THE EFFECT OF SKEWNESS ON LIVE LOAD REACTIONS AT PIERS OF CONTINUOUS PRESTRESSED CONCRETE SKEWED BRIDGES

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ABSTRACT

This paper presents a study on the skewness effect on live load reactions at piers of prestressed concrete bridges. Finite element modeling and analysis were performed on selected prestressed concrete BT-72 bridges with various skew angles. The bridges were analyzed for the live load reactions at piers and live load shear at the beam ends. The comparison of live load reactions and shear revealed that the distribution factor for reaction at piers was higher than that of shear at beam ends near the same support location. The increase in reaction distribution factor was more significant than that in shear distribution factor on the interior beam line when skew angle was greater than 30 degrees. It is recommended that more research be performed for the distribution factor for live load reaction to quantify the responses.

KEYWORDS: Distribution Factor, Shear, Reaction, Skew Angle, Live load, Finite Element Analysis

INTRODUCTION

Currently, the lateral distribution factors for live load moment and shear are determined using the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Specifications[1]. In the AASHTO LRFD Bridge Design Specifications, it requires that shear in the exterior beam at the obtuse corner of the bridge be adjusted when the line of support is skewed. The specifications provide correction factors for this adjustment and require that the correction factors be applied to all beams in the cross-section. The commentary to the specifications states that the proscribed corrections are conservative. The current AASHTO Specifications do not address any specific modification for live load reactions in skewed continuous bridges. As a result, the skew effect on reactions at piers of skewed continuous bridges is determined either by using the skew correction factor for shear or by using no skew correction factor.

It has been observed in some studies that the reactions at piers in a skewed continuous bridge are amplified and the skew correction factors for reactions are unique from those for beam shear[2,3]. The researchers at Modjeski and Masters, Inc. conducted research on shear in skewed multi-beam bridges in the NCHRP Project 20-7/Task 107[2]. They found that skew correction factor for reactions at the piers of continuous bridges are present and are different from those calculated from shear at the piers. The effects of the obtuse and acute corners on the girder shear on opposite sides of the bearings do not eliminate the need for a correction factor for reaction. Their study recommended that further research be performed to investigate the skew correction factors for reactions at the piers of continuous bridges.

Because most of the modern bridges are continuous, skewed, or both, use of incorrect estimation of live load reactions would lead to somewhat incorrect design for bridge substructures, such as pier caps and piers. Underestimating the live load reactions could cause the design to be unsafe and would directly affect the performance and service life of bridge substructures. On the other hand, overestimating the live load reactions could increase the cost of bridge substructure unnecessarily. Although extensive studies have been conducted for the skew effect on live load shear distribution, very little research has been done on the effect of bridge skewness on reactions of continuous bridges. The objective of this research was to investigate the effect of bridge skewness on live load reactions at supports of continuous bridges. The bridge design community has interests to learn how the live load reactions being affected by the skewness of bridges and to understand the difference between skew corrections for shear and reactions

INFORMATION ABOUT SELECTED BRIDGES

The bridges studied are two-span prestressed concrete Bulb-Tee girder bridges. Fig. 1 shows the typical cross section of the bridges. The skew angle of the bridges varies from 0 to 60 degrees with a 15-degree increment, and a total of five bridges are studied. Fig. 2 shows the plan view of the bridges of varied skew angles.

