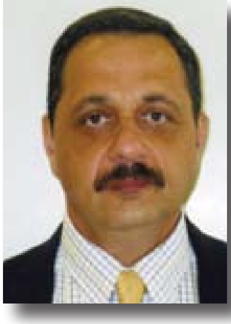
Effectiveness of Continuity Diaphragm for Skewed Continuous Prestressed Concrete Girder Bridges



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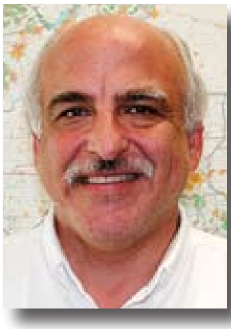

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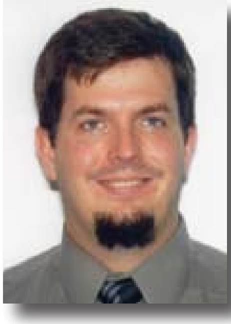

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Continuity diaphragms have caused difficulties in detailing and construction when used in bridges composed of prestressed concrete girders supported on skewed bents. This study investigates the effect of full-depth continuity diaphragms on the deflection of, and stress in, skewed precast, prestressed concrete girders. Bridge models used in this study had the following parameters: girder type and spacing, bridge skew angle, span length, and diaphragm type. As either the skew angle increases or the girder spacing decreases in these types of bridges, construction becomes more difficult and the effectiveness of the diaphragms becomes questionable. If diaphragms are determined to be unnecessary as an outcome of this research, the construction and maintenance costs of these types of bridges could possibly be reduced. The objectives of this research were to determine the need for continuity diaphragms in skewed, precast, prestressed concrete girder bridges; study the load transfer mechanism through full-depth continuity diaphragms; and determine the minimum skew angle at which a diaphragm becomes ineffective in performing its function.

The majority of highway bridges in the United States are built with cast-in-place (CIP) reinforced concrete slabs on precast, prestressed concrete girders. Composite action between the CIP concrete slab and precast concrete girders is ensured by the interface shear between the tops of the girders and the slab. Bridge design guidelines in section 8.12 of the American Association of State Highway and

Transportation Officials' (AASHTO's) *Standard Specifications for Highway Bridges*[1] indicate that diaphragms should be installed for T-girders but may be omitted where structural analysis shows adequate strength without diaphragms.

However, the design of the girders does not account for the effects of diaphragms. Continuity diaphragms cause difficulties in detailing and construction when used in bridges composed of prestressed concrete girders supported on skewed bents. As the skew angle increases or the girder spacing decreases in these types of bridges, construction becomes more difficult and the diaphragms become less effective in carrying and distributing the loads.

The objectives of this research were to determine the need for continuity diaphragms in these types of bridges, to study the load transfer mechanism through full-depth continuity diaphragms, and to determine the minimum skew angle at which a diaphragm becomes ineffective at transferring and resisting loads.

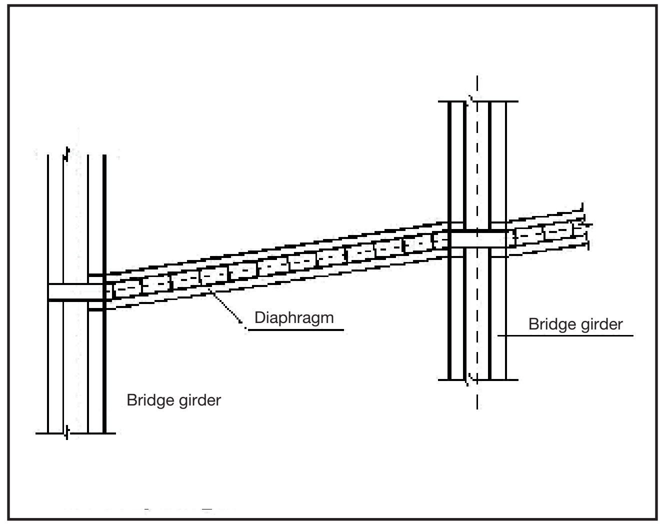

Fig. 1. Partial plan view for continuity diaphragm.

