EFFECT OF CONNECTIONS BETWEEN ADJACENT UNITS ON DECKED PRECAST/PRESTRESSED CONCRETE GIRDER BRIDGES

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ABSTRACT

Using the calibrated 3D FE models, parametric studies are performed to study the effect of shear connectors and intermediate diaphragms. It has been found that: (1) In all cases studied, the live load distribution factor (DF) for a single-lane loaded bridge is smaller than one for a double-lane loaded bridge; (2) When bridges with one intermediate diaphragm at midspan only are compared with bridges with five uniformly distributed diaphragms the difference in DF is very small; (3) The spacing of shear connectors plays a very small role in live load DF; (4) Connector forces caused by wheel loads are not uniform along the longitudinal joint. Adding intermediate diaphragms tends to reduce the difference among horizontal shear forces in connectors; (5) The maximum horizontal shear force increases with the increase of the connector spacing. Intermediate diaphragms reduce the maximum horizontal shear force in connectors; (6) The maximum vertical shear force and in-plane normal tensile-force in connectors do not necessarily increase with the increase of the connector spacing; and (7) The summation of connector forces in each direction along the longitudinal joint remains constant irrespective of the number of connectors in the joint.

Keywords: Shear Connectors, Intermediate Diaphragms, Load Distribution, Connector Forces, Bridges, Load Rating, Field Test, 3D Finite Elements, AASHTO Specifications, Decked Bulb-Tee.

INTRODUCTION

Speed of construction, especially for the case of bridge replacement and repair projects, has become a critical issue more than ever. A strong momentum exists for spread of precast construction for bridges with a push to expand the limits specially for the use in long-span bridges. One of the promising systems for precast bridge construction has used decked precast, prestressed concrete (DPPC) girders for superstructure. Despite several major benefits, the construction of this type of bridges has not shown the growth it deserves and has been mostly limited to the Pacific Northwest states of Alaska, Idaho, Oregon, and Washington. The reason is two-folded, one is because of the concerns and limitations in design and construction using DPPC girders, and the other is the lack of understanding due to limited research in this area. These issues include connections between adjacent units, live load distribution[1] and other factors.

These DPPC girders are erected such that flanges of adjacent units abut each other. Load transfer between adjacent units is provided using special connections: shear connectors and intermediate diaphragms. There are no guidelines available for the design of these connections[2]. According to a survey study[2], design of these connections was based on empirical experience, such as “details used many years with success”. In a recent study[3] regarding intermediate concrete diaphragms, it has been found that the effects of diaphragms are more pronounced for straight bridges than for skew ones and the effect of the diaphragms should be made from case to case. The effect of diaphragms are more pronounced at wider girder spacing and also for longer spans[4].

Using ABAQUS CAE, three-dimensional (3D) finite element (FE) models have been developed and calibrated with in-situ bridge testing results[5]. This paper summarizes research results on the effect of the varying number of shear connectors and intermediate steel diaphragms.

3D FINITE ELEMENT MODELING AND CALIBRATION

The finite element method offers an improvement over most other methods. A three-dimensional model can accommodate interaction between girders, decks, shear connector joints, intermediate diaphragms and supports. This type of model treats the bridge deck as a three-dimensional system. Bearings are placed at actual locations in the model. The mesh density is based on the location of the girder relative to the loading position.

ELEMENTS AND MESH

The 3D FE modeling was done by using ABAQUS Version 6.3 software available at the Arctic Region Supercomputing Center at UAF (http://www.arsc.edu)[5]. ABAQUS Version 6.3 contains a library of solid elements for three dimensional applications. The library of solid elements in ABAQUS contains first and second order isoparametric elements. These isoparametric elements are generally referred for most cases because they are usually the most cost effective of the elements that are provided in the ABAQUS. The 20-node brick element has been used to model the DPPC girders for its improved inter-element compatibility.

Between DPPC girders, there are two types of connections: shear connectors (Figure 1) and intermediate steel diaphragms (Figure 2). The spacing of the connectors is typically 4 ft throughout the entire length of the structure. They are made of steel angles welded together by ¼" thick steel plates through the girder's top flange. These angles, 6 inches long in the longitudinal traffic direction, are embedded into the girder concrete through #4 steel reinforcement. The intermediate steel diaphragms are also made of steel angles, as shown in Figure 2. In the 3D FE model, 2-node hinge-connector elements were used to model shear connectors. And 3D truss elements were used to model the intermediate steel diaphragms, as shown in Figure 3. A sufficiently refined mesh was used to ensure that the results from ABAQUS simulation were adequate.

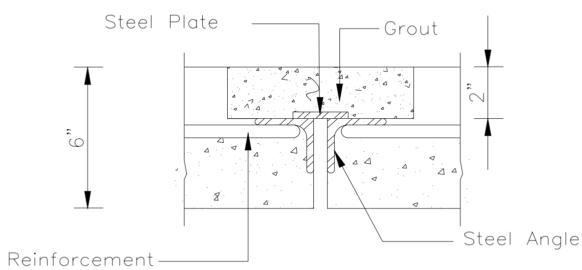

Fig. 1 Cross Section of the Shear Connector

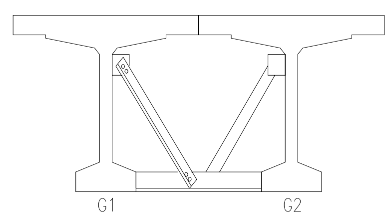

Fig. 2 Steel Diaphragms

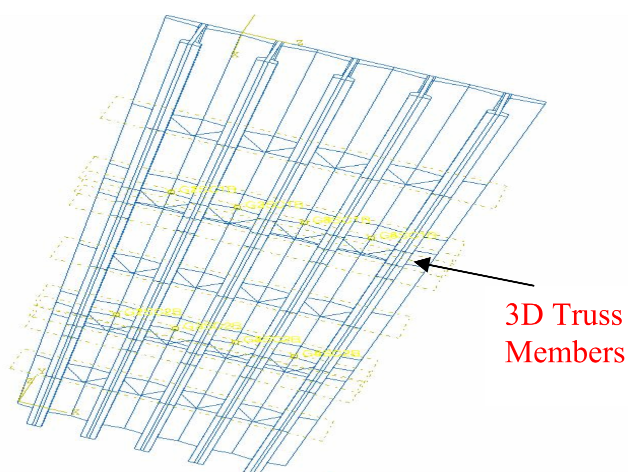

Fig. 3 Modeling Intermediate Steel Diaphragms

BOUNDARY CONDITIONS

The following assumptions were made in the 3D FE model. One end of the bride was assumed to be a roller support by restraining the bottom flange at the girder's end section in the vertical direction and in the transverse direction. The other end of the bridge was assumed to be a pin support by restraining all three directions. In modeling end diaphragms, two end sections of the girder were restrained in the transverse direction.

MODEL CALIBRATION

The 3D FE models were calibrated by a field testing program which included four sets of bridges, as shown in Table 1.

Table 1 Field Tested Bridges (From May 6 to May 19, 2003)[5]

Name		Bridge Geometry			Girder	
		Span(ft)	**Width(ft)**	**Skew(^{o})**	**Spacing(in.)**	**Depth(in.)**
Set 1	100th NB	116.0	37.0	0	88.4	54.0
	100th SB					
Set 2*	Dimond	110.0	107.0	0	90.6	54.0
	Dowling					
Set 3	Campbell NB	139.0	37.0	4.3	88.4	65.0
	Campbell SB					
Set 4	Huffman NB	128.0	37.0	27.5	72.0	54.5
	Huffman SB					

** Note: Tee shape girder in Set 2 instead of decked Bulb-Tee shape used in Set 1, 3, and 4.*

Full-bridge reusable strain transducers fabricated by Bridge Diagnostics, Inc. (BDI) were used in the field tests. Please refer to Reference 5 for detailed information about the field testing program. Comparisons of 3D FE model results with field tests are shown in Figures 4 to 7. The labeling system, such as "100th NB – 3 – G1", had been used in these figures. The first term indicates the name of the bridge being loaded while the second and third terms represent the longitudinal location and transverse location of the load. The bridge labels are as following: "100th NB", "100th SB", "Huffman NB", "Huffman SB", "Campbell NB", "Campbell SB", "Diamond" and "Dowling". Three labels define the longitudinal position of the load: "1" represents the shear loading position located a distance of H (height of the girder) away from the abutment; "2" represents the vehicle loading at ¼ span; and "3" represents the vehicle loading at midspan. The transverse position of the load is labeled by the girder ("G1", "G2", and so on) over which the majority of the load is positioned.

