Investigation of a Folded-Plate Bridge

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Closing a bridge for rehabilitation or emergency repairs always causes costly delays and inconveniences the traveling public. A bridge system that is economical, relatively easy and quick to construct, and capable of withstanding the live loads and volume of today's traffic would alleviate some of these problems. As a possible solution to the nation's need for an emergency or "bypass" bridge, a new type of bridge—the shell bridge—has been developed. The feasibility and practicality of the shell bridge system have been verified through analytical and experimental investigations. The use of a folded-plate deck structure instead of a circular-shell deck structure in a shell bridge system was investigated. The obvious advantage of using a folded-plate cross section is that fabrication would be much simpler (i.e., flat form work instead of curved form work). The folded-plate bridge system was investigated analytically using the ANSYS general-purpose finite-element program. In the experimental portion of the investigation, a 1:24 Plexiglas scale model of a folded-plate bridge was fabricated and tested. The model was subjected to in-plane forces to simulate posttensioning forces and vertical forces to simulate live loading. In this preliminary investigation, the folded-plate deck structure, except for the higher transverse stresses caused by the lack of arch action, was determined to be an improvement over the circular-shell deck structure.

Because bridges are a vital element of any country's surface transportation system, the closing of a bridge for any reason (emergency repairs, strengthening, rehabilitation, etc.) always causes costly delays, detours, and inconvenience to the traveler. This is especially true in the cases of isolated bridges where the next available bridge is several miles away or bridges subjected to high volumes of traffic. To help alleviate some of these problems, a shell bridge system has been developed that is economical, relatively easy and quick to construct, and capable of carrying legal loads and today's volume of traffic. Although it is primarily intended to be used for "bypass" bridges, this system can be used with appropriate modification in permanent installations.

Several prefabricated elements and systems are available today for replacing damaged and deficient bridges relatively quickly and at a relatively low cost (e.g., precast, prestressed beams plus precast slabs). These systems are applicable for short spans; if intermediate supports are used, these systems can also be used for long multispan bridges. The shell bridge system developed in this study can be used for both short and relatively long spans without intermediate supports. The shell bridge is segmental, which eliminates many handling and transportation problems. Using the technology of segmental construction, individual shell segments are posttensioned together at the site to construct a bypass bridge of the desired span length. The shell bridge combines the advantages of prefabrication and segmental construction and also has high torsional rigidity plus arch action in the transverse direction.

Fanous et al. reported preliminary investigations of this system (*1*). In their study, 15 different cross sections were analyzed. From these, four different configurations of the integrated deck and circular shell structure (i.e., potential shell bridge cross sections) were investigated using finite-element techniques. The primary emphasis of this study was the investigation of the shell-deck connection and various methods of connecting the edge of the deck to the shell. The most efficient was the cross section with the lightest shell-deck connection (relatively long but thin) and inclined members (for connecting the edge of the deck and shell).

The second phase of the study involved the construction and testing of a 1:3 scale model shell bridge (*2*). The scale of the posttensioned reinforced concrete model was determined by available laboratory space and the minimum thickness of concrete that could be cast. The model consisted of six segments posttensioned together to create a model bridge 10 ft wide and 34 ft long. Thus, the prototype of this model would be 30 ft wide (two lanes) and more than 100 ft long, which is considerably longer than the usual simple span bridges. The primary purpose of the laboratory model testing was to determine potential construction problems and potential stress concentrations that could not be determined with finite-element analysis.

The third phase of the shell bridge investigation involved the analytical and experimental investigation of a folded-plate bridge (*3*)—one in which the shell portion of the shell bridge is replaced with plate elements (Figure 1)—to determine its behavior and response to various loading conditions. Although the transverse arch action is lost, the folded-plate structure would be much easier to fabricate (e.g., flat elements in the cross section). Although the use of folded-plate structures for bridges is a new concept, folded-plate roof structures have been used extensively when long spans without intermediate supports are required. In most situations, folded-plate roofs usually require posttensioning.