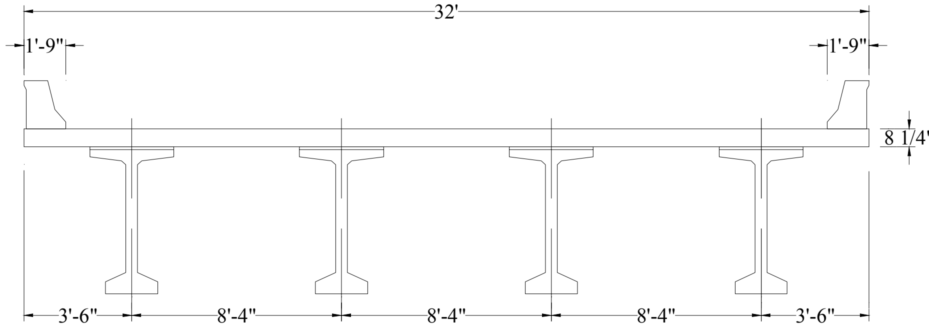

Fig. 1. Typical Cross Section of Prestressed Concrete Bulb-Tee Girder Bridge

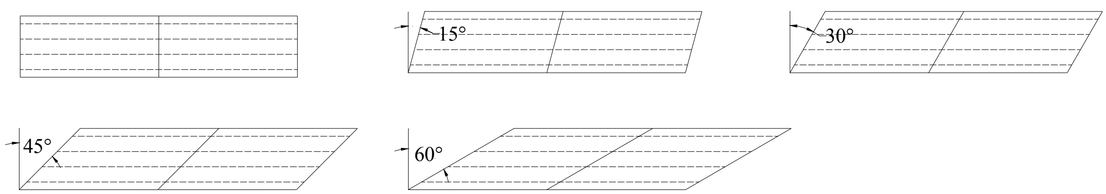

Fig. 2. Plan View of Skewed Bridges Studied

ANALYSIS OF SELECTED BRIDGES

BRIDGE MODELING

SAP 2000 Structural Analysis software was used to determine the response of bridge structures due to vehicle live loads. Bridge superstructures were typically modeled with frame elements of composite beam sections. Shell elements were used to model the transverse members that connected the beams to form an integrated superstructure. These shell elements contributed to the transverse stiffness of the structure, but were not considered for the effect of vehicle live load.

The frame element uses a general three-dimensional beam-column formulation, which includes the effects of biaxial bending, torsion, axial deformation, and biaxial shear deformations. The cross-section of frame element is defined as a non-prismatic, steel-concrete composite section. The non-prismatic formulation allows the element length to be divided into any number of segments over which properties may vary. The shell element is a three- or four-node formulation that combines separate membrane and plate-bending behavior. The membrane behavior uses an isoparametric formulation that includes translational in-plane stiffness components and a rotational stiffness component in the direction normal to the plane of the element. The plate bending behavior includes two-way, out-of-plane, plate rotational stiffness components and a translational stiffness component in the direction normal to the plane of the element.

Support conditions were defined using hinge at the beginning of the bridge and rollers at the other supports. A hinge was modeled by restraining all three translational degrees of freedom, e.g. UX, UY, and UZ. A roller was modeled by restraining only the UY and UZ degrees of freedom, which allowed translation in only the global X direction, the longitudinal direction of the bridge.

LOADING ON BRIDGES

The live load applied to the bridges under consideration was an AASHTO Standard HS20-44 truck, also referred to as an HL-93 truck in the AASHTO LRFD Specifications. This vehicle is shown in Fig. 3. For a beam line analysis, which consisted of one longitudinal beam line from the bridge superstructure, a single truck was positioned longitudinally so that the maximum response of shear and reaction could be obtained. These values were later used to determine the live load distribution factor associated with the response in question.

The bridge was loaded with a series of two-truck moving loads. The maximum responses of interior and exterior girders were determined by placing the trucks at various locations in the transverse directions until the maximum response was obtained. The fixed-spacing vehicles were applied on the bridges to simplify the live load placement because live load distribution factors were relatively insensitive to vehicle spacing (Patrick, et al. 2006). An example of the transverse vehicle spacing is shown in Fig. 4.

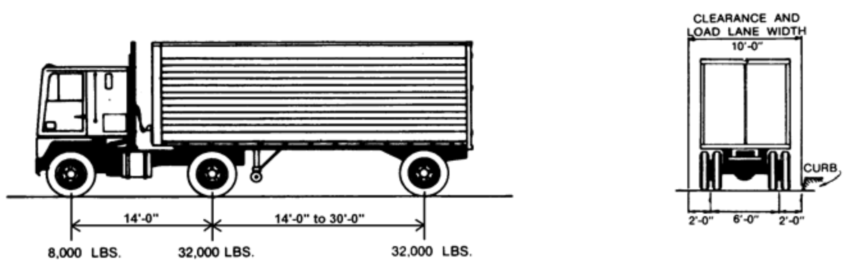

Fig. 3. AASHTO Standard HS20-44 Truck (HL-93 Truck)