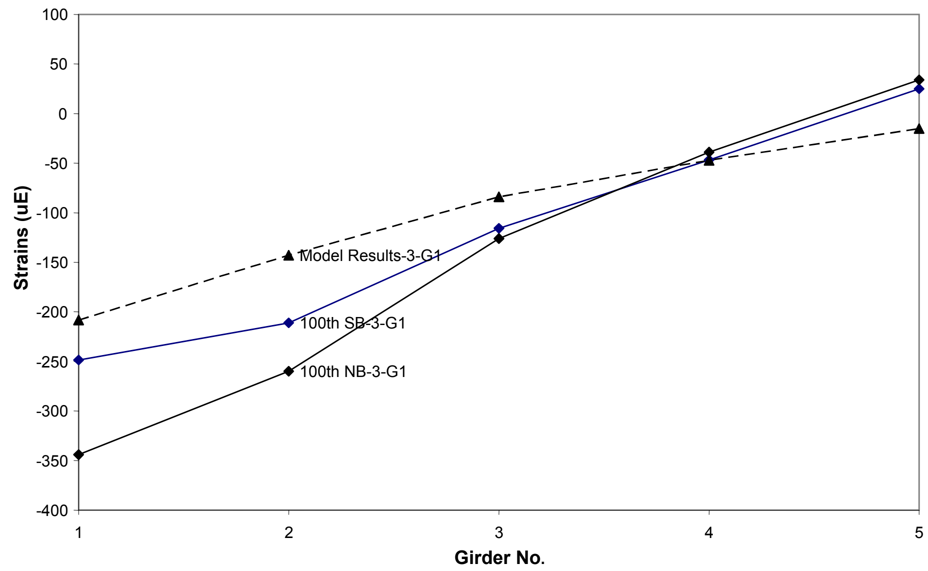

Fig.4 Comparison of Flexural Strains for 100^{th} Bridge

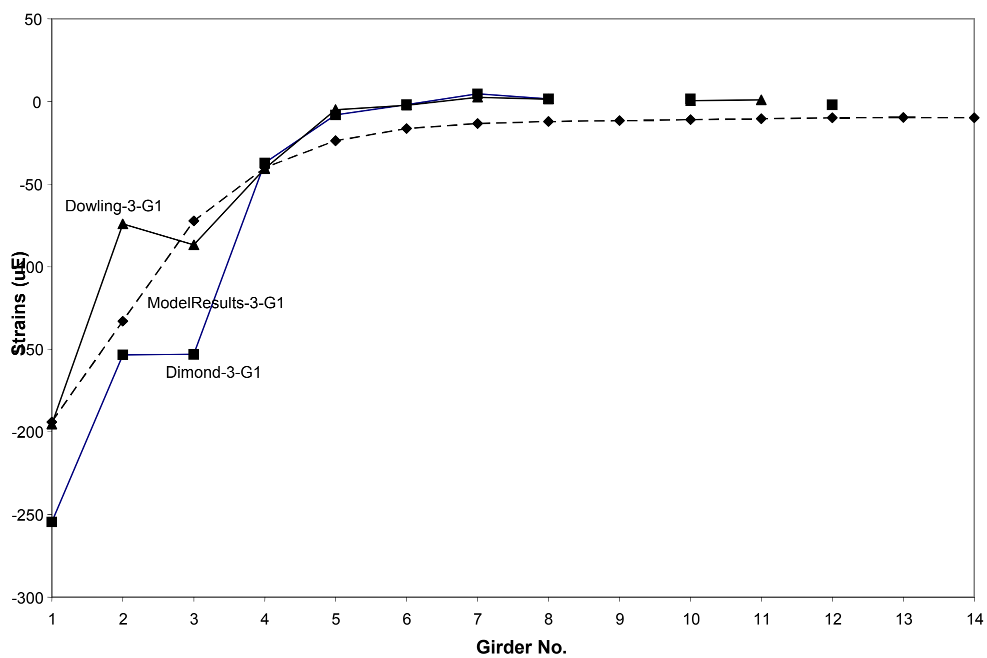

Fig. 5 Comparison of Flexural Strains for Dimond and Dowling Bridges

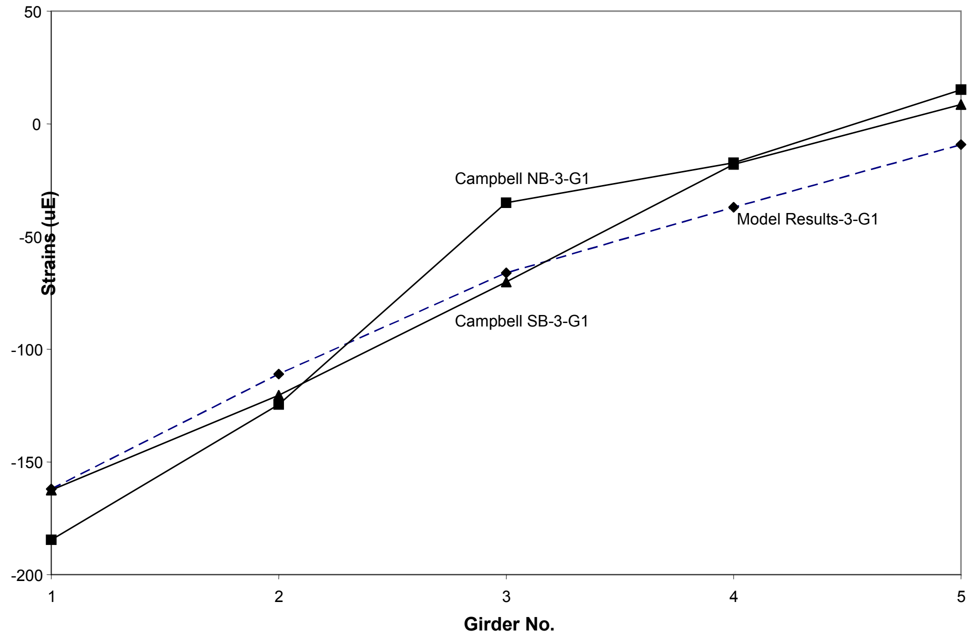

Fig.6 Comparison of Flexural Strains for Campbell Bridge

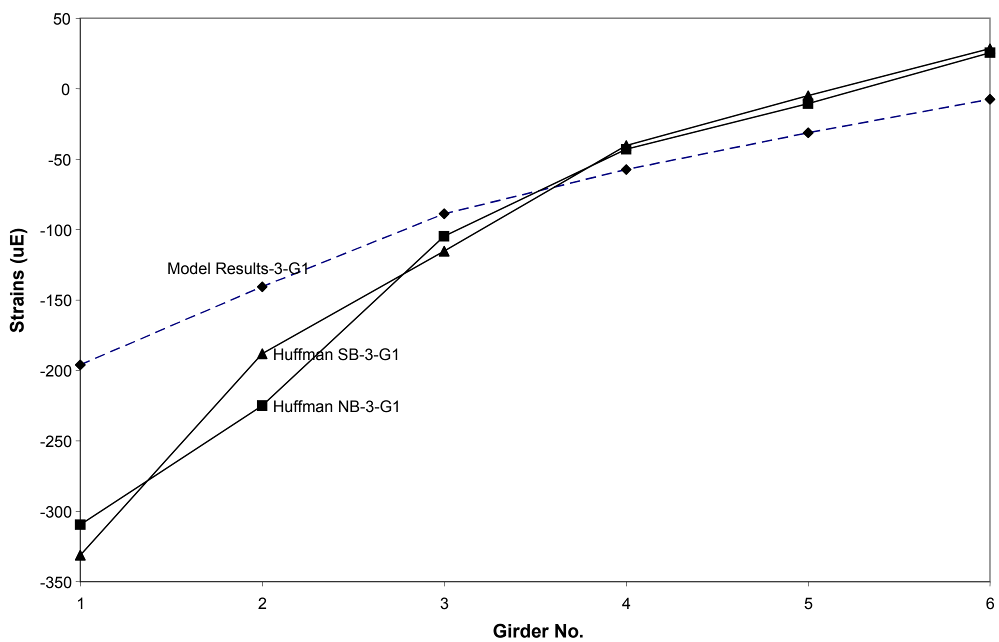

Fig. 7 Comparison of Flexural Strains for Huffman Bridge

The dotted line in these figures shows the model results while the continuous line shows the experimental results. The x-axis refers to the girder number while the y-axis refers to the flexure strains at the midspan of the girder. The strains are in the order of 10^{-3}. The experimental strains are directly tabulated from the BDI strain gages which were connected to the computer. The model strains are evaluated from the software. Negative strains refer to tension whereas positive ones refer to compression. Figures 4 to 7 show that 3D FE models match experimental results well.