EXPERIMENTAL PHASE

Model

Plexiglas was selected for the model material; this resulted in several problems that will be discussed later. Use of the Phase II prototype bridge (length, 100 ft; width, 30 ft) and Plexiglas that was readily available (thickness, ¼ in.) resulted in a 1:24 scale model. The cross section and side view of the model are shown in Figures 2*a* and *b*, respectively. Curbs and diagonal

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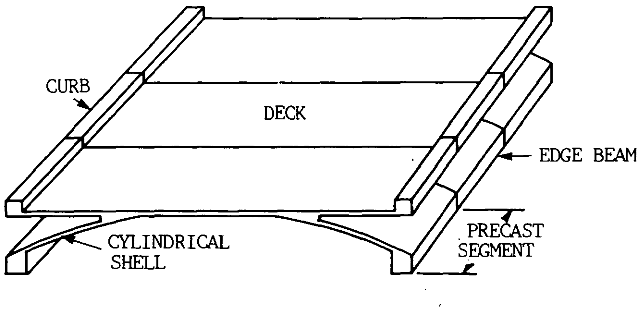
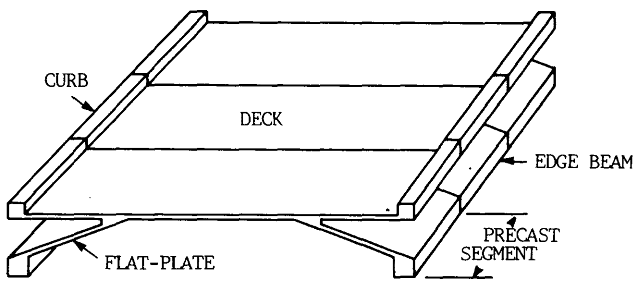


(a)



(b)

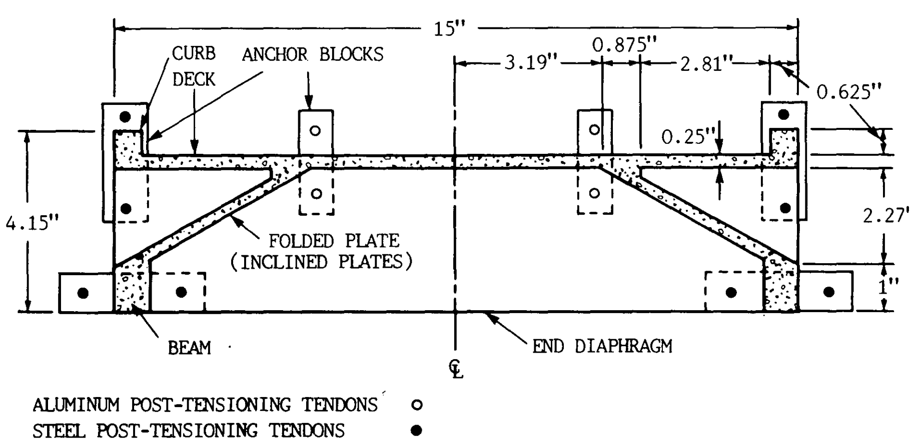
FIGURE 1 Shell bridge cross sections: (*a*) circular-shell elements and (*b*) folded-plate elements.

members were bolted to the model so it could be tested with and without curbs and diagonals.

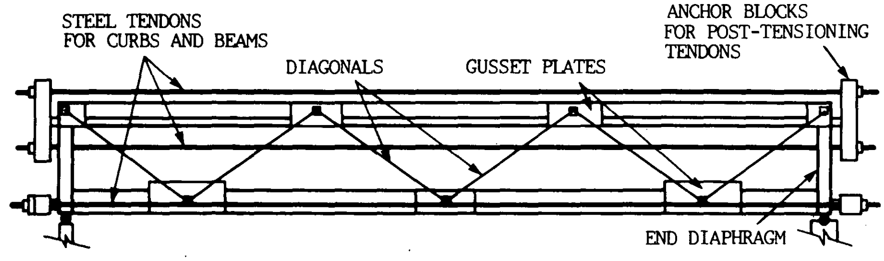
Although the Plexiglas model was fabricated as a unit (i.e., no individual segments), posttensioning was included because it would be required in the prototype. Shown in Figure 2*a* is the location of the posttensioning applied to the model. Initially, annealed aluminum rods were used for the posttensioning; however, after repeated use, the threads would wear out. The aluminum rods were then replaced with steel rods; the higher modulus of elasticity resulted in smaller strains in the rods, which were obviously more difficult to measure accurately.