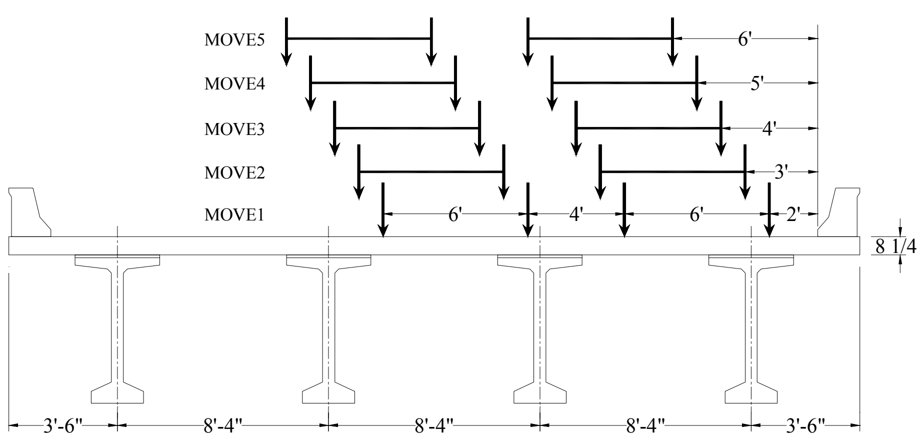

Fig. 4. Loading Positions for Two Lanes Loaded

RESULTS OF ANALYSIS

Reaction forces due to truck loads were obtained at the locations shown in Fig. 5. Distribution factors of reactions at supports A1 through B3 were determined by dividing the maximum reaction responses from bridge analysis by the maximum reaction from single beam line analysis at the corresponding location. Table 1 shows the distribution factors of reaction at supports. For the exterior beam line, according to the results in Table 1, the reaction distribution factor at the acute corner A1 decreased as the bridge skew angle increased, varying from 0.680 to 0.565. At the end of the bridge, the reaction distribution factor at obtuse corner A3 increased with the increase of skew angle, varying from 0.680 to 0.824. At the pier support A2, the reaction steadily increased as the skew angle increased. A similar trend was observed for the reactions at B1 through B3 on interior beam line.

The maximum response of live load shear typically occurred at beam ends. The shear distribution factors at the beam end of studied locations are shown in Table 2. For the exterior beam, as skew angle increased from 0 to 60 degrees, the shear distribution factor at the acute corner decreased while the one at the obtuse corner increased. For example, on beam A2-A3, the shear distribution factor at acute corner A2 decreased from 0.691 down to 0.577 and that at obtuse corner A3 increased from 0.674 up to 0.824. The shear distribution factors at interior beam-ends followed the similar trends as the ones at exterior beam-ends.

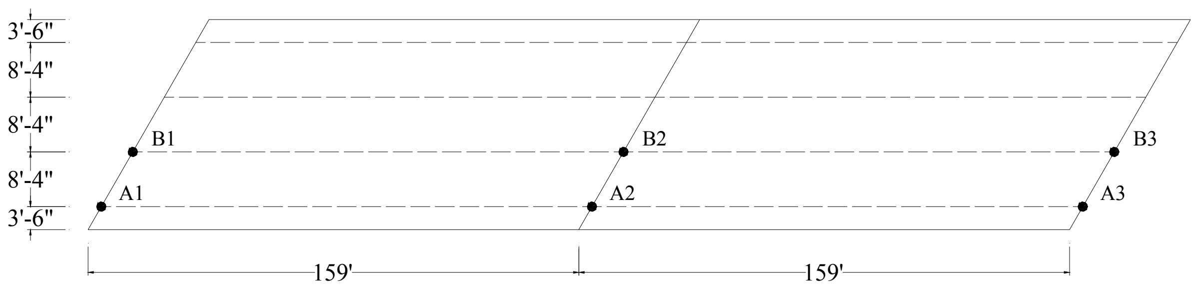

Fig. 5. Locations of Bridge Supports Studied

Table 1 Distribution factor for Reaction at Supports

Skew angle (deg)	A1	A2	A3	B1	B2	B3
0	0.680	0.689	0.680	0.891	0.936	0.891
15	0.663	0.716	0.699	0.841	0.989	0.892
30	0.639	0.754	0.712	0.802	1.026	0.914
45	0.610	0.816	0.753	0.770	1.120	0.942
60	0.565	0.886	0.824	0.733	1.223	0.946