PARAMETRIC STUDIES ON CONNECTIONS

Using the calibrated 3D FE models, parametric studies are performed to study the effect of shear connectors and intermediate diaphragms. Take the "100th NB" bridge as an example. This bridge has five DPPC girders, thus four longitudinal joints connecting five girders together. Each joint has 28 shear connectors which have the same detail as shown in Figure 1. This bridge has also five intermediate steel diaphragms uniformly distributed along the bridge span. In the parametric study, this case is named as "WISD". Other cases considered are one intermediate steel diaphragm located at midspan only (named as "WISD-Center") and no intermediate steel diaphragm in the bridge (named as "WOISD"). The number of shear connectors is also varied in the parametric study. After the model analysis is done on the original 28 connectors, alternate connectors are then removed which reduces the number of connectors to 14. Further reduction leads to 7 connectors in each longitudinal joint.

LIVE LOAD DISTRIBUTION

We calculated the live load distribution factor (DF) for moment by using the following method:

$$DF_{moment} = \frac{\varepsilon_x}{\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4 + \varepsilon_5}$$

where ε_x is the strain calculated directly under the loaded girder at the midspan; and ε_1 to ε_5 is the calculated flexure strain at midspan on each girder. Figure 8 shows the distribution factor for moment for different intermediate diaphragm cases ("WISD", "WISD-Center", or "WOISD") when the live load is positioned at "100th NB – 1 – G1". Because the load is close to the abutment, the impact of intermediate diaphragms on live load distribution is very small as shown in Figure 8.

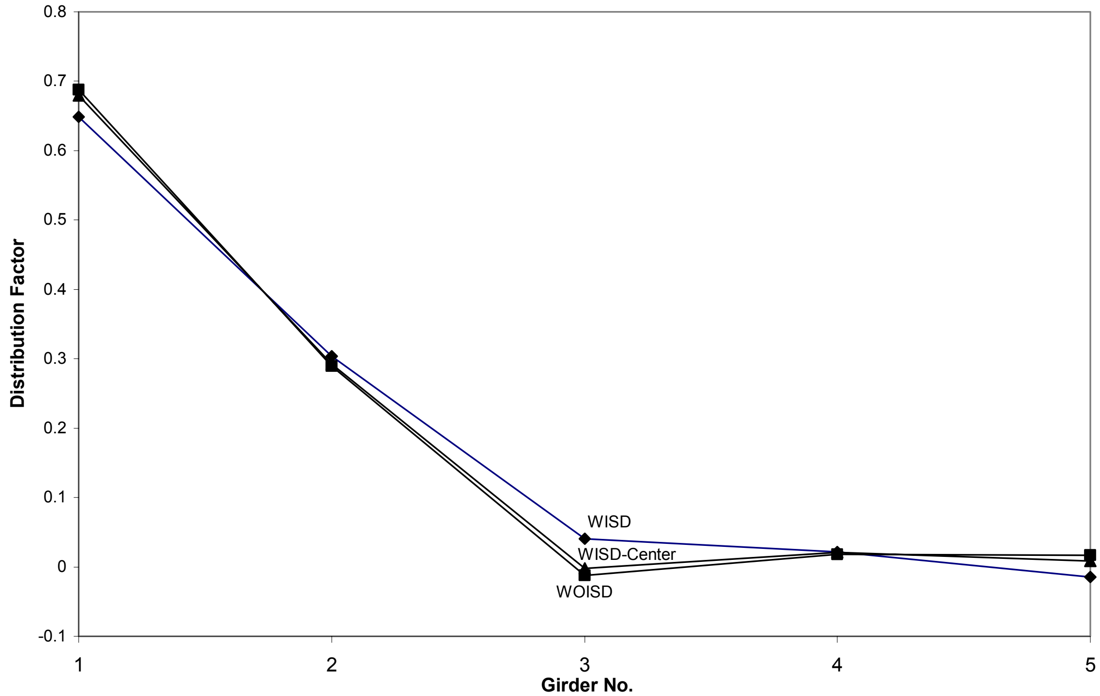

Fig. 8 Comparison of DF for Moment with Load at "100th NB – 1 – G1"

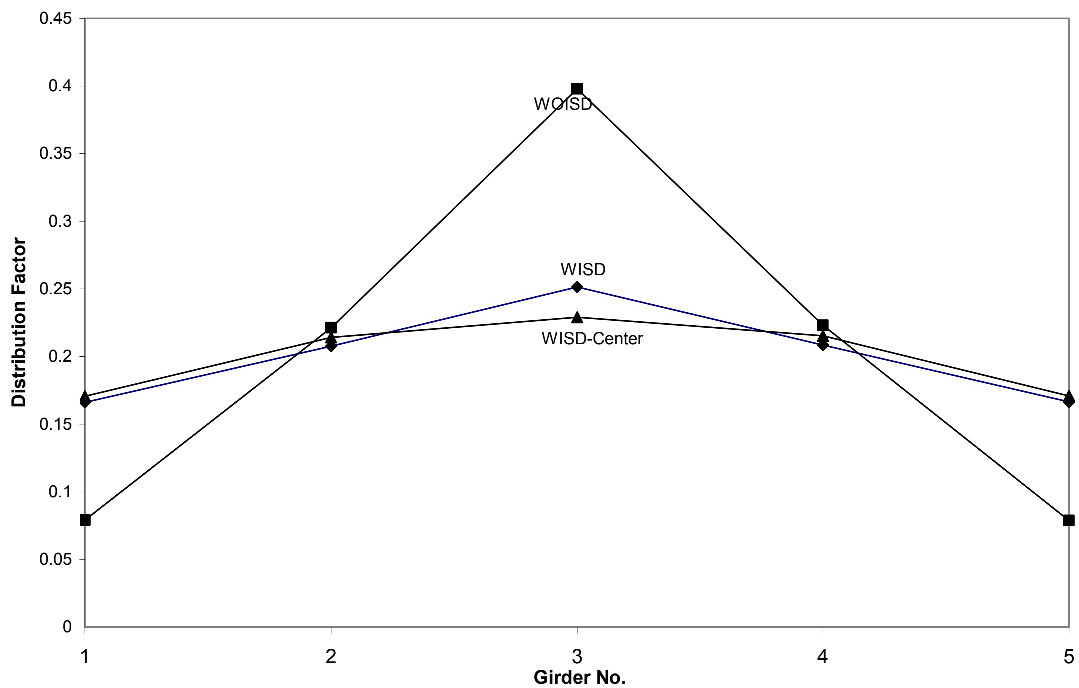

Fig. 9 Comparison of DF for Moment with Load at "100th NB – 3 – G3"

Figure 9 shows DFs for different intermediate diaphragm cases when the live load is positioned at "100^{th} NB – 3 – G3". As shown in Figure 9, the load distribution factor for moment for "WOISD" is higher than ones for "WISD" and "WISD-Center". The load is distributed more uniformly in bridges with "WISD-Center" than in bridges with "WISD". However, the difference between the two is very small.

Please note that there are 28 shear connectors in the longitudinal joints of bridges shown in both Figure 8 and Figure 9. Take the diaphragm case of "WOISD" as an example. Figure 10 shows that the impact of the number of shear connectors on the live load distribution is small. There is almost no change in distribution factors when the connector spacing is changed from 4 ft (28 connectors) to 8 ft (14 connectors).