DESCRIPTION OF DIAPHRAGMS

The *AASHTO LRFD Bridge Design Specifications*[2] defines a diaphragm as a member that resists lateral forces and transmits loads to points of support. For many years, diaphragms were believed to contribute to the overall distribution of live loads in bridges. Consequently, most bridges built in the United States have included diaphragms that are either continuous or simple. Some diaphragms are post-tensioned, while others, depending on the type of bridge, have nonprestressed reinforcement.

CIP concrete diaphragms are most commonly used in prestressed concrete I-girder bridge construction. Full-depth diaphragms are terminated at the end of the sloping portion of the bottom flange, as shown in **Fig. 1** and **2**. Generally, the diaphragm is integrated with the deck through continuous reinforcement and tied to the girders with anchor bars (Fig. 2). For this study, the skew angle of the bridge was defined as the angle β between the centerline of a support and a line normal to the roadway centerline, as shown in **Fig. 3**.

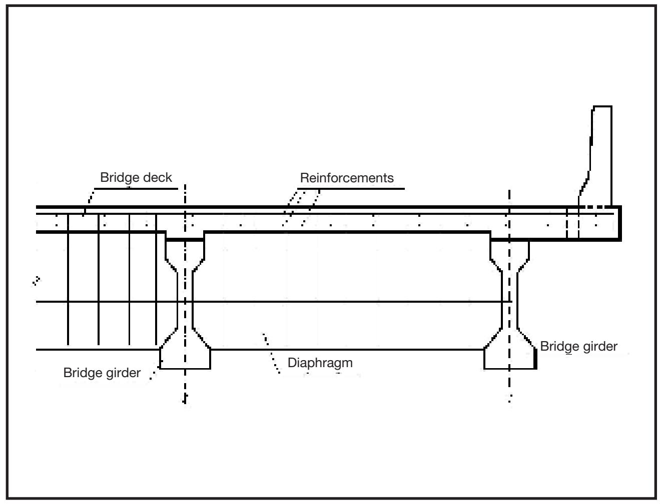

Fig. 2. Partial section at continuity diaphragm.

LITERATURE REVIEW

Using various analytical methods to analyze load distributions in highway bridges, the following assumptions have been made to simplify bridge modeling and to allow for a manageable solution:

- Slab-and-girder bridges are assumed to be plate structures stiffened by girders; and
- Orthotropic plate theory assumptions are used for bridges with closely spaced girders.

Although an approach based on these assumptions has been popular in analyzing slab on girder bridges, the method has limitations in the cases of continuous and skew bridges, or bridges with diaphragms, and more elaborate methods may be necessary in such cases.

Wong and Gamble[3] indicate that while the diaphragms may improve the load distribution characteristics of some continuous slab and girder highway bridges that have large beam

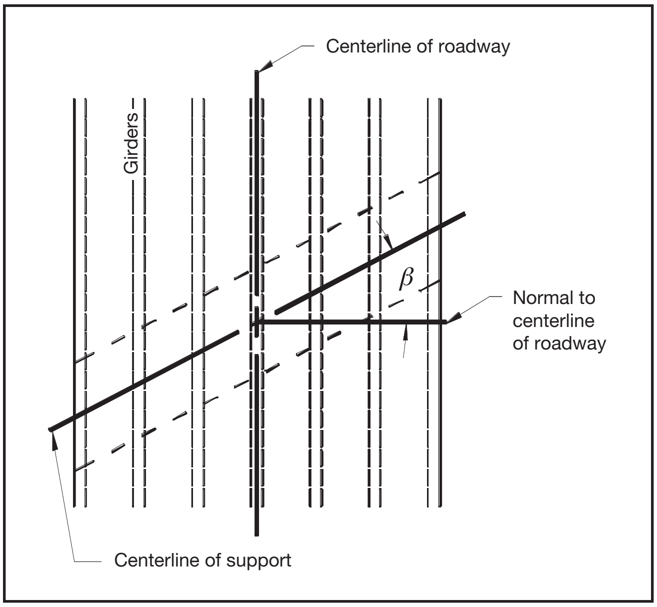

Fig. 3. Bridge skew angle.

spacing–to–span ratios, diaphragms should be eliminated from prestressed concrete I-beam bridges unless required for erection purposes.