Material Properties

To determine the modulus of elasticity and Poisson's ratio of the Plexiglas, an instrumented simply supported beam, fabricated from the Plexiglas used in the model, was tested using third-point loading (*2*). Midspan transverse and longitudinal strains were recorded at 15-sec intervals. Results revealed that the rate of creep became negligible after a few minutes. Based on the test results, instantaneous Young's modulus and Poisson's ratio were determined to be 443,800 lb/in.^{2} and 0.36, respectively. After 1 min, Young's modulus of the Plexiglas was found to be 414,900 lb/in.^{2}; after 2 min it had decreased to 409,700 lb/in.^{2}. In the analytical studies, an average mod-



(a)



(b)

FIGURE 2 Plexiglas bridge model: (*a*) cross section of bridge and (*b*) side view of bridge model with six diagonals.

ulus of elasticity (428,000 lb/in.^{2}) and Poisson's ratio (0.36) were used.

Instrumentation

Basic instrumentation for the model consisted of electrical-resistance strain gauges (henceforth referred to as gauges) for measuring strains and mechanical dial gauges for measuring deflections. The gauges were monitored using a computer-controlled data acquisition system.

General-purpose temperature-compensate gauges were installed and waterproofed on the model as well as on the posttensioning tendons in accordance with the manufacturer's guidelines. Two gauges were mounted on each posttensioning tendon longitudinally and diametrically opposite each other so that the axial force could be measured accurately and bending strains cancelled.

Because the model is geometrically symmetric about the longitudinal and transverse axes, its response under symmetrical loading can be assumed to be symmetric. Taking advantage of the assumed symmetry, the majority of the gauges were installed on one-quarter of the model. However, to verify the assumed symmetric behavior of the bridge, 10 gauges were installed on the other quarter-sections of the model.

As will be shown, only longitudinal strains in the curbs and beams are significant; transverse strains are essentially negligible. Hence gauges were positioned so that strains could be monitored along the tops and bottoms of the curbs and beams. Along the longitudinal and transverse centerlines of the deck and near the deck-plate connection, two separate gauges perpendicular to each other were installed at points of interest to measure the longitudinal and transverse strains. This combination was used instead of rosettes to avoid gauge heating problems. Mechanical dial gauges were used to measure midspan beam and curb deflection. Space limitations (i.e., smallness of model) prevented monitoring the deflections at additional locations.

FINITE-ELEMENT ANALYSIS

Modeling

The integrated folded-plate deck bridge model was analyzed using the ANSYS finite-element program (*4*). Eight-node solid elements (STIF45 in ANSYS element library) were used to idealize the bridge deck, folded plates, anchor plates, and gusset plates (see Figure 3). These elements were also used to analyze the shell bridge structures studied in previous related work (*1,2*). Posttensioning tendons, the vertical and the diagonal elements connecting the shell edge beam to the deck, were modeled using three-dimensional truss elements (STIF8 in ANSYS element library).

Because of the geometrical symmetry of the bridge model about the longitudinal and transverse axes, only one-quarter of the bridge structure was modeled. Appropriate symmetry and asymmetry boundary conditions were applied at the nodes on the symmetry planes. However, for general cases of loading, four computer runs with various combinations of boundary conditions were needed. For loads symmetric with respect to one of the symmetry planes, only two runs were used. The model was analyzed considering the following configurations and was tested in Configurations 1 and 2.

- Configuration 1: Model without diagonal members connecting the deck to the folded plate.
- Configuration 2: Model with six diagonal members connecting the deck to the folded plate.
- Configuration 3: Model with 12 diagonal members connecting the deck to the folded plate.

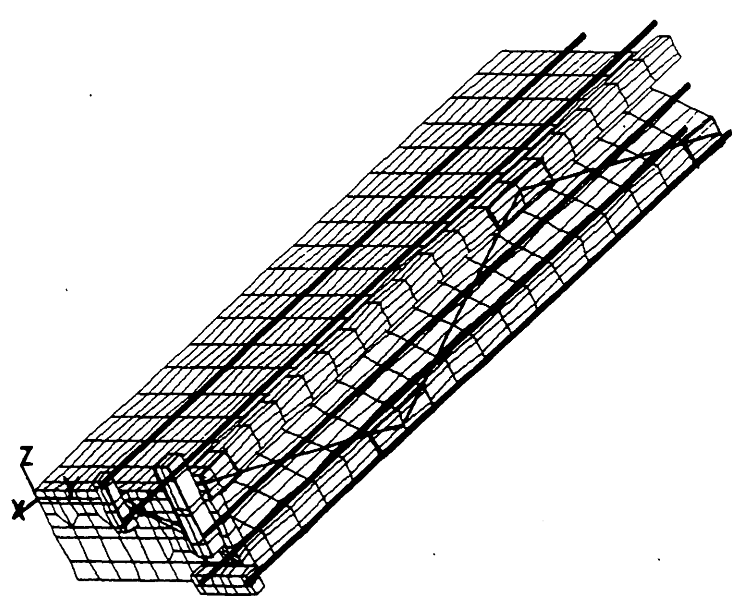


FIGURE 3 Finite-element model (perspective view) of integrated folded-plate deck bridge.