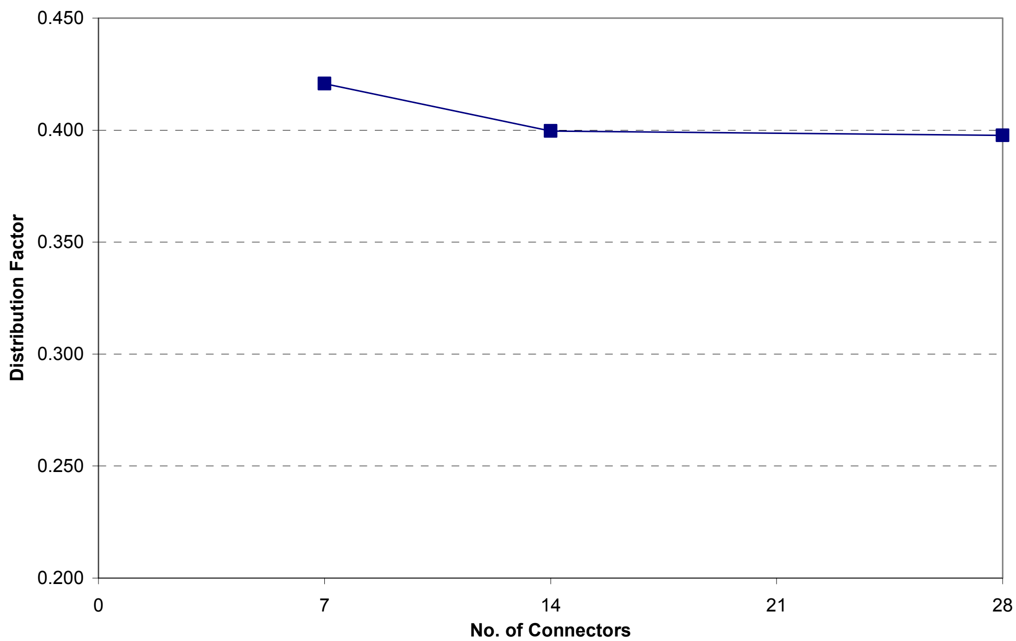

Fig. 10 Impact of Number of Shear Connectors on Distribution Factor

According to AASHTO LRFD Specifications[6], the live load DF for moment for single-lane is the same as one for double-lane. Figures 11 and 12 show the comparison of DFs for different load conditions and different intermediate diaphragm cases. In all cases studied, the distribution factor for single-lane loaded bridge is smaller than one for double-lane loaded bridges. This confirms the conclusions made in Reference 1.

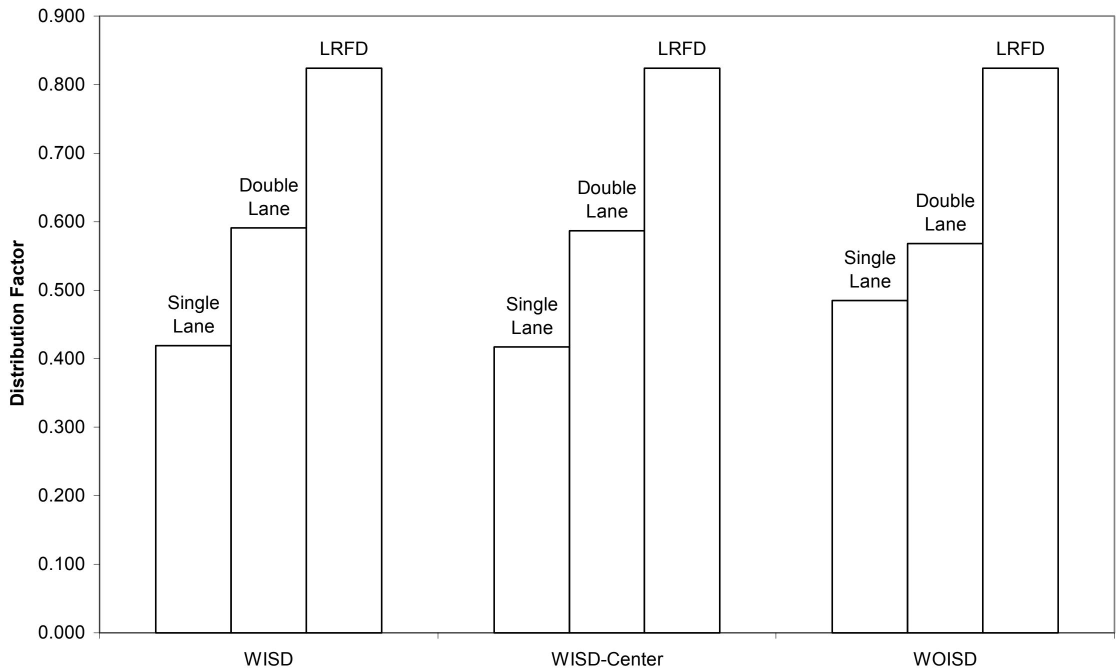

Fig. 11 Comparison of Distribution Factors for Load at "100th NB – 3 – G1"

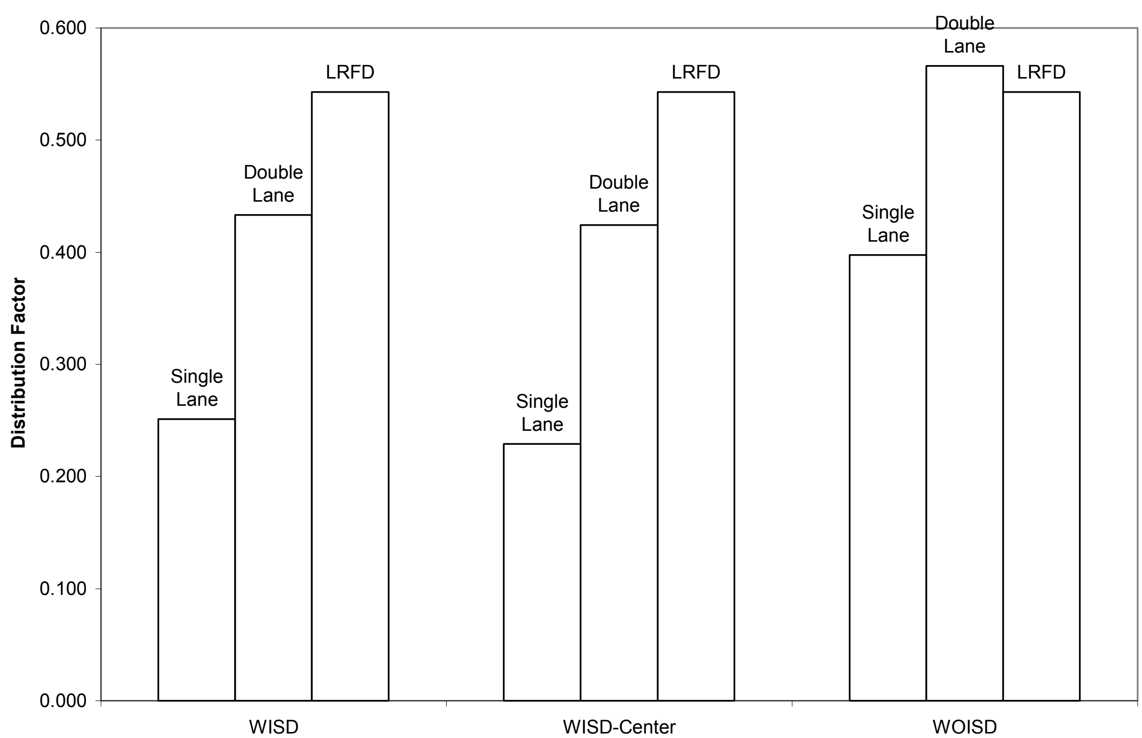

Fig. 12 Comparison of Distribution Factors for Load at "100th NB – 3 – G3"

CONNECTOR FORCES

The primary function of connections in service is to transfer shear forces between adjacent precast units so that lateral distribution of concentrated wheel loads to several units can occur. The connections also serve to carry any in-plane normal forces arising from torsional stiffness of the members, and to tie the structure together. Design of joints and connections between DPPC girders are determined by using rule-of-thumb methods and historical performance, rather than by rational analysis. Because of this lack of design methods, sizes and spacing of connectors vary significantly. The shape and size of the grouted shear key also vary significantly. In order to develop a connection design criteria for DPPC girders, pilot tests had been carried out in Reference 2 to investigate the following parameters: (1) location of connector hardware in the thickness of the slab; (2) the weight of the connector hardware; and (3) the size and shape of the grout key. Experiments were also conducted to test the welded connectors both acting alone and with a grout key. Based on that study, the strength of the grouted and ungrouted welded connectors was proposed for the selected shape of the grout key and the selected connector detail. However, forces in connectors between members caused by wheel loads were not studied in that study. These forces are needed for design of shear connectors.

Using the calibrated 3D FE models, parametric studies are performed in this study to fill the gap. By using 3D FE modeling, connector forces in the three directions can be calculated: two forces in the plane of the bridge deck and one force perpendicular to the deck surface. Two in-plane forces are named as "Horizontal Shear Force" (parallel to the longitudinal joint) and "In-Plane Normal Force" respectively. The force perpendicular to the deck surface is named as "Vertical Shear Force". Again, take the 100th NB bridge as an example. This bridge has five girders (G1 to G5). The longitudinal joint between G1 and G2 is referred to as "G1-G2". The other three joints are labeled as "G2-G3", "G3-G4", and "G4-G5" respectively. When the live load is placed at "100th NB – 3 – G1", Figure 13 shows the impact of intermediate diaphragms on the distribution of horizontal shear forces in connectors. Please note that the "x-axis (horizontal axis)" in Figure 13 represents the location of the 28 connectors along the longitudinal joint (G1-G2). For example, "10" in the "x-axis" means that the tenth connector is located about 40 ft ("10" x 4 = 40) from the end of girder. Thus, the "14th" connector is located at the midspan of the bridge. As shown in Figure 13, horizontal shear forces in the connectors are not uniform along the joint. In the case of "WOISD", there exists a high torsion force in the connectors. Adding intermediate diaphragms tends to reduce the difference of horizontal shear forces in the joint.