Another study investigated the effect of diaphragms on prestressed concrete slab-and-girder bridges by varying span length, skew angle of the bridge, diaphragm stiffness, and location and number of diaphragms.[4] In this study, the diaphragms distributed the load more evenly, but diaphragms never significantly reduced the governing design moment for the girders.

Results from research on simply supported bridges were the basis for much of the present AASHTO design criteria on live load distribution. Provisions for the design of negative moment regions were inferred from the behavior of the positive moments. Because of the difference in effective span length due to the negative moment at the interior support of a continuous bridge, a direct comparison between the results of an analysis of a simply supported bridge and a continuous bridge are difficult. Because most highway bridges are continuous, analyses of the effects of diaphragms on continuous bridges will undoubtedly provide new data as well as supplement the current data on the design of slab-and-girder bridges.

Marx et al.[5] developed wheel load distribution equations using finite element analysis of 108 simply supported, skewed–slab-and-girder bridges. The research included models for the concrete bridge deck and prestressed girders as an eccentrically stiffened shell assembly. Kennedy and Grace studied the effects of diaphragms in skew bridges that had been subjected to concentrated loads and concluded that diaphragms enhance the distribution of point loads.[6] Nutt, Zokaie, and Schamber analyzed multigirder composite steel bridges using equivalent orthotropic plate and ribbed plate models.[7] Simplified equations were developed, modified, and included in the 1994 *AASHTO LRFD Bridge Design Specifications.*

Background information on the development of wheel load distribution factors can be found in Hays et al., Sanders and Elleby, and Stanton and Mattock.[8–10] Chen studied load distribution in bridges with unequally spaced girders. AASHTO empirical formulas for estimating live-load distribution factors were compared with the results from the refined method.[11] Parametric studies were conducted with a number of nonskewed, simply supported bridges that had no diaphragms. Load distribution equations were proposed.

Subsequent work by Chen and Aswad[12] sought to review the accuracy of the formulas for live load distribution for flexure contained in the *AASHTO LRFD Bridge Design Specifications* for prestressed concrete I-girder bridges. Research conclusions stated that the use of a finite element analysis led to the reduction of the live-load distribution factor in I-beams when compared with the simplified LRFD guidelines. Tarhini and Frederick[13] presented additional revisions to the load-distribution equations. Contrary to the *AASHTO Standard Specifications for Highway Bridges* assumptions, the finite element analysis revealed that the entire bridge superstructure acts as one unit rather than a collection of individual structural elements.

Bakht reported on a simplified procedure by which skewed bridges could be analyzed to acceptable design accuracy using methods originally developed for the analysis of straight bridges.[14] The study concluded that beam spacing and skew angle are important criteria when analyzing a skewed bridge. Results from error analysis using experimental data indicated that the process of analyzing a skew bridge as an equivalent straight bridge is conservative for longitudinal bending moments but not for longitudinal shear forces.

Using the results from previously published experiments, Nassif and Nowak attempted to quantify the dynamic load factor (DLF) associated with the trucks available in the United States.[15] The study concluded that the DLF decreases as

Table 1. Bridge Parameters

Bridge Group	AASHTO Girder Type	Bridge Skew Angle, Degrees	Girder Spacing, ft	Span Length, ft	Diaphragm Condition
A	II	10	5	75	Yes
	II	10	5	75	No
B	II	10	9	55	Yes
	II	10	9	55	No
C	II	20	5	75	Yes
	II	20	5	75	No
D	II	20	9	55	Yes
	II	20	9	55	No
E	IV	10	5	111	Yes
	IV	10	5	111	No
F	IV	10	9	92	Yes
	IV	10	9	92	No
G	IV	20	5	111	Yes
	IV	20	5	111	No
H	IV	20	9	92	Yes
	IV	20	9	92	No

Note: AASHTO = American Association of State Highway and Transportation Officials;1 ft = 0.3048 m.