Posttensioning

In the finite-element analysis, the posttensioning forces in the tendons were included as a prestrain in the truss elements used to model the tendons. This was accomplished in steps to obtain the desired value of posttensioning force in each tendon. In the first step, the strain in each tendon was estimated using the desired posttensioning forces. However, examination of the analysis results indicated that the forces in the tendons were slightly less than desired. This lessening of the tendon forces was caused by losses in the specified prestrain because of the axial shortening of the bridge caused by posttensioning forces. The prestrain was then modified to account for these differences, and the structure was reanalyzed until the desired posttensioning forces were obtained. The final posttensioning forces applied in the analysis were used in the comparisons with experimental results.

TESTING AND RESULTS

Test Procedure

The bridge model was first tested using a 7.5-lb, single concentrated load simulating the scaled load of one axle of a standard HS20-44 truck (*5*). This load was adequate to produce strains of a magnitude sufficient to be accurately measured. Strains and deflections were recorded for the single load positioned at various locations defined by the longitudinal and transverse axes, as illustrated in Figure 4, to determine maximum deflections, shear stresses, and longitudinal and transverse strains. The model was also subjected to simulated AASHTO HS20-44 trucks positioned to produce maximum stress in the model.

Results

As previously noted, posttensioning of the tendons in the model to the desired force required adjustment to account for the creep in the Plexiglas material. Adjustments were made until the posttensioning forces were essentially stabilized. Posttensioning results (analytical versus experimental) were significantly different; the more noticeable differences occurred in the vicinity of the applied posttensioning force. These differences resulted from the higher creep that occurred in these areas and the way creep was included in the analytical model.

Response of the Model Under Single Load

Bridge Deck

The deflection of the bridge model deck at midspan with various web member configurations (Figure 2) loaded with a single load near the curb at midspan is shown in Figure 5. The difference between the measured and theoretical deflections was within 13 percent. Connecting the deck to the folded-plate edge beam reduced the overall deflection and resulted in higher torsional stiffness, as indicated by the smaller differential displacement between Edges *A* and *C* shown in Figure 5.

The transverse strains across the top of the deck at midspan when the load is placed at Points *G*1 and *G*3 (Figure 4) are shown in Figure 6. Note the excellent agreement between the finite-element analysis and the experimental results. Connecting the deck to the folded-plate edge beam reduced the magnitude of the transverse strains (Figure 6*a*). These strains were significantly reduced when the number of the diagonal members was doubled (12 diagonals versus 6 diagonals). Increasing the number of diagonals increased the stiffness of the cross section and significantly reduced the transverse strains near the connection between the folded plate and the deck. On the other hand, the distribution and magnitude of the transverse strains in the deck are essentially independent of the type of deck-edge beam connection when the load is applied at Point *G*3 (Figure 6*b*). The presence of diagonal members improved the overall structural behavior of the section under non-symmetrical loadings.

The distribution of the longitudinal strain across the top of the deck and along the bridge centerline when the load is positioned at Point *G*3 is shown in Figure 7. As can be seen, the strain distribution is not affected by the presence of the diagonal members connecting the deck to the folded plate's edge beam. Also illustrated in this figure is the overall agreement between the analytical and experimental results; however, the results differ significantly at the point of loading. This difference most likely results from idealizing the load as a true point load in the finite-element analysis instead of distributing the load, as presented in the model testing.