Table 2 Distribution Factors of Shear at Beam Ends (Exterior Beams & Interior Beams)

Skew angle (deg)	A1	$A2_{left}$	$A2_{right}$	A3	B1	$B2_{left}$	$B2_{right}$	B3
0	0.674	0.691	0.691	0.674	0.891	0.748	0.748	0.891
15	0.663	0.710	0.670	0.691	0.841	0.856	0.745	0.892
30	0.639	0.715	0.653	0.695	0.802	0.882	0.736	0.909
45	0.610	0.758	0.624	0.739	0.770	0.927	0.708	0.933
60	0.565	0.794	0.577	0.824	0.733	0.969	0.602	0.946

COMPARISON STUDY

The distribution factors of shear and reaction at the same location were compared to study the difference between shear and reaction. Fig. 6 shows the distribution factor for reaction and shear at abutment A1 versus skew angle. The distribution factors of reactions were the same as the ones of shear at beam ends for any skew angle. Similarly, the distribution factors of reactions at the obtuse corner abutment were the same as the distribution factor for shear.

The distribution factors of reaction and shear at piers are shown in Figs. 7 and 8. It can be observed in both figures that the distribution factors of reactions at piers were higher than those of shear near the piers. Furthermore, the reaction distribution factor at the *interior pier* (the pier on the interior beam line) was consistently higher than the shear distribution factor even at skew angle of zero degree. As mentioned in the previous section, the shear distribution factor increased at the obtuse corner and decreased at the acute corner. When compared the reaction with the larger shear at the obtuse corner, the reaction distribution factors increased faster than the shear distribution factors at *interior pier* and *exterior pier* (the pier on the exterior beam line) with the increase of skew angle. The results indicated that the increase in reaction distribution factor became more significant than that in shear as skew angle increased. To eliminate the difference in shear due to geometric condition, the average values of shear distribution factors were calculated and used to compare with the reaction distribution factors. It is clear that the reactions at piers in a skewed continuous bridge were amplified as skew angle increased.