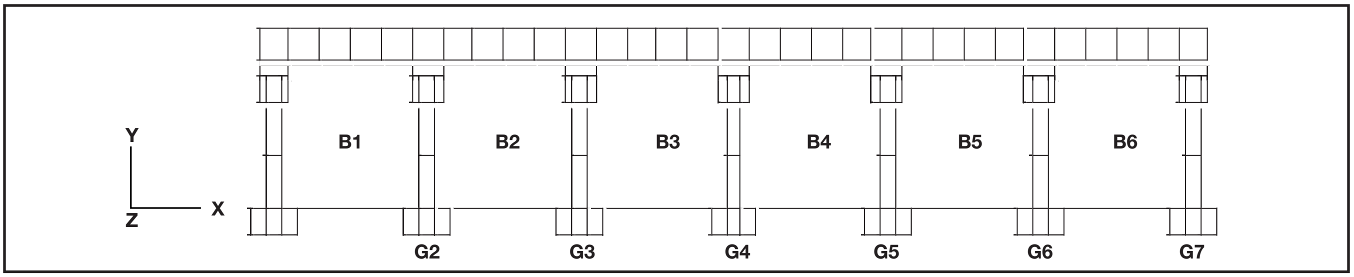

Fig. 4. Cross section of bridge models with a 5 ft (1.5 m) girder spacing.

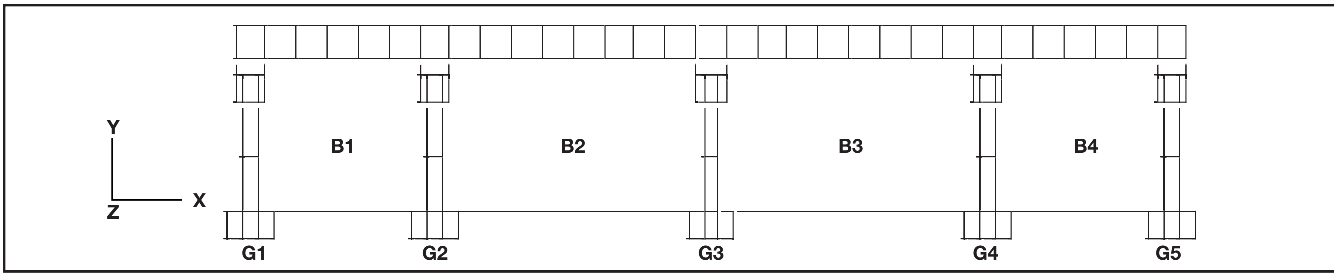

Fig. 5. Cross section of bridge models with a 9 ft (2.7 m) girder spacing.

the static stress in each girder increases. The lateral stability of prestressed concrete girders was investigated by Saber in analyses for long-span, simply supported, nonskewed bridges.[16] Results indicated that the AASHTO 1996 recommendations were conservative, involving T-girder construction for one intermediate diaphragm at the point of maximum positive moment of spans in excess of 40 ft (12.2 m). Barth and Bowman studied the effect of diaphragm details on the service life of bridges and found that even though some fatigue cracking might occur in certain locations, cracking did not reduce the service life of the bridge.[17]

ANALYTICAL STUDIES

The objectives of the research presented in this paper were to determine the need for continuity diaphragms in skewed, precast, prestressed concrete girder bridges; to study the load transfer mechanism through full-depth continuity diaphragms; and to determine the minimum diaphragm skew angle at which a diaphragm becomes ineffective at transferring and resisting load. The bridge parameters considered in this study were based on results of a survey sent to all 50 U.S. state bridge engineers.