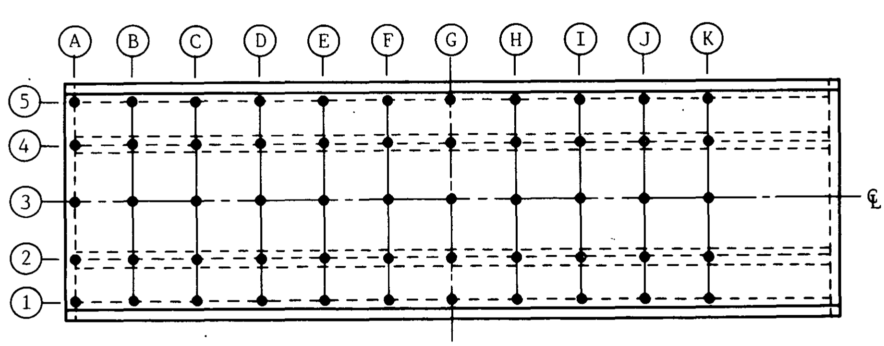


FIGURE 4 Load point locations.

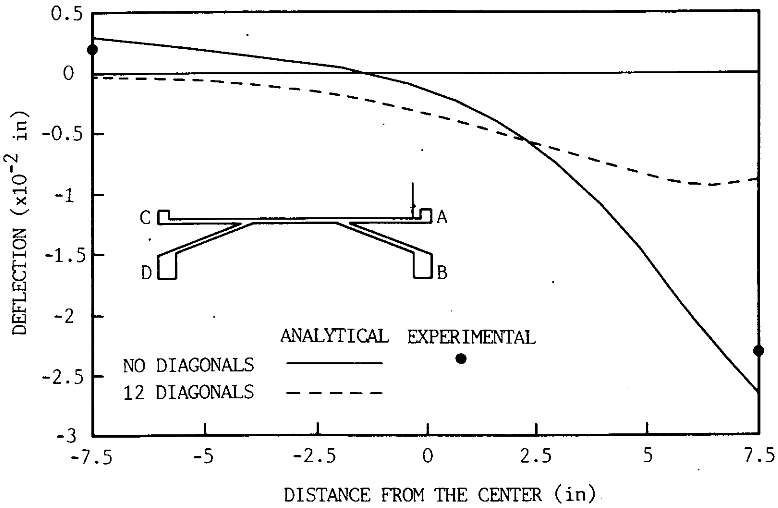
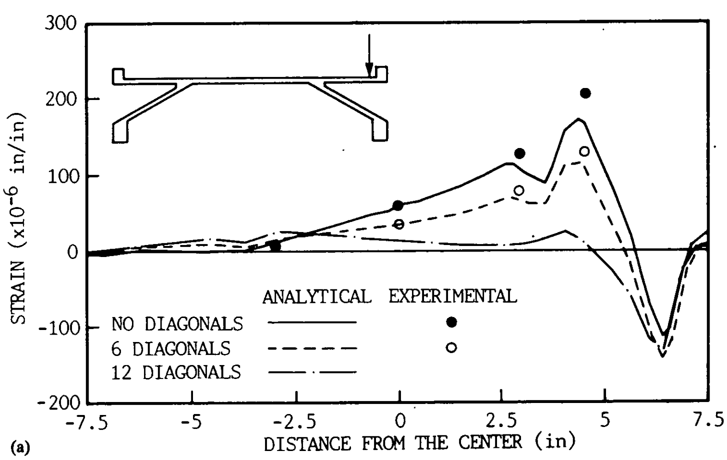
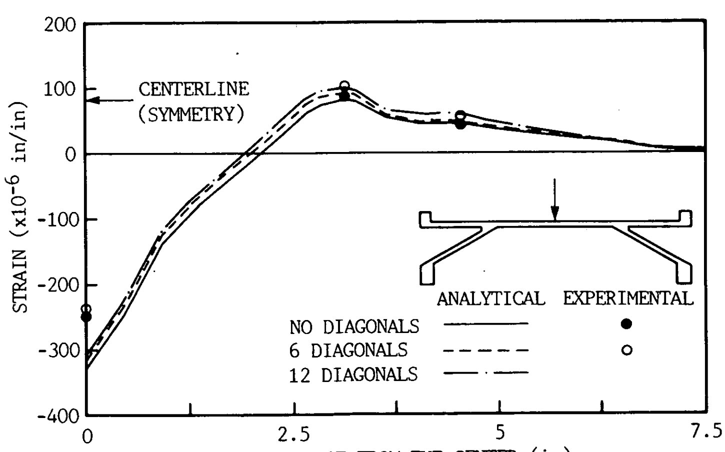