When the live load is placed at "100th NB – 3 – G1", the connector force distributions along the different joints in the case of "WOISD" are shown in Figures 14 and 15. When the load is placed over "G1", horizontal shear forces of connectors in the joint "G1-G2" are higher than ones in the joint "G4-G5" (Figure 14). The vertical shear forces are much higher when connectors are close to the loads (Figure 15). If we move the load to "100th NB – 3 – G3", we find the same trend from Figures 16 and 17.

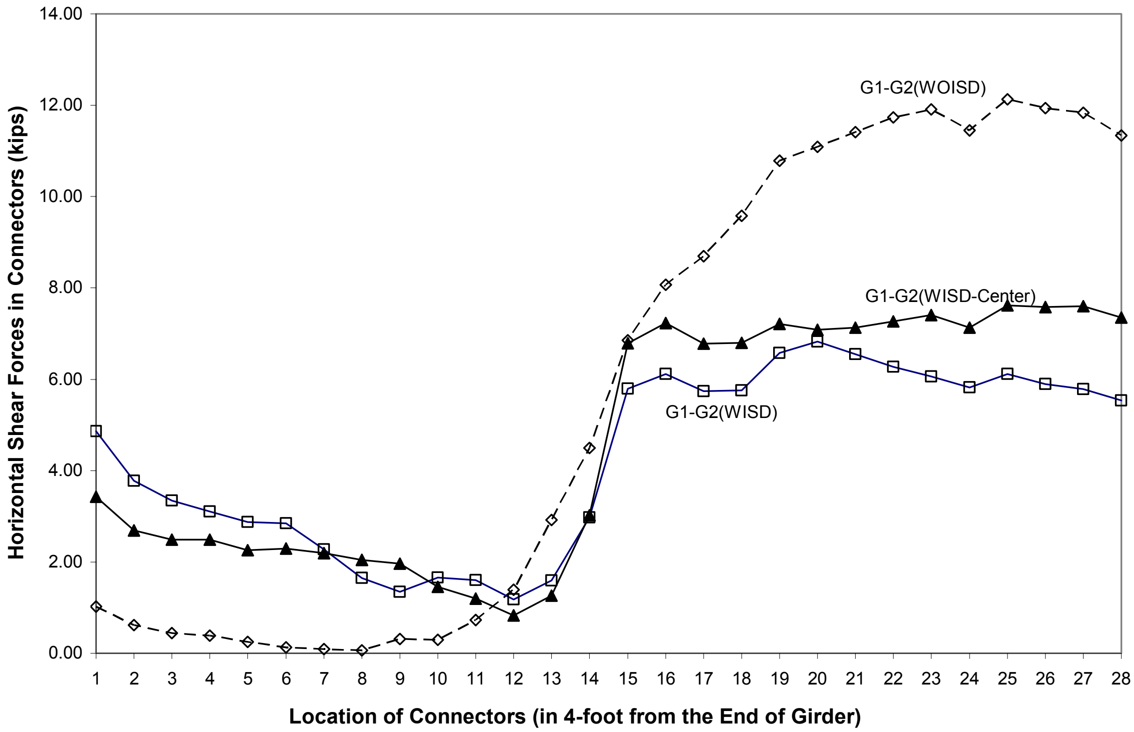

Fig. 13 Impact of Intermediate Diaphragm (“100th NB – 3 – G1”)

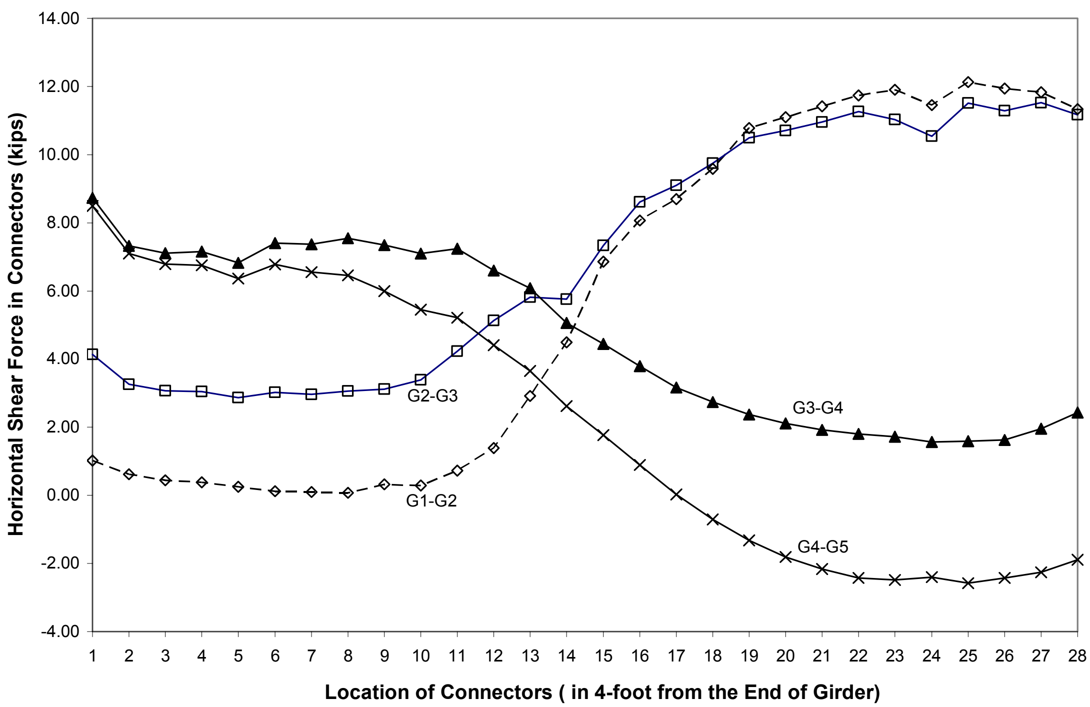

Fig. 14 Distribution of Horizontal Shear Forces in Connectors (“100th NB – 3 – G1”)

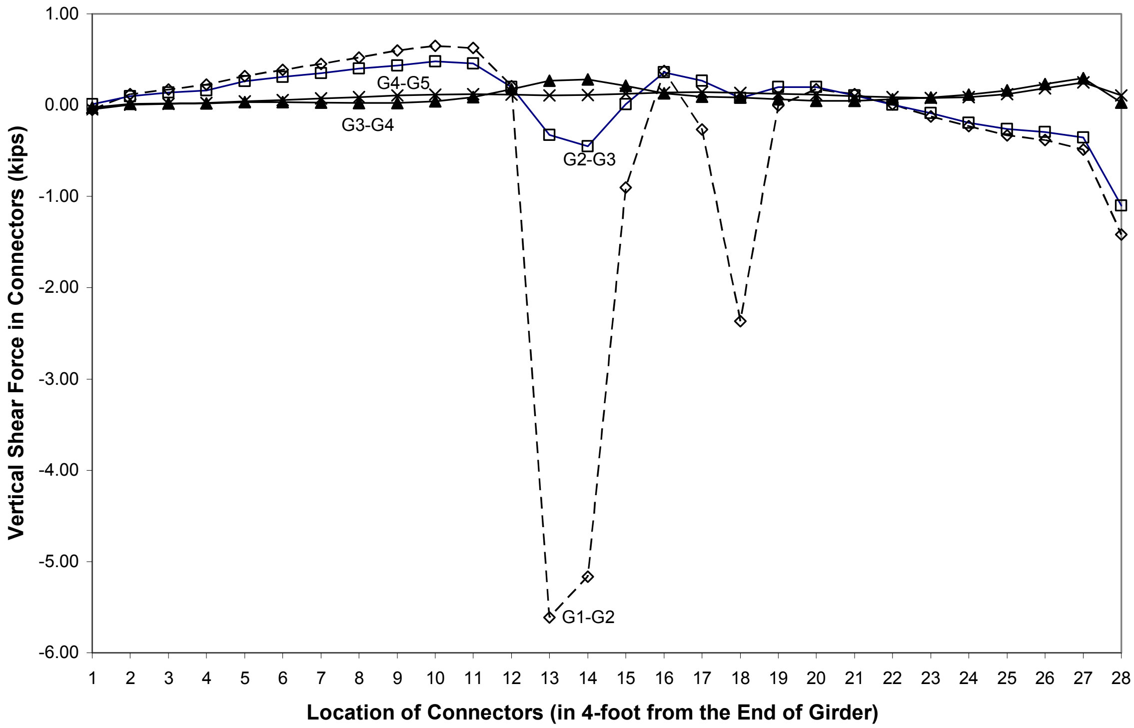

Fig. 15 Distribution of Vertical Shear Forces in Connectors ("100th NB – 3 – G1")