Bridge parameters included girder type (AASHTO Type II and Type IV), bridge skew angle (10 degrees and 20 degrees), girder spacing (5 ft and 9 ft [1.5 m and 2.7 m]), span length (55 ft, 75 ft, 92 ft, and 111 ft [16.8 m, 22.9 m, 28 m, and 33.8 m]), and diaphragm conditions (full depth and without diaphragms). The bridge width and slab thickness remained constant at 30 ft (9.1 m) and 8 in. (200 mm), respectively.

In evaluating the stresses and deflections in the girders, bridges were grouped based on the bridge parameters. **Table 1** lists the 16 combinations of bridge configurations included in this study. For all cases, the bridge deck is continuous over the intermediate supports. For the cases in which diaphragms were not used, the bridge girder was continuous over the intermediate supports.

METHOD OF APPROACH

Significant advances in computer technology have made finite element modeling one of the most popular methods for constructing and analyzing complex structures. The finite element models (FEM) developed in this investigation simulated the behavior of skewed continuous-span bridges. **Figures 4** and **5** present the girder and diaphragm labels as used in models generated using GTSTRUDL structural design and analysis software, version 25. **Figure 6** shows a typical girder and deck FEM configuration. The maximum aspect ratio for the FEM is four. The boundary conditions for the end and

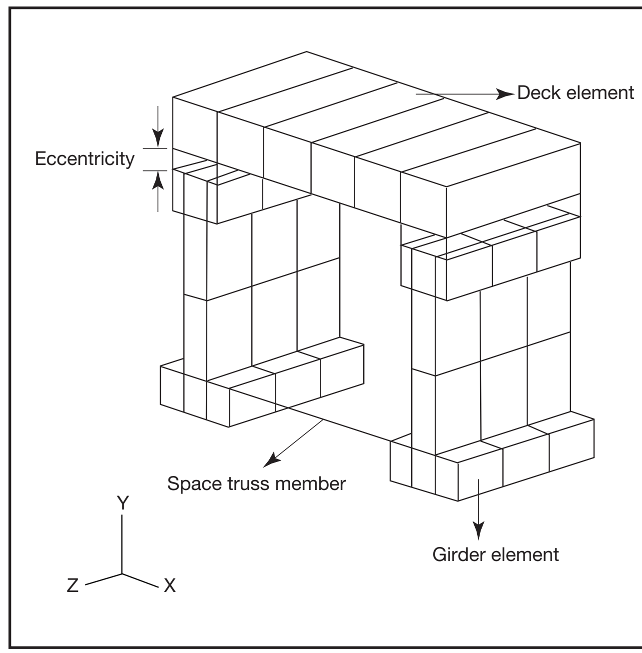

Fig. 6. Typical plate and girder finite element configuration.

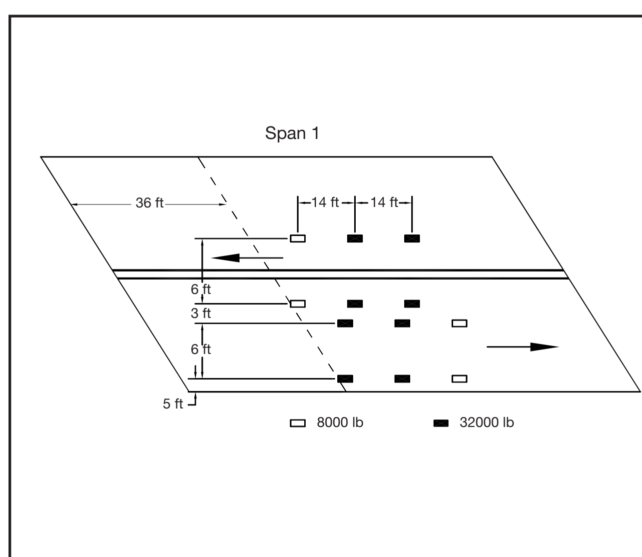

Fig. 7. Placement of the axle loads on span 1 of the bridge.
Note: 1 ft = 0.3048 m; 1000 lb = 4.4 kN.