FIGURE 5 **Midspan deck deflection: single load at Point *G*1.**



(a)



(b)

FIGURE 6 **Transverse strain distribution on top of deck at midspan: (*a*) single load at Point *G*1 and (*b*) load at Point *G*3.**

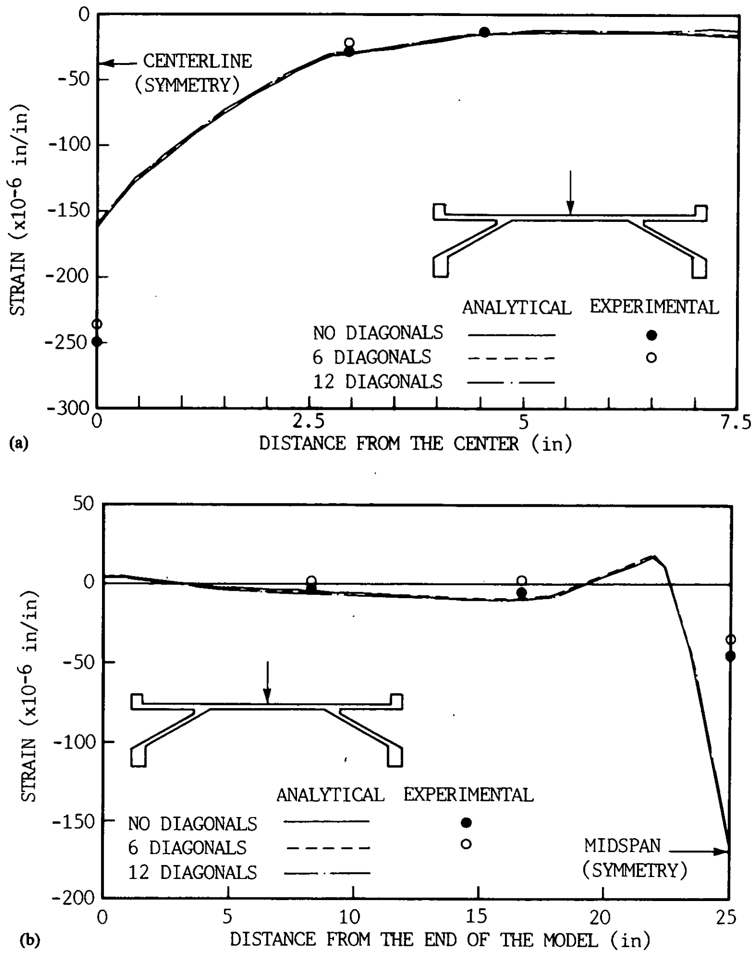


FIGURE 7 Longitudinal strain distribution on top of deck at midspan—single load at point *G*3: (*a*) strains across the deck and (*b*) strains along the bridge span.

Folded Plate

To investigate the response of the folded plate, the longitudinal and transverse strains were recorded for the single-load position at various locations along Section *G* (Figure 4). The longitudinal strain at midspan at Point *P* in the inclined plate was not significantly affected by the addition of the diagonal members, as shown in Figure 8*a*. However, adding diagonal members increased the torsional rigidity of the section and reduced the rotation of the deck-plate connection, resulting in a smaller transverse strain in the inclined plate when the load was applied near the curb (Figure 8*b*). The experimental results also illustrated that the transverse strain at Point *P* rapidly decreases as the load moves toward the other side of the deck (Figure 8*b*).

The experimental results also indicated that the maximum shear stresses in the inclined plate occurred when the load was applied at Point *B*2 (Figure 5). In this case, most of the load is transferred to the supports through the inclined plates, resulting in higher shear stresses in the inclined plate near the end diaphragm. Shear stresses were determined to be essentially uniform along the width of the plate except in the regions where the plate is connected to the edge beam and the deck. The presence of diagonal members did not have a significant effect on the shear stresses in the folded plates.

Response of the Model Under Truck Loading

After verifying the analytical results with the experimental results, the model was analyzed with scaled loads equivalent to AASHTO HS20-44 truck loading at various locations. For the case of maximum bending moment, two trucks were placed side by side at midspan. The model was also analyzed under a truck loading at midspan, with each truck positioned as close to the curb as the AASHTO specifications permit to produce maximum transverse stress in the deck.