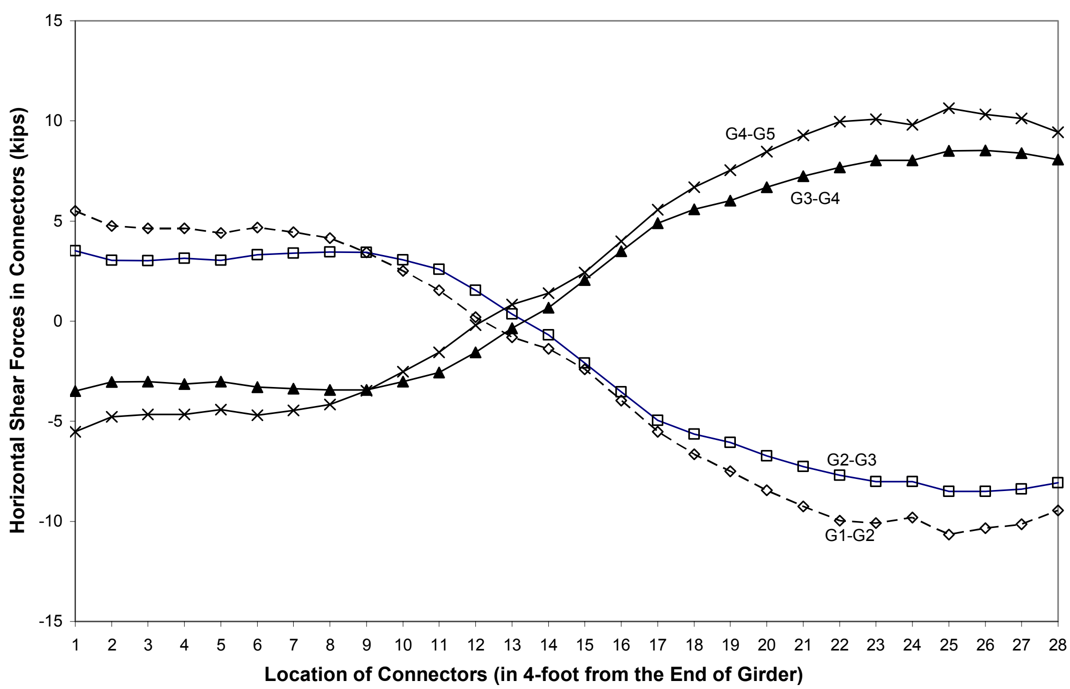

Fig. 16 Distribution of Horizontal Shear Forces in Connectors ("100th NB – 3 – G3")

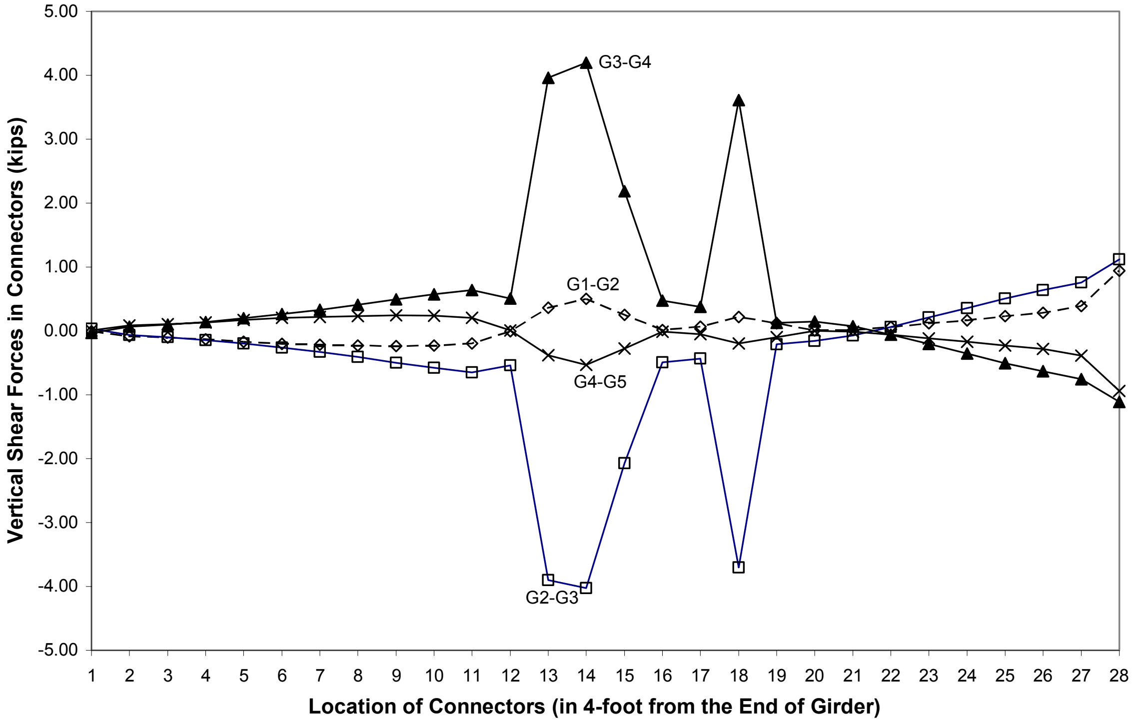

Fig. 17 Distribution of Vertical Shear Forces in Connectors ("100th NB – 3 – G3")

Figures 13 to 17 indicate that connector forces in the three directions are changing with load positions and intermediate diaphragms. It is important to study the maximum connector forces in the three directions to develop connector design criteria. Figure 18 shows the maximum horizontal shear force. In the figure, bars with continuous thin-lines, dotted lines, and continuous heavy-lines represent results for bridges with "WOISD", "WISD", and "WISD-Center" diaphragm cases respectively. A total of four different load positions are shown in Figure 18. For the same load position and the same diaphragm case, there are three bars with "28", "14", and "7" representing 28, 14, and 7 connectors in each longitudinal joint respectively. Take the bridge with "WOISD" and 28 connectors in each joint for example. The maximum horizontal shear force in the connector is 5.6 kips when the load is located at "100th NB – 1 – G1", 12.1 kips when at "100th NB – 3 – G1", 6.0 kips when at "100th NB – 1 – G3", and 10.7 kips when at "100th NB – 3 – G3". For the same bridge, if we increase the connector spacing from 4 ft ("28"-connector case) to 16 ft ("7"-connector case), the maximum horizontal shear force in the connector will be increased to 10.6 kips, 38.9 kips, 10.0 kips, and 31.6 kips for the same four load-positions. That is, the maximum horizontal shear force increases with the increase of connector spacing. Similar to Figure 13, the intermediate diaphragms reduce the maximum horizontal shear force for all connector cases.