Table 2. Results for Comparison of Diaphragm to No-Diaphragm Models

Bridge Group	Change Tensile Stress over First Intermediate Support, %	Change Compressive Stress under Truck Load, %	Change Critical Tensile Stress, %	Change Maximum Deflection, %
A	0.4	0.1	2.8	0.1
B	1.0	0.2	0.7	0.0
C	0.5	0.0	3.5	0.0
D	1.2	0.2	0.5	0.1
E	0.3	0.0	1.0	0.0
F	0.1	0.1	0.6	0.0
G	0.3	0.1	1.0	0.0
H	0.6	0.0	0.3	0.0

intermediate support nodes for the girders were modeled as simple and continuous supports, respectively.

AASHTO Loading

AASHTO LRFD Bridge Design Specifications loading conditions were used in this investigation. The applied loads were dead load, HL 93 vehicular load, surcharge load for future overlays, and wind load. The location of the axle loads that would produce the maximum moment was determined based on influence line analyses, as shown in **Fig. 7**.

DISCUSSION OF RESULTS

The results of all bridge configurations listed in Table 1 were examined to determine the effects of continuity diaphragms on skewed, continuous, precast prestressed concrete girder bridges.

Effects on Maximum Stress

The study of the effects of continuity diaphragms on the maximum stresses in the girders was investigated in two parts. The first part focused on the stresses in the critical girder as a function of the distance along the bridge. The maximum compressive stress in the top fiber of the girder occurred in span 1 where the applied load was placed and the maximum tensile stress occurred over the first intermediate support in the negative moment region (Fig. 7).

The general behavior of stress in the critical girder for all bridge configurations followed the same pattern as the stress in the critical girder (girder 5) of group A, as shown in **Fig. 8**. The stress in the top fiber of the critical girder of the bridge configurations in group A is shown on the vertical

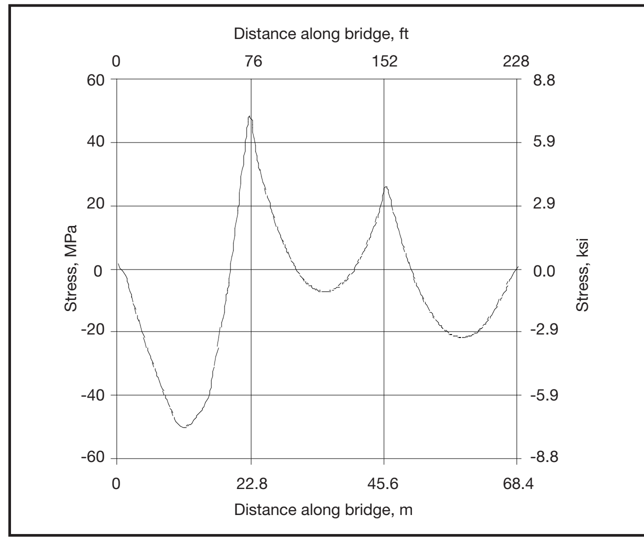

Fig. 8. Stress in critical girder as a function of distance, group A with diaphragm.

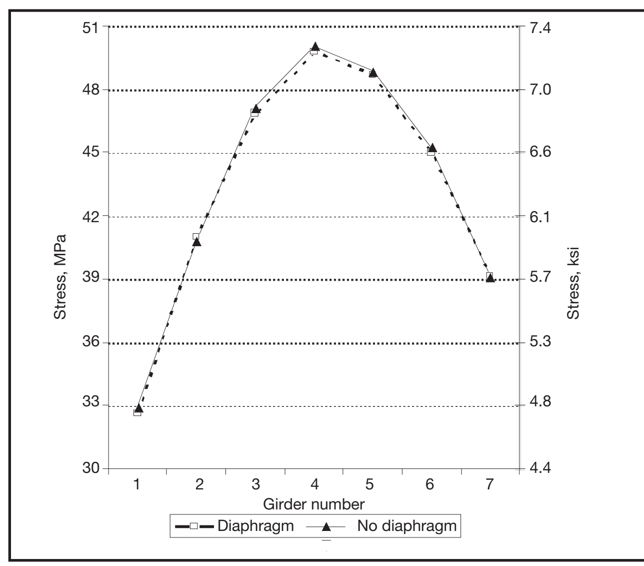

Fig. 9. Maximum stress at the bottom of the girder, group A.