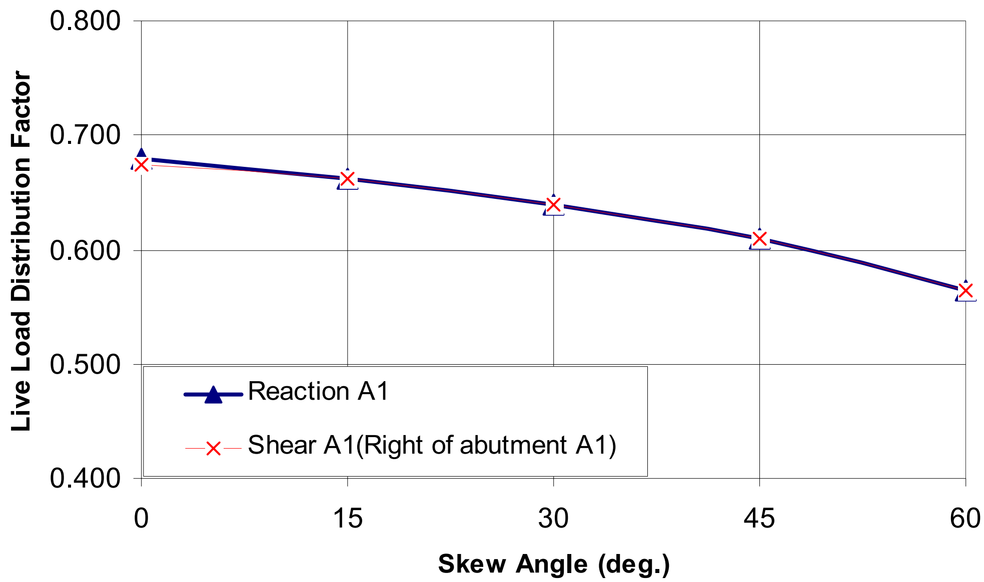

Fig. 6. Distribution Factors of Reaction and Shear at Support A1

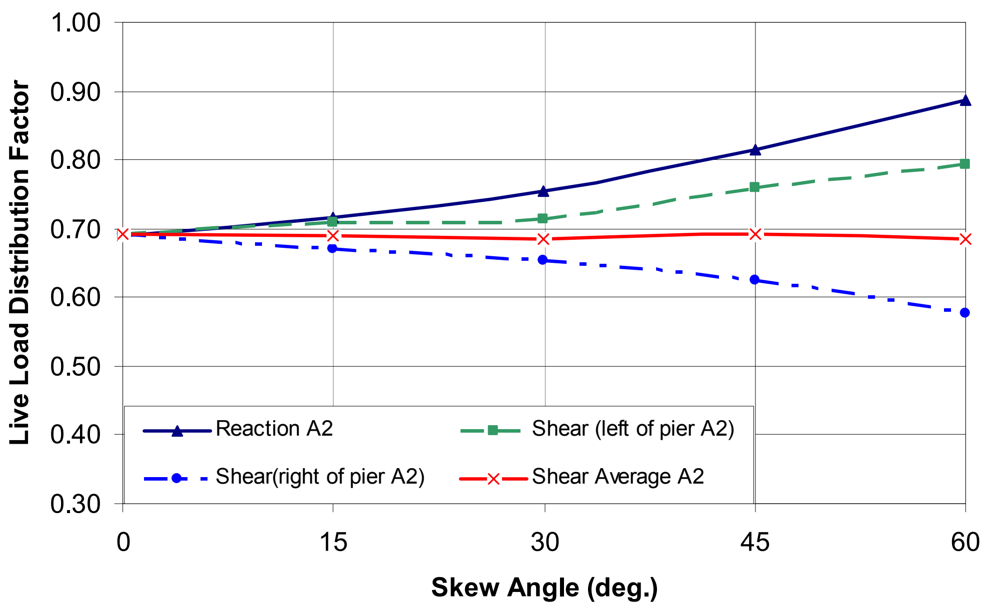

Fig. 7. Distribution Factors of Reaction and Shear at Pier A2

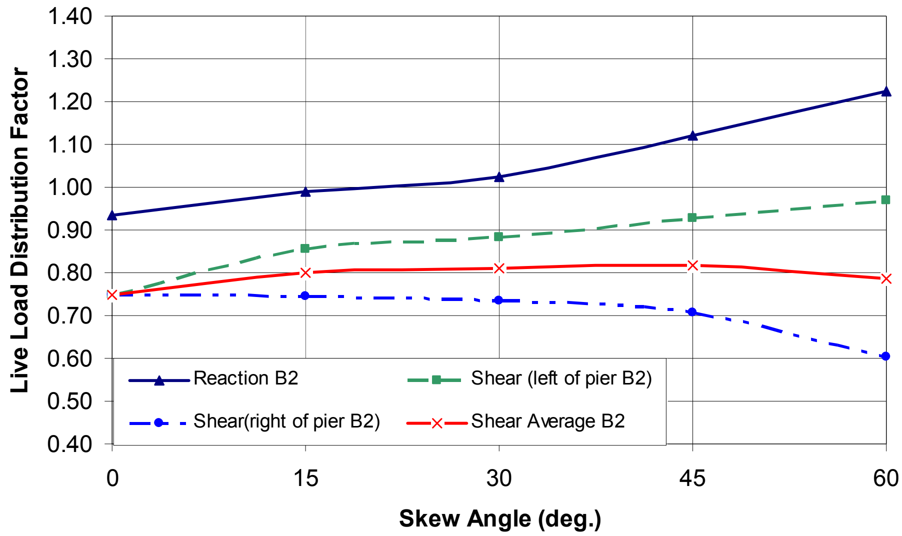

Fig. 8 Distribution Factors of Reaction and Shear at Pier B2

To further study the difference between reaction and shear responses, the ratio of reaction distribution factor to the average shear distribution factor were calculated. Fig. 9 shows the ratio of the two distribution factor versus skew angle. At *exterior pier* A2, the ratio of reaction and shear distribution factors varied linearly in a constant rate for skew angles 0 – 30 degrees. The ratio became slightly larger when the skew angle varied from 30 to 60 degrees, indicating an amplification on reaction distribution as the skew angle increased. At *interior pier* B2, the ratio of reaction and shear distribution factors was almost the same for skew angles 0 - 30 degrees. However, the difference between shear and reaction distribution factors became very large when skew angle was greater than 30 degrees. The ratio of reaction and shear distribution factors increased from 1.27 to 1.56, about 23% increase.