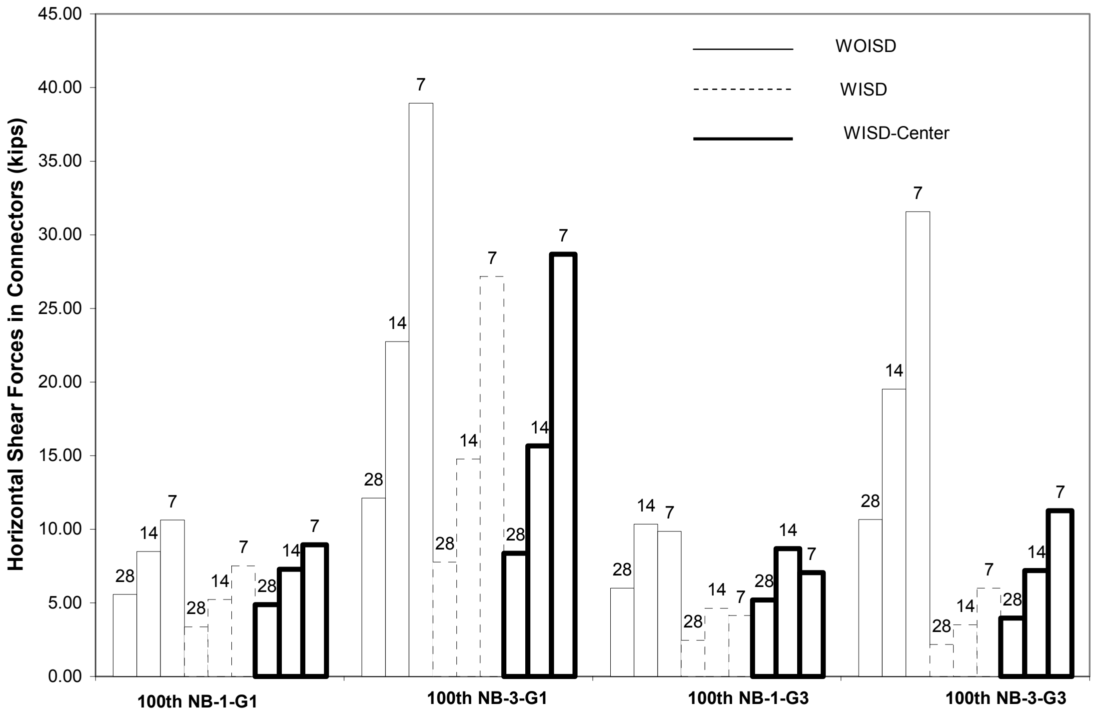

Fig. 18 Comparison of Maximum Horizontal Shear Forces in Connectors

Similar to Figure 18, the maximum vertical shear force and In-Plane normal tensile-force are shown in Figures 19 and 20. These two forces do not necessarily increase with the increase of the connector spacing. As expected from Figures 15 and 17, they are strongly influenced by the location of connectors with respect to the location of the wheel load. Connectors next to the wheel loads tend to have a higher vertical shear force and in-plane normal force.

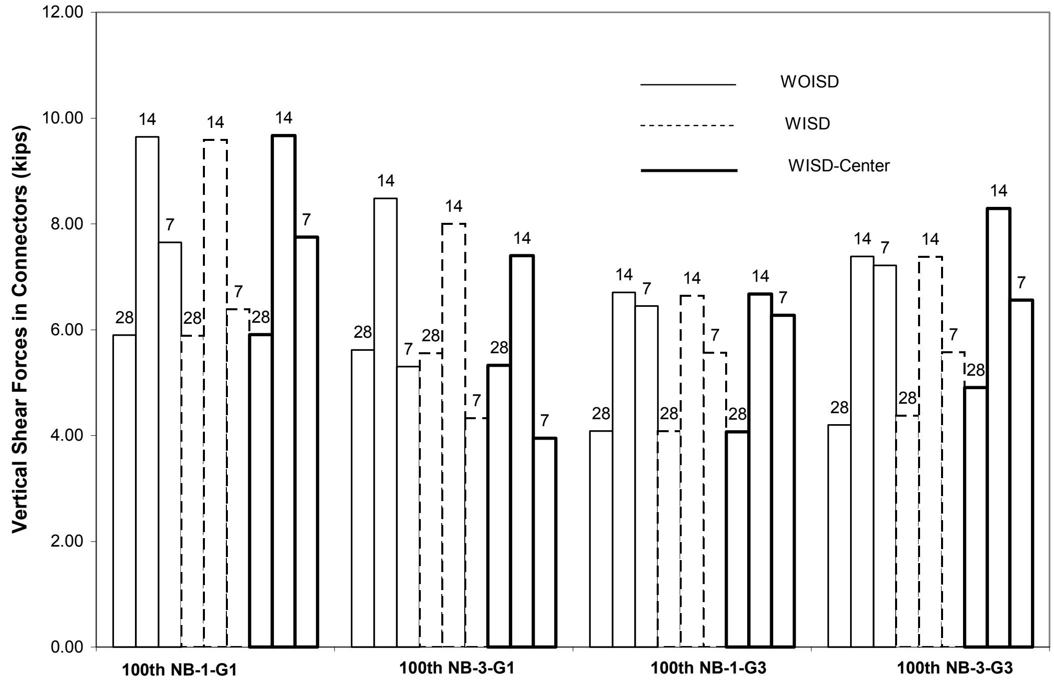

Fig. 19 Comparison of Maximum Vertical Shear Forces in Connectors

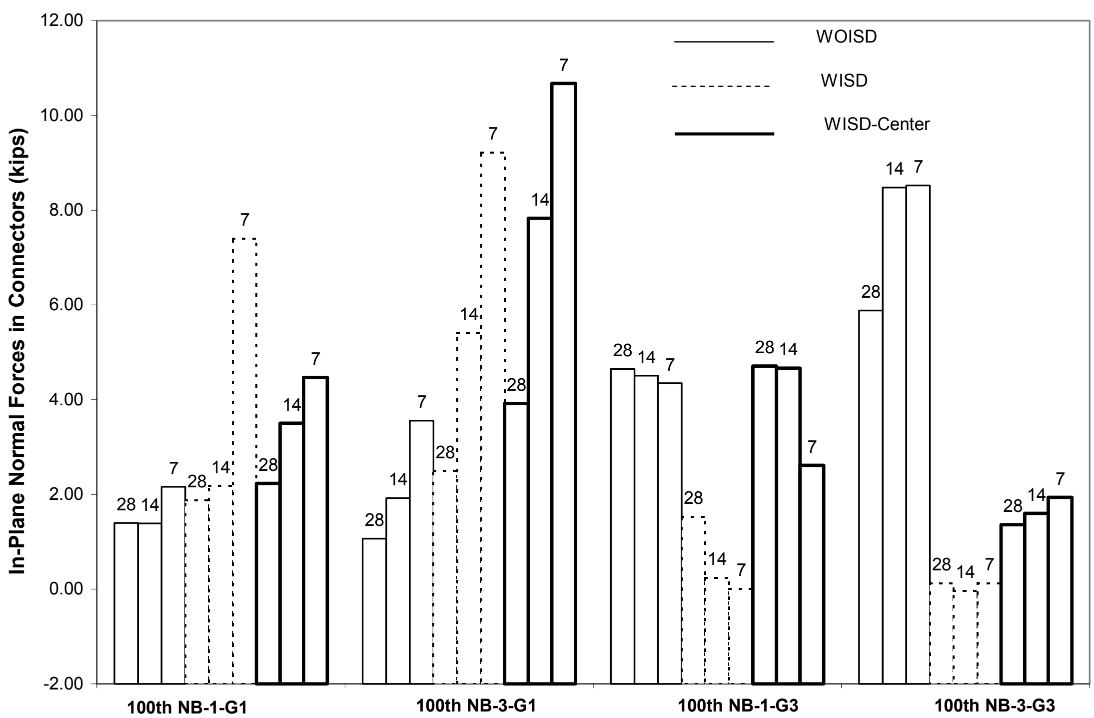

Fig. 20 Comparison of Maximum In-Plane Normal Forces in Connectors

From Figure 18, we know that the maximum horizontal shear force increases with the increase of the connector spacing in the joint for all different load positions. Take the bridge with the load positioned at "100th NB – 3 – G3" for example. This bridge has four longitudinal joints. Add the horizontal shear forces in connectors in the same joint to get the total horizontal shear force in that joint. As shown in Figure 21, the summation of the horizontal shear force in connectors for the same intermediate diaphragm case remains constant irrespective of the number of connectors in the joint. The similar conclusions can be found for the vertical shear force and in-plane normal force in connectors from Figures 22 and 23.