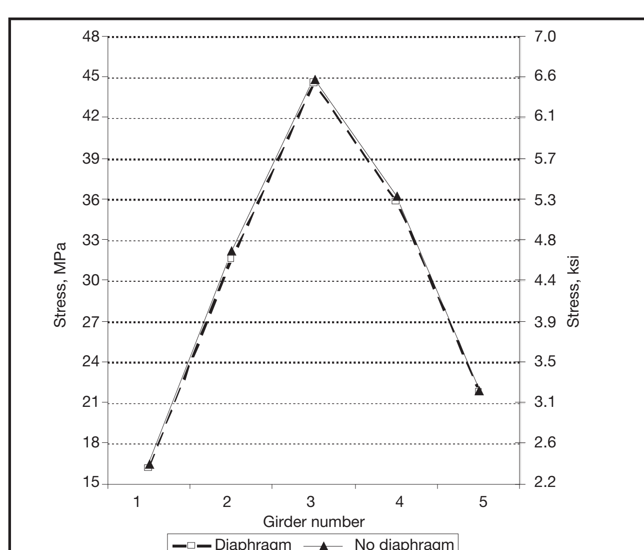

Fig. 10. Maximum stress at the bottom of the girder, group B.

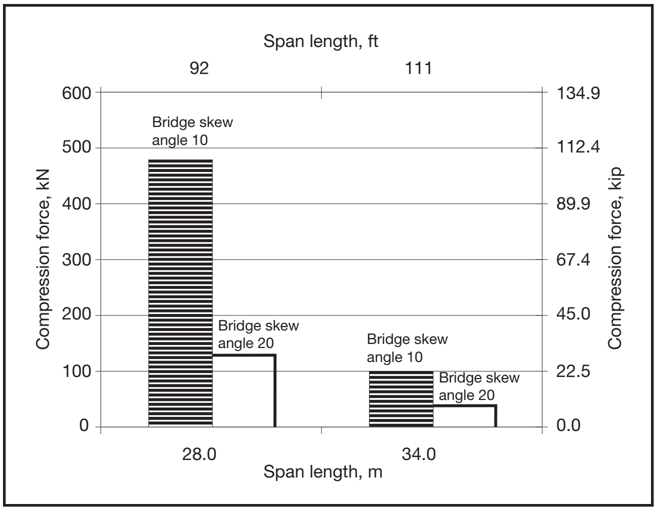

Fig. 11. Axial force in diaphragms for bridge groups E, F, G, and H. Note: Skew angle in degrees.

axis in Fig. 8, and the distance along the span is shown on the horizontal axis. Saber et al.[18] contains all the plots of the stress distribution along the girders for each bridge configuration group.

Table 2 shows the percentage change in stress between each model within the bridge configuration groups. Due to the use of the continuity diaphragms, there was little difference in the magnitude of the tensile stresses. The differences in the tensile stresses between the diaphragm and the no-diaphragm conditions ranged from 0.0 ksi to 0.01 ksi (0.0 MPa to 0.07 MPa), and the maximum tensile stress increased 1.2%. Due to the use of the continuity diaphragms, the differences in the compressive stresses were less than 0.02 ksi (0.14 MPa) and the maximum compressive stress decreased 0.2%. Based on the small changes in stress in the girders, the effects of continuity diaphragms on the maximum stress in the girders were determined to be negligible.

The second part of the study focused on the maximum tensile stresses over the first intermediate support in the top fibers of the critical girder. Two patterns were observed in this study. Bridge configurations with a girder spacing of 5 ft (1.5 m) (groups A, C, E, and G) followed the first pattern for the bridge configuration group A, as shown in **Fig. 9**. The maximum tensile stress is shown on the vertical axis in Fig. 9, and girder number is represented on the horizontal axis. The middle girder (girder 4) was the critical girder for all cases, and the tensile stresses in the remaining girders were similar in magnitude for all diaphragm conditions (approximately 7.3 ksi [50 MPa]).

