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INVSETIGATION OF LATERAL LOAD DISTRIBUTION ON CURVED STEEL I-GIRDER BRIDGES

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ABSTRACT: The primary aim of this paper is to investigate live load distribution on curved steel I-girder bridges. Finite element method was used to carry out the detailed analyses to study the various parameters affecting wheel load distribution. The study was carried out based on AASHTO live loads. The influence of the parameters such as radius of curvature, girder spacing, span length, slab thickness, number of girders, cross frame spacing, overhang width and girder longitudinal and torsional stiffnesses was studied for curved steel I-girder bridges. A comparison was performed between the results from the finite element method and the AASHTO (1993) *Guide Commentary* formula.

Keywords: Curved bridges, steel I- girder, Load distribution, AASHTO live load

INTRODUCTION

Complex interchanges and the desire to conform to existing terrain have made curved steel I-girder bridges the suitable choice due to its simplicity in fabrication and construction, fast speed of erection, and excellent serviceability performance. These bridges are mostly located in on- and off- ramps with different radii of curvature and are characterized by complex vertical and horizontal geometries. The simple presence of curvature in curved girders causes non-uniform torsion and consequently, lateral bending moment (warping) in the flanges of the girder must be considered, which greatly complicates the analysis and design of the structure. Torsion can be neglected in straight girders, whereas it plays an important part in curved bridge stability. Although box girder provides very strong torsion capacity, I-shaped girder bridges are relatively strong and stiff under service loading and the behavior gravitates towards that of a multi-cell box section when adequately provided with diaphragms and cross frames.

This paper is a part of a study to investigate live load distribution for curved steel I-girder bridges based on both the AASHTO (American *Association of State Highway* *and Transportation Officials*) and ECP (*Egyptian Code of Practice*) live loads. This paper will focus on the AASHTO live load distribution. A similar study was conducted based on the ECP loads and simplified formulas was proposed for ECP live load distribution (will be presented in another paper)

The main objectives of this paper is to investigate load distribution factors based on AASHTO live load, identify the key parameters that influence the lateral load distribution for curved I-girder bridges, and compare the finite element models results with those based on AASHTO (1993) *Guide Commentary* formula.

METHOD OF ANALYSIS

The finite element method was used in this study due to its ability to consider unusual geometry and complex configuration, which helps in modeling the bridge elements in a more realistic manner and can get the most accurate results.

In this study, the concrete slab and steel girder web were modeled using four nodded quadrilateral shell elements have double action as they act simultaneously as membrane and plate bending shell elements as shown in Figure 1. Girder flanges were modeled as space frame elements, while flange to deck eccentricity was modeled by imposing a rigid link between the two centroids of the slab and the steel girder top flange. Cross frames members were modeled as pin jointed truss elements with the flexural and torsional stiffness ignored. All models were simply supported with the bearing supports located at the centroid of the frame element representing the bottom flange of the girder.

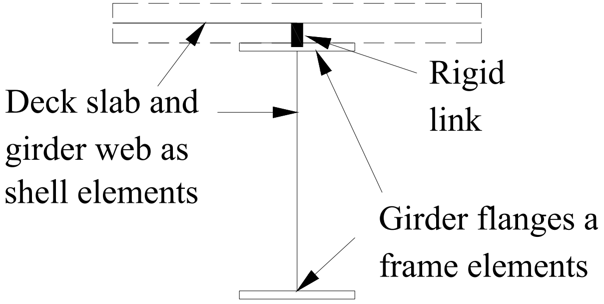

Figure 1 Finite element model

CURVED STEEL BRIDGES FIELD DATA

In order to get a representative sample of real bridges, data of some existing and newly designed bridges in the United States were collected through *American bridges database* available on the Internet. Bridge parameters were extracted from bridge drawings and data were used in the bridge database (Nasr 2004).

The bridges data were used to perform a statistical analysis on various bridge parameters. The data contains information such as bridge design load, in-plane radius of curvature, R, span length, L, number of girders, N, edge to edge deck width, curb to curb roadway width, year built, slab thickness, t_s, distance from centerline of exterior girder to the interior edge of curb or traffic barrier (overhang), d_e, girder spacing, S, cross frame or diaphragm spacing, S_c, with or without lateral bracing, girder dimensions (girder web thickness, web height, top and bottom flange thickness and width). Girder area A, girder moment of inertia I and torsional inertia J, and girder longitudinal stiffness parameter, defined as $K_g = I + Ae^2$, where e is the slab eccentricity were calculated using the girder dimensions for each bridge. The database also includes information about cross frame configurations (K-frame or X-frame).