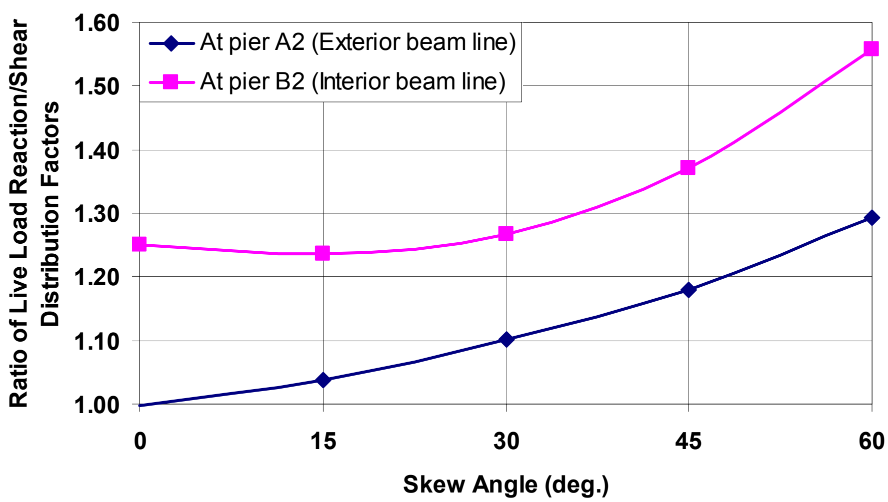

Fig. 9. Ratio of Reaction Distribution Factor vs. Shear Distribution Factor

COMPARISON TO THE CURRENT PRECEDURES

Currently the reaction distribution factors are determined by using either Lever Rule method or the LRFD Shear distribution equations with skew correction. To make a comparison of analytical results and the current procedures, the distribution factors of reaction were calculated using the two methods, and are shown in Table 3. Figs. 10 and 11 show the distribution factors of reactions versus skew angle for exterior pier and interior pier, respectively.

For exterior pier, as shown in Fig. 10, both the Lever Rule method and LRFD shear equation predicted higher reaction distribution factors than the results from finite element analysis. The LRFD equation presented the trend of the reaction distribution varying with skew angle, but with higher values. The Lever Rule method, although without skew correction factor, reasonably predicted the maximum reaction distribution factor with a larger skew angle. These current methods could predict the live load reaction distribution for exterior beams conservatively.

According to Fig. 11, both current procedures underestimated the live load distribution of reaction for the interior support. Although the LRFD equation showed the trend of the reaction distribution development with the increase of skew angle, the predicted shear distribution factors were much smaller than the obtained reaction distribution factors. The result was very similar to what was observed in the comparison of analytical reaction and shear distribution factors in the previous section.

Because the comparison was made from a limited study, the data was insufficient to make a quantified conclusion. More research is needed to study the distribution of live load reactions and to develop an accurate and simple distribution factor equation for live load reaction.

Table 3 Reaction Distribution Factors from Various Methods

Skew angle (deg.)	Ext. Beam			Int. Beam		
	Pier A2	Shear Equation	Lever Rule	Pier B2	Shear Equation	Lever Rule
0	0.689	0.850	0.856	0.936	0.838	0.900
15	0.716	0.889		0.989	0.877	
30	0.754	0.934		1.026	0.921	
45	0.816	0.996		1.120	0.982	
60	0.886	1.103		1.223	1.087	