The second stress pattern was observed in the bridge configurations with girder spacing of 9 ft (2.7 m), groups B, D, F, and H, as shown in **Fig. 10**. The maximum tensile stress is shown on the vertical axis of Fig. 10, and the girder number is shown on the horizontal axis. The critical girder for all diaphragm conditions was girder 3, which was located in the center of the bridge configurations. The tensile stresses in each of the girders were similar in magnitude for all of the diaphragm conditions.

As shown in Fig. 10, the tensile stresses over the first intermediate support behaved as expected for all diaphragm conditions, with the critical stresses occurring in the center girder. The tensile stresses in the top fibers of the girders over the first support for all diaphragm conditions were of the same magnitude (about 6.5 ksi [45 MPa]). Saber et al. contains the graphs of the maximum tensile stress in the girder top fibers for all of the bridge configuration groups.

Again, Table 2 shows the percentage change in maximum tensile stress between each model within the bridge configuration groups. Bridge configurations with a 5 ft (1.5 m) girder spacing (groups A, C, E, and G) with or without a diaphragm had critical tensile stresses in girder 4. The maximum tensile stress for bridges with a diaphragm increased 3.5% compared with the no-diaphragm condition.

Bridge configurations with a 9 ft (2.7 m) girder spacing (groups B, D, F, and H) had critical stresses in girder 3. The maximum tensile stress for bridges with a diaphragm increased 0.7% compared with the no-diaphragm condition. Again, the effects of continuity diaphragms on the maximum stress in the girders were determined to be negligible.

Effects on Maximum Deflection

The bridge configurations listed in Table 1 were evaluated to determine the effect of continuity diaphragms on deflection. The behavior of the girder deflections for all of the bridge configurations was as expected: the maximum deflection occurred in span 1 near the truck axle loading. Table 2 presents the percentage change for deflection data between each model within a bridge configuration group.

As the diaphragm condition changed from the skew condition to the no-diaphragm condition, the maximum increase in deflection was 0.1%. This suggested that continuity diaphragms did not contribute to reducing girder deflection. Therefore, the effects of continuity diaphragms on the maximum deflection of the girders were determined to be negligible.

Effects of Skew Angle on Axial Force in the Continuity Diaphragms

The axial forces in the continuity diaphragms for all bridge configurations listed in Table 1 were evaluated to determine the minimum diaphragm skew angle at which a diaphragm becomes ineffective. The results of the analyses that were performed indicated that for AASHTO's critical loading condition, Strength I Maximum, the axial force in the diaphragm decreased as the skew angle increased. Results for the bridge configuration groups E, F, G, and H considered in this study are presented in **Fig. 11**. Based on the analyses in this study, it can be concluded that a continuity diaphragm with a skew angle larger than 20 degrees will be ineffective in performing its function.

CONCLUSIONS AND RECOMMENDATIONS

This study investigated the load transfer mechanism through full-depth continuity diaphragms. The effect of continuity diaphragms on the maximum stress in the girders and maximum deflection of the girders was negligible. This indicated that continuity diaphragms could be eliminated from skewed, continuous, precast prestressed concrete girder bridges. Thus, continuity diaphragms are ineffective and full-depth diaphragms are not needed to control deflections or reduce member stresses but may be needed for construction, lateral stability during erection, or resisting/transferring earthquake or other transverse loads.

The theoretical results of this investigation were based on finite element analysis to determine the effects of full-depth continuity diaphragms for skewed, continuous, precast prestressed concrete girder bridges. Based on the study of the load transfer mechanism through full-depth continuity diaphragms, it is recommended that laboratory tests and field measurements be compared with the theoretical results. Further research is needed to instrument similar bridges, perform field load tests, and compare measured strains and deflections with data reported in this study. The outcome of this research has the potential to reduce the construction and maintenance costs of bridges throughout the United States.

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