The results of these analyses are summarized in Figures 9 and 10. Although the posttensioning forces were calculated so that no tensile strain would be induced in the model, some tensile strain was induced in the top of the curb near the end diaphragm (Figure 9*a*). This strain was the result of local moment caused by applying the posttensioning force at the bottom instead of the center of the curb. The analysis dem-

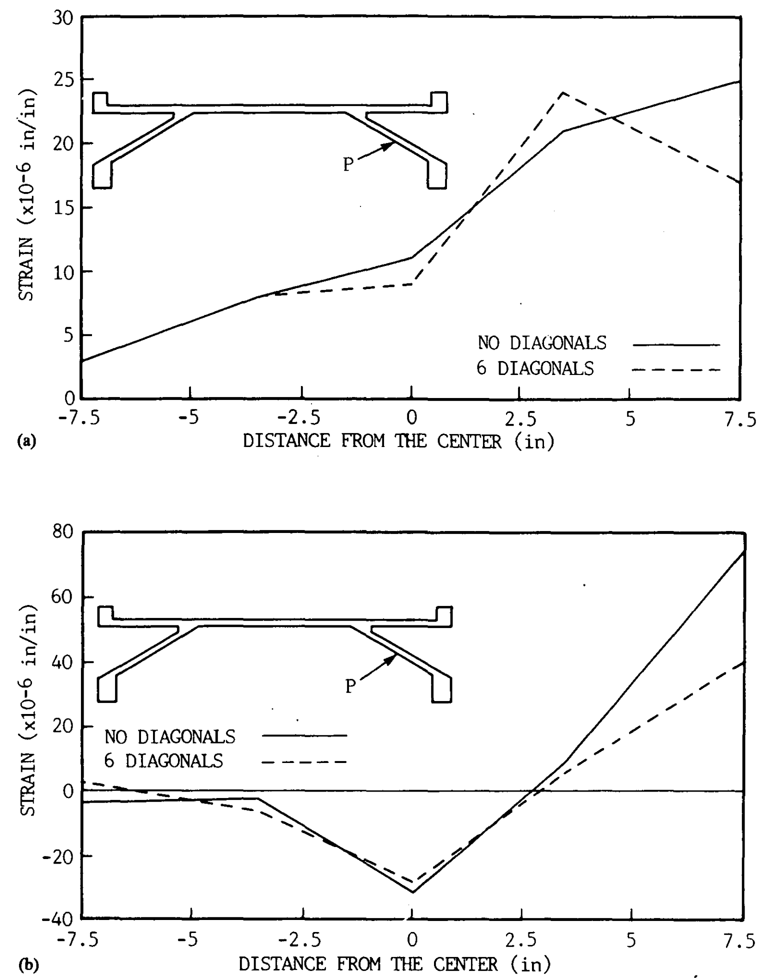


FIGURE 8 Longitudinal strain (*a*) and transverse strain (*b*) at Point *P* as single load moves along Section *G*.

onstrated that no tensile strains were induced in the bottom of the edge beam (Figure 9*b*). This verifies that the ordinary beam theory is adequate to estimate the required post-tensioning forces.

Figure 10 illustrates that the transverse strain in the top of the deck is reduced by approximately 50 percent when diagonals are used. The advantage of connecting the curb to the deck is also demonstrated. The differential deflection across the deck is minimized and the cross section is forced to act as a unit.

SUMMARY AND CONCLUSIONS

Aging, lack of maintenance, increases in legal loads, and increased traffic volumes cause more bridges to be added to the list of deficient bridges every year. Detouring traffic to avoid the problems associated with posted or closed bridges causes costly delays and inconveniences the traveling public. This paper summarizes one of the several phases of ongoing research to develop a new type of bridge that is economical, relatively easy to construct, and useful as an emergency bypass bridge. Through analytical and experimental studies, the feasibility and practicality of using an integrated folded-plate deck system were investigated. The folded-plate bridge system was analyzed using the ANSYS finite-element program. In the experimental portion of the investigation, a 1:24 Plexiglas scale model of a folded-plate bridge was fabricated and tested under forces simulating posttensioning and legal live loads.

The experimental and analytical investigations illustrate that folded-plate bridges can be constructed for short- or relatively long-span bridges. The results show that connecting the beams along the bottom edges of the folded plates to the curbs increases the stiffness of the bridge section and improves the overall behavior of this bridge system. The close agreement between the experimental and analytical results illustrates the capability of using finite element methods to analyze this complex bridge type. The performance of the model under simulated service loads also demonstrates that the folded-plate deck bridge is an alternative to some of the currently used bridge systems, except for the higher transverse stresses that were caused by the lack of arch action.