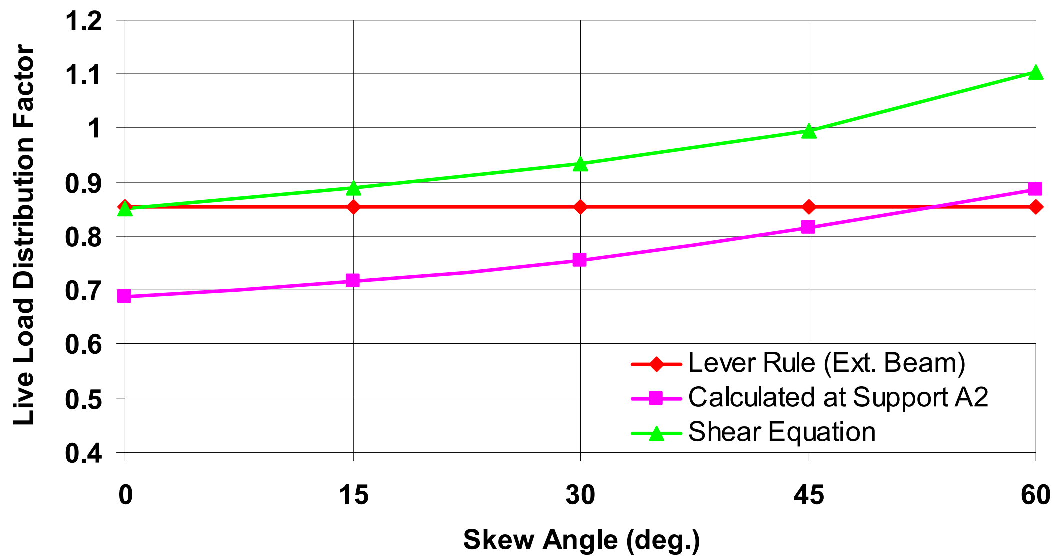

Fig. 10. Comparison to the Current Procedures (Exterior Beam)

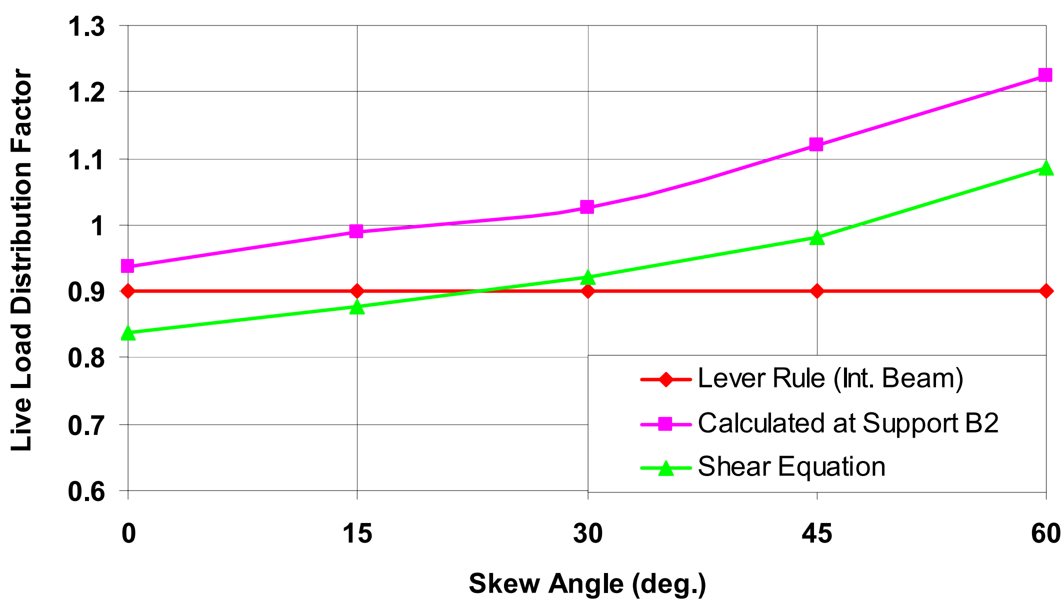

Fig. 11. Comparison to the Current Procedures (Interior Beam)

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this limited study, the following conclusions and recommendations have been made:

- The variation of live load reactions depended on the location and geometric condition of support and skew angle. On the exterior beam line, the distribution factor for live load reactions decreased at abutment A1 acute corner and increased at abutments A3 obtuse corner as the skew angle increased. The reaction distribution factor at the exterior pier increased with the increase of skew angles. On the interior beam line, the reaction distribution factors varied in a similar manner as that on the exterior beam line.
- The distribution factors of reactions at piers were higher than those of shear near the piers. The reaction distribution factors increased faster than the shear distribution factors at piers as the skew angle increased. The increase in reaction distribution factor on the interior beam line was more significant than that in shear distribution factor when skew angle was greater than 30 degrees.
- The LRFD shear equations and the Lever Rule method could conservatively predict live load reaction distribution for piers on exterior beam lines but clearly underestimate live load reaction on interior beams.
- It is recommended that more research be performed for the distribution factor for live load reaction and that accurate and simple distribution factor equations for reactions be developed.

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