Statistical analysis was conducted on bridges data to determine the minimum, maximum, mean and standard deviation values for each parameter. A simply supported bridge model with parameters equal to the mean values of the parameters was defined and referred to as the "Average Bridge" Table 1. A correlation study was carried out between each two parameters to identify the independent parameters in the database. Figure 2 shows the relation between girder spacing and slab thickness as a sample. This study resulted that the parameters are mostly not correlated.

Table 1 Average bridge properties

Bridge Parameters

R (m)	S (m)	t_s (cm)	N	Span length L (m)	d_e (m)	S_c (m)
70.0	3.0	23.0	4	24.0	0.61	4.0

Girder Dimensions (cm)

Top Flange Width	Top Flange Thickness	Web Height	Web Thickness	Bottom Flange Width	Bottom Flange Thickness
40	4	130	1.3	55	7

Girder Properties

A (cm^2)	I (cm^4)	J (cm^4)	K_g (cm^4)
1507.5	6398936.34	89827.97	9911501

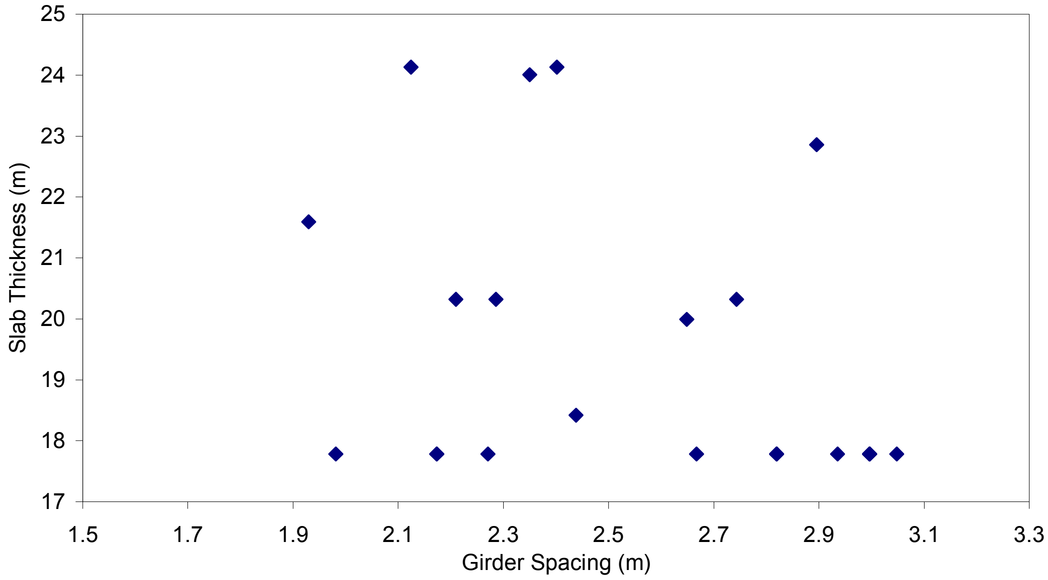

Figure2 Relationship of girder spacing and slab thickness

BRIDGE LOADING

AASHTO HS20-44 truck is shown in Figure 3, which is specified as per lane load, is used in D.F (Distribution Factor) calculation. The axles were assumed to be oriented radially. It is to be noted that for a multilane loading, the design per lane load is reduced to account for the reduced probability of several lanes being loaded simultaneously by heavy vehicles. After several trials to calculate the load distribution factors, it was found that 2-lane truck loading produces the maximum girder response.

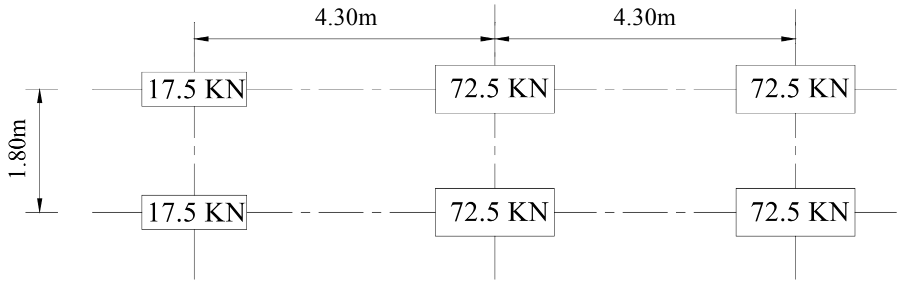

Figure 3 AASHTO HS20-44 truck wheel loads

PARAMETRIC STUDY

A parametric study was conducted to investigate the effect of each of the bridge parameters on load distribution factors based on AASHTO live loads. Also a comparison was carried out between F.E.M results and those from AASHTO (1993) *Guide Commentary* formula.