The results obtained in this investigation using a 1:24 scale model must be interpreted with care. Problems associated with using small-scale models fabricated with Plexiglas to model

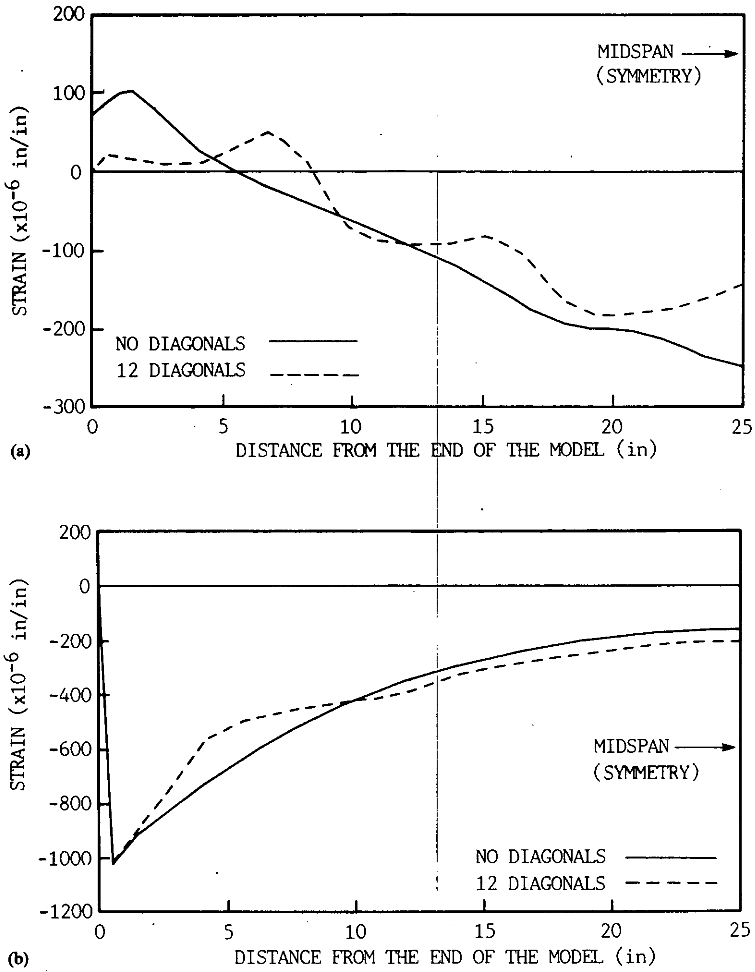


FIGURE 9 Longitudinal strain distribution along top of curb (*a*) and bottom of beam (*b*): two trucks at midspan, prestressing force applied.

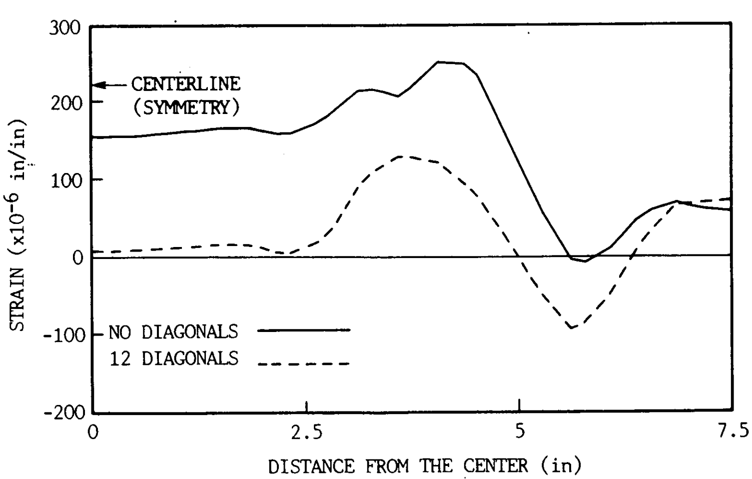


FIGURE 10 Transverse strain distribution along top of deck at midspan: two trucks at midspan, prestressing force applied.

actual structures need to be carefully considered. Research is still needed to determine the most economical fabrication and erection techniques for shell or folded-plate bridges.

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