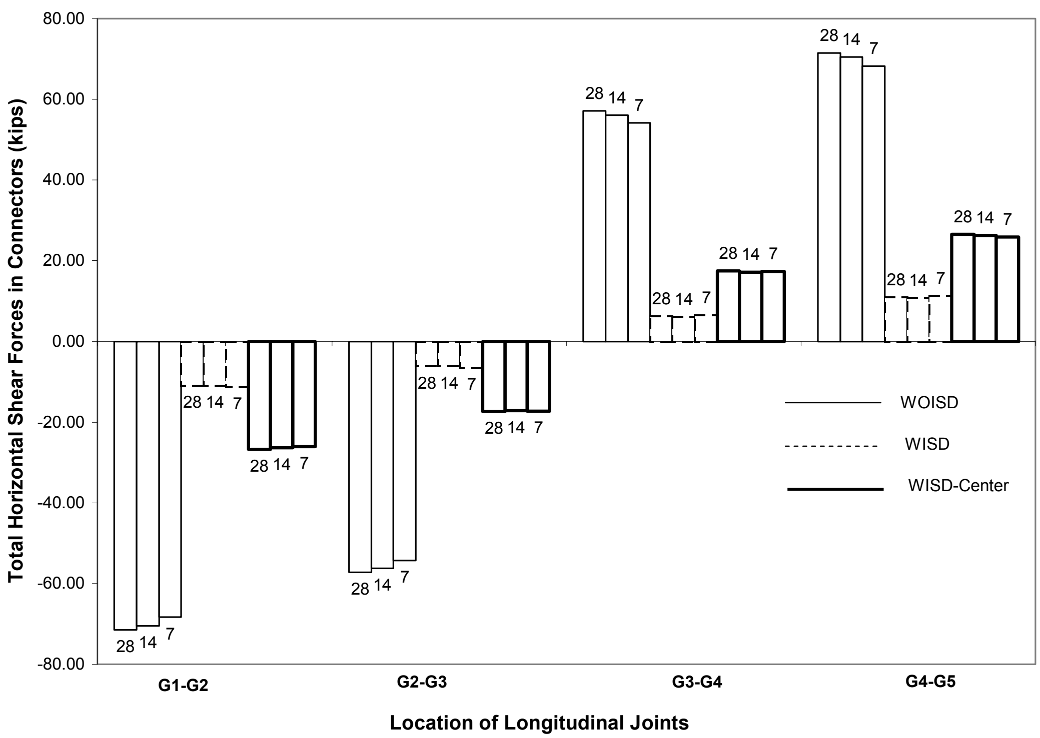

Fig. 21 Comparison of Total Horizontal Shear Forces in Connectors ("100th NB – 3 – G3")

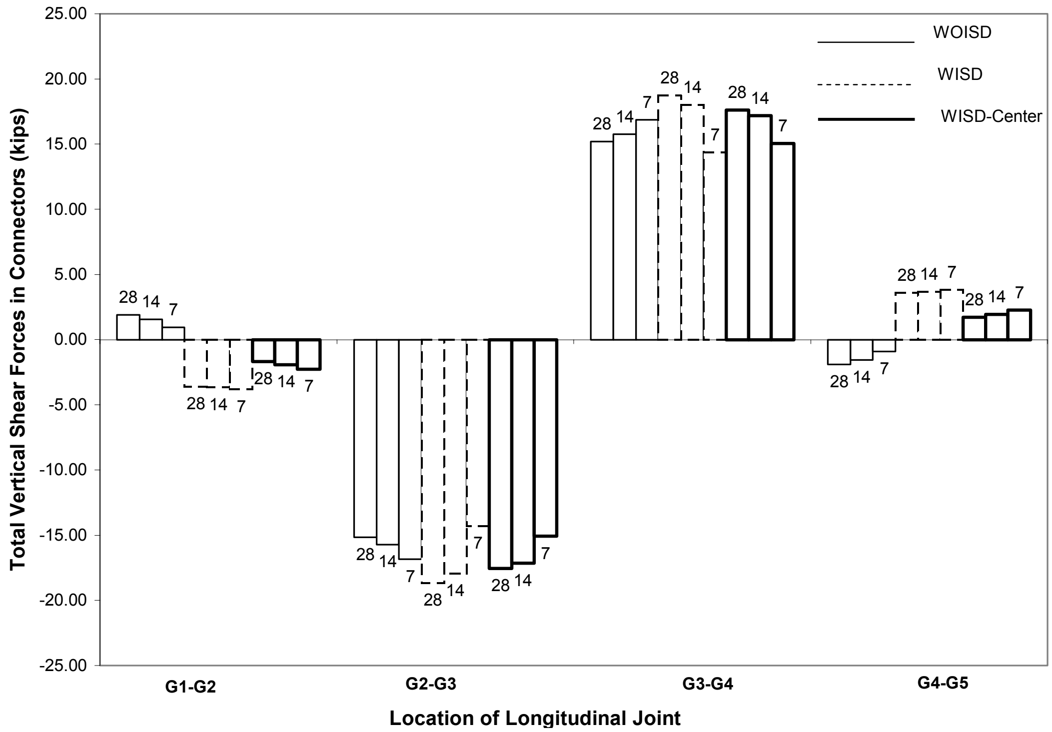

Fig. 22 Comparison of Total Vertical Shear Forces in Connectors ("100th NB – 3 – G3")

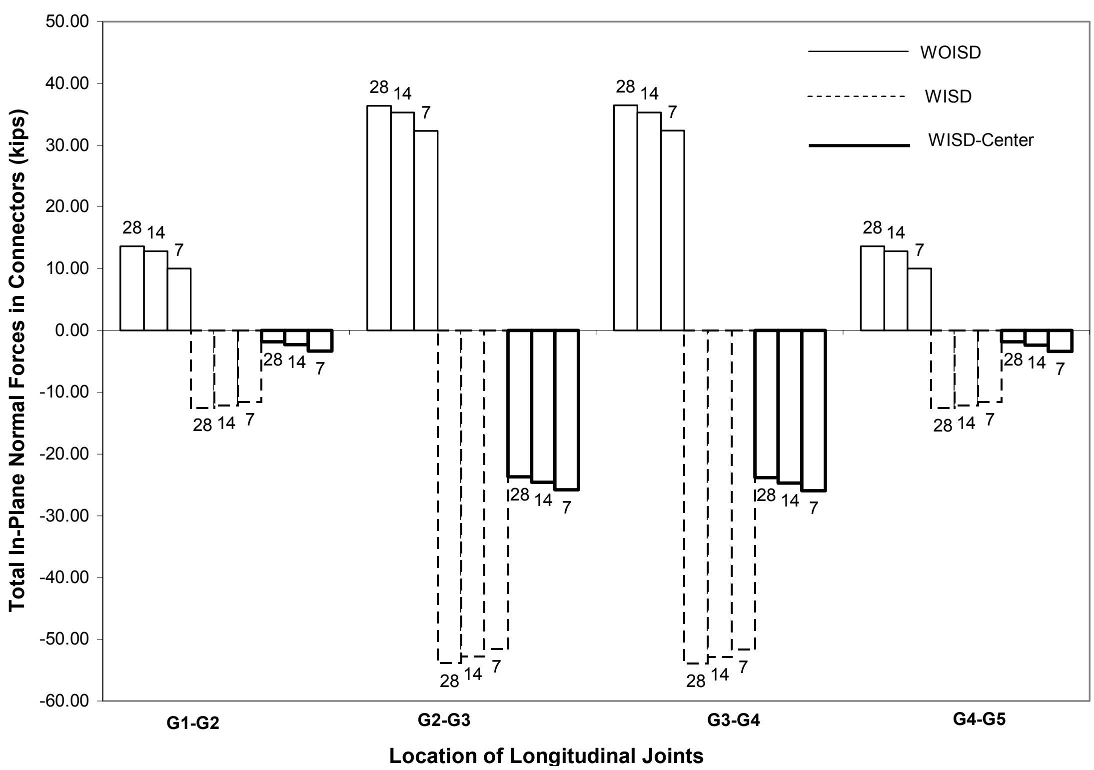

Fig. 23 Comparison of Total Normal Forces in Connectors ("100th NB – 3 – G3")

CONCLUSIONS

Using the calibrated 3D FE models, parametric studies are performed to study the effect of shear connectors and intermediate diaphragms. The following conclusions can be drawn from the study:

1. In all cases studied, the live load distribution factor (DF) for a single-lane loaded bridge is smaller than one for a double-lane loaded bridge. The relative articles in the AASHTO LRFD Specifications need to be revised.
2. The DF for bridges without any intermediate diaphragms is higher than one for bridges with intermediate diaphragms.
3. When bridges with one intermediate diaphragm at midspan only are compared with bridges with five uniformly distributed diaphragms the difference in DFs is very small.
4. The spacing of shear connectors plays a very small role in the live load distribution.
5. Connector forces caused by wheel loads are not uniform along the longitudinal joint. Adding intermediate diaphragms tends to reduce the difference among horizontal shear forces in connectors.
6. The maximum horizontal shear force increases with the increase of the connector spacing. Intermediate diaphragms reduce the maximum horizontal shear force in connectors.
7. The maximum vertical shear force and in-plane normal tensile-force in connectors do not necessarily increase with the increase of the connector spacing. They are strongly influenced by the location of connectors with respect to the location of the wheel load. Connectors next to the wheel loads tend to have a higher vertical shear force and a higher in-plane normal force.
8. The summation of connector forces in each direction along the longitudinal joint remains constant irrespective of the number of connectors in the joint.

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