The Guide Specification Commentary gives expressions for moment distribution factors to be used in preliminary live-load analysis of curved girders which reduces to the following (AASHTO *Guide* 1993):

$$\text{D.F} = \left(\frac{S}{5.5}\right)\left(\frac{L}{400} + \frac{3L}{4R} + 0.7\right)\left(1.0 + \frac{15L}{R^2}\right) \tag{1}$$

Where S = the girder spacing; L = the bridge centerline span length; and R = the bridge centerline radius of curvature (all in feet). It is intended to represent the worst-case girder (outside girder) and would be increasingly conservative for the other girders across the bridge.

The following bridge parameters were considered: in-plane radius of curvature, girder spacing, distance between center of exterior girder to inside edge of traffic barrier or curb, span length, slab thickness, girder longitudinal stiffness, number of girders, girder torsional inertia, cross frame spacing. The effect of each parameter was studied separately by varying this parameter while keeping all other parameters at their average value.

The bottom flange forces obtained from finite element results were used to compute moment distribution factors of the girders. The following criteria were used for load distribution factors calculation:

For bending moment distribution factor

$$\text{D.F} = \frac{\text{Max. bottom flange force in the actual bridge F.E.M model}}{\text{Max. bottom flange in single straight girder}} \tag{2}$$

For shear (reaction) distribution factor

$$\text{D.F} = \frac{\text{Max. beam reaction in the actual bridge F.E.M model}}{\text{Max. reaction of single straight girder}} \tag{3}$$

PARAMETRIC STUDY RESULTS

Effect of Radius of Curvature, R

The radius of curvature was varied between 40 m and 200 m Figure 4 shows the variation of moment and shear distribution factors with radius of curvature. This figure shows that when the radius of curvature increases, the outside exterior girder moment decreases. The results agree with the trend of AASHTO *Guide Commentary* (1993) formula. However, the AASHTO formula values are slightly conservative. Shear distribution factors have the similar trend as that of moment distribution factors. However, the shear distribution factors are smaller than moment distribution factors for the outside exterior girder.

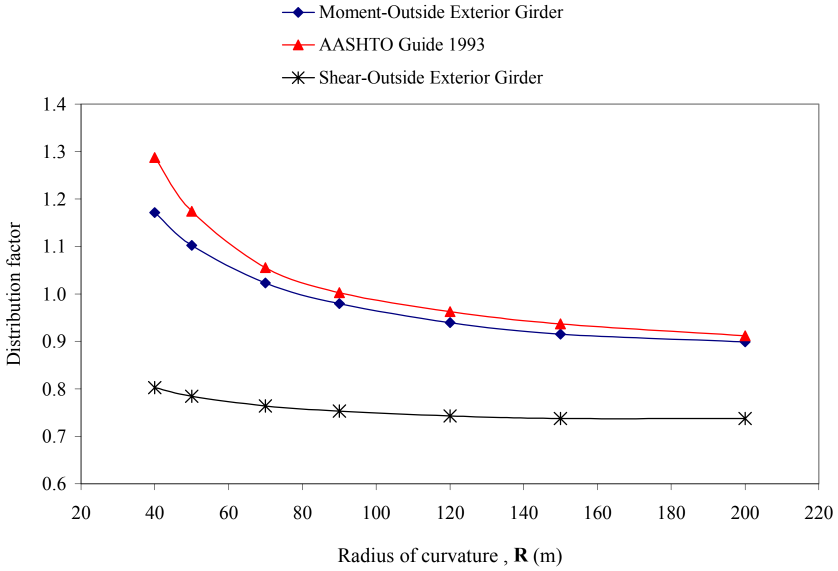

Figure 4 Effect of radius of curvature on moment and shear distribution

Effect of Girder Spacing, S

The girder spacing was varied between 2 m and 4 m. The effect of girder spacing is shown in Figure 5.Girder spacing has significant effect on curved bridge load distribution. Smaller girder spacing will cause more girders to share the load and therefore smaller load distribution. The moment and shear distribution factors have a non-linear relationship with girder spacing. The trends of moment distribution factors for outside exterior girder and AASHTO *Guide Commentary* (1993) formula has a linear relationship between moment distribution factors and girder spacing. For multiple-lane loading with girder spacing less than 2.8 m, AASHTO *Guide Commentary* results are unconservative, whereas it is conservative when girder spacing exceeds this limit.

