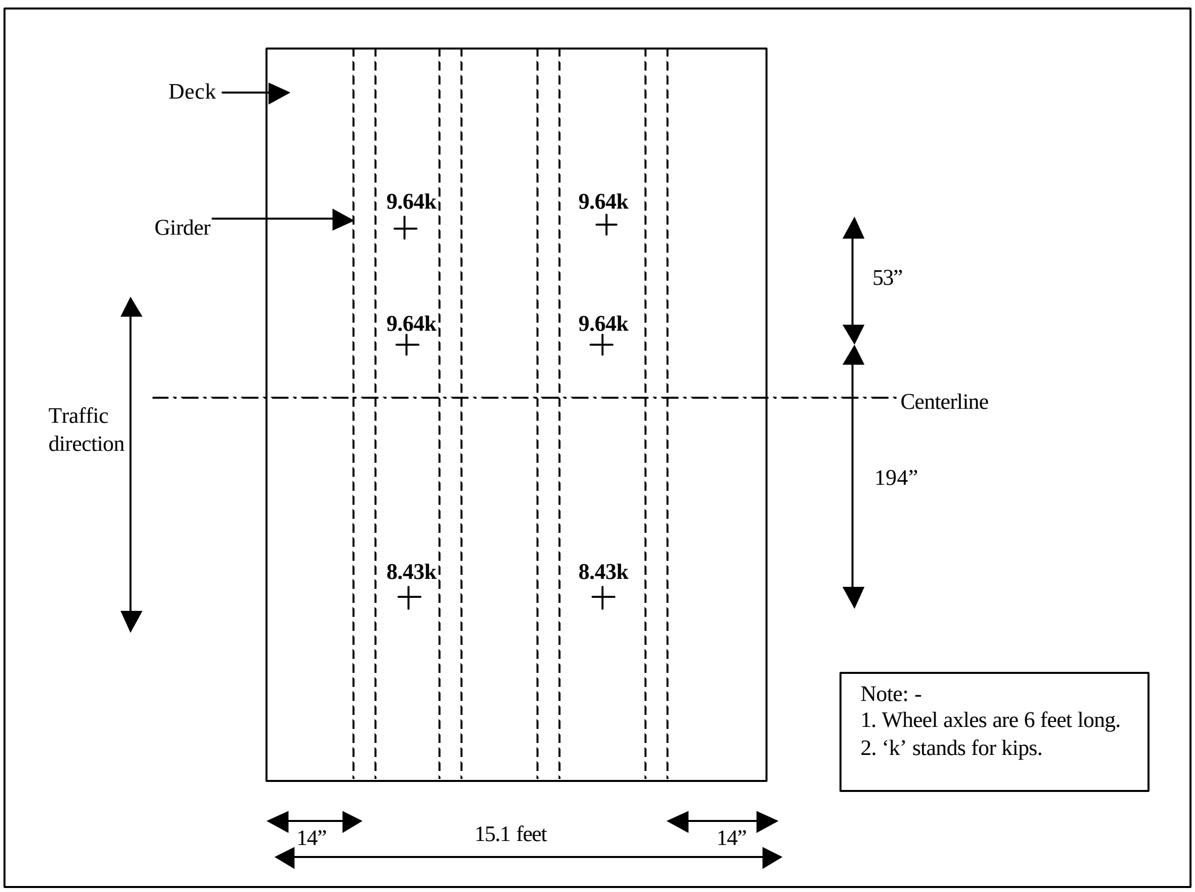


Fig. 9 – Plan layout of the Tuscaloosa Bridge, Alabama

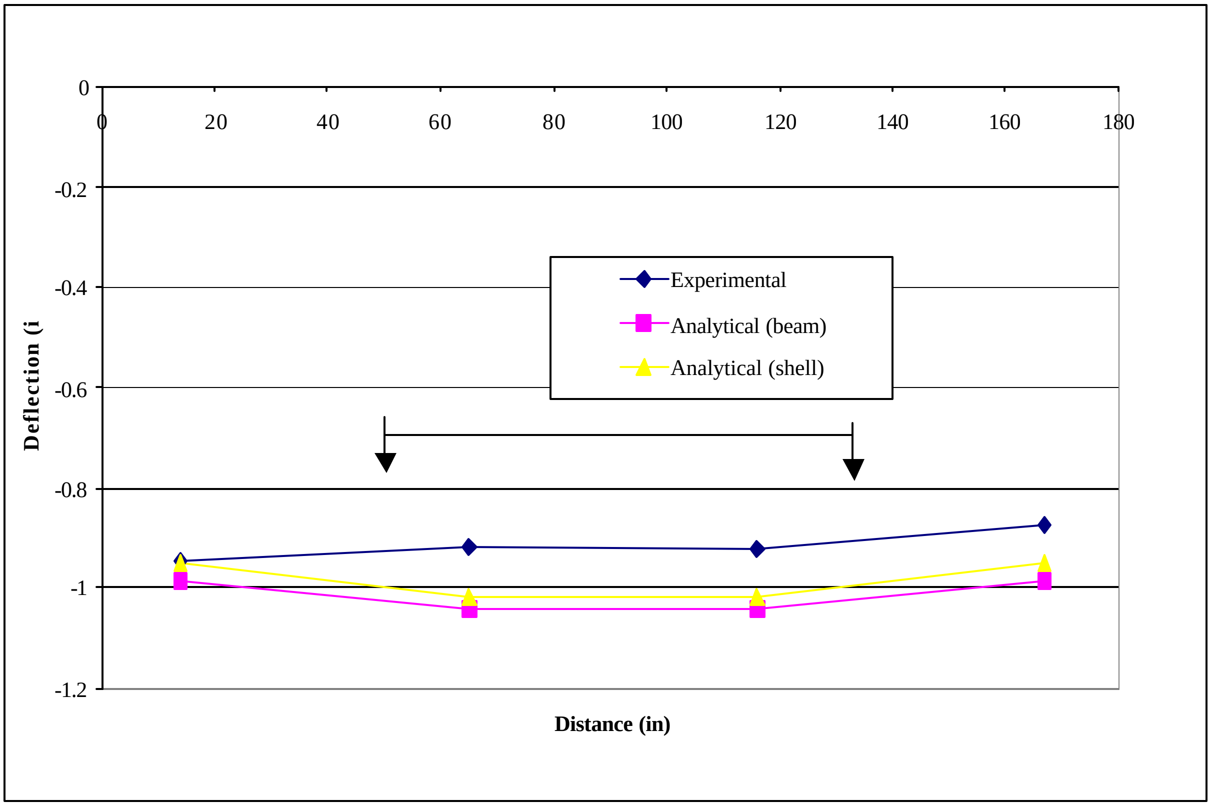


Fig. 10 – Panel deflections at midspan of girders – Tuscaloosa Bridge

Results and Discussion

A comparison between experimental data and analytical results for the Tuscaloosa Bridge is shown in Fig. 10. The graph shows the midspan deflection at each girder. The analytical results showed good correlation with the experimental values. The deflections of the girders based on the analytical model are about 12% larger than the experimentally measured deflections. The difference can be attributed to assumed material properties.

Model 1 and Model 2 compare very well with each other. As observed for the Cow Gulch Bridge, the deflections obtained from Model 2 are slightly lesser than the deflections from Model 1. This is attributed to the better simulation of composite action between the deck and the girder in Model 2 than in Model 1. The problem of location of supports did not seem to affect Model 1 and hence, it can be safely assumed that Model 1 is a very good approximation of the glued laminated girder bridge.

A mesh sensitivity analysis on the analytical bridge showed that differenced in deflection and bending stresses in the girders were smaller than 3% when the mesh size was 17 inches by 17 inches. The results discussed in the preceding paragraphs were obtained with a mesh size of 17 inches by 17 inches.

SUMMARY AND CONCLUSIONS

Two analytical models have been developed to analyze glued laminated girder bridges. Both models were validated by comparing the analytical results with experimental data from field bridges. The maximum difference between analytical deflections and experimental deflections was about 12% and this can be attributed to the assumed material properties in the analytical model. The following conclusions were drawn from the comparison of the analytical models to the field bridges:

1. The analytical models developed accurately predict the behavior of the girder bridge.
2. Experimental results support the conservatism of the analytical model.
3. Since Model 2 represents the real situation better than Model 1, the author recommends Model 2 to be the best idealization of a glued laminated girder bridge. Model 1, however, can be used as a good approximation to Model 2.

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