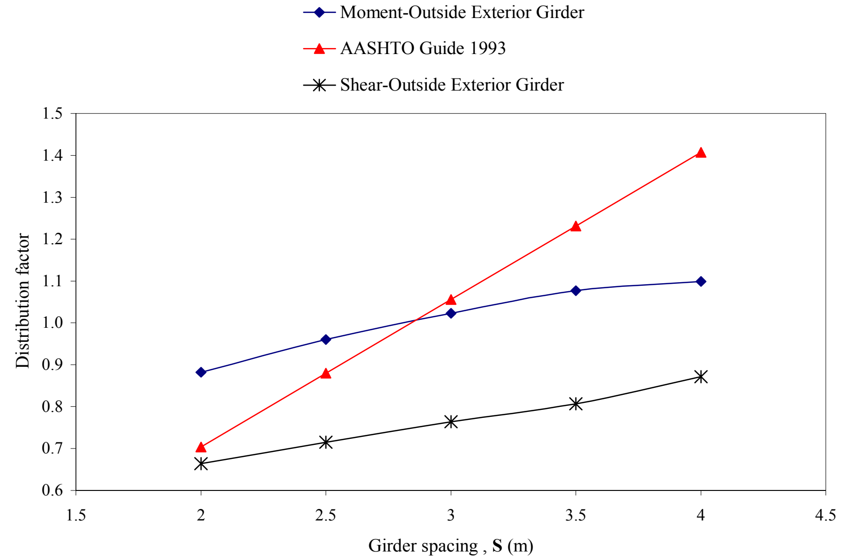

Figure 5 Effect girder spacing on moment and shear distribution

Effect of Span Length, L

The span length was varied between 16 m and 40 m. Figure 6 shows the effect of span length on load distribution. From Figure 6, it can be seen that with the increase of span length, moment distribution factor for outside exterior girder increases. AASHTO *Guide Commentary* (1993) has a linear relationship between moment distribution factors and span length. The effect of span length for outside exterior girder is noticeable. Span length has small effect on shear distribution.

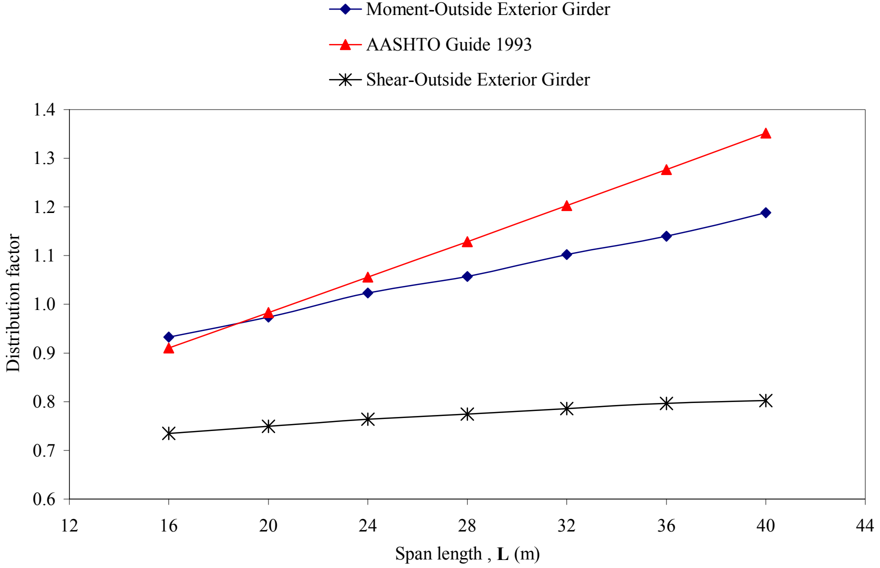

Figure 6 Effect of span length on moment and shear distribution

Effect of Slab Thickness, t_s

The slab thickness was varied between 19 cm and 27 cm. The effect of slab thickness on moment distribution is approximately a linear relationship. The effect of slab thickness on shear distribution is negligible.

Effect of Number of Girders, N

The number of girders was varied between 3 and 7. For constant girder spacing, bridge width changes with the variation of number of girders, this causes the overall bridge transverse stiffness to change significantly. The effect of number of girders on moment and shear distribution factors for curved bridges is presented in Figure 7. Figure 7 shows that moment distribution factor for outside exterior girder decrease when the number of girders increases. The number of girders has small effect on shear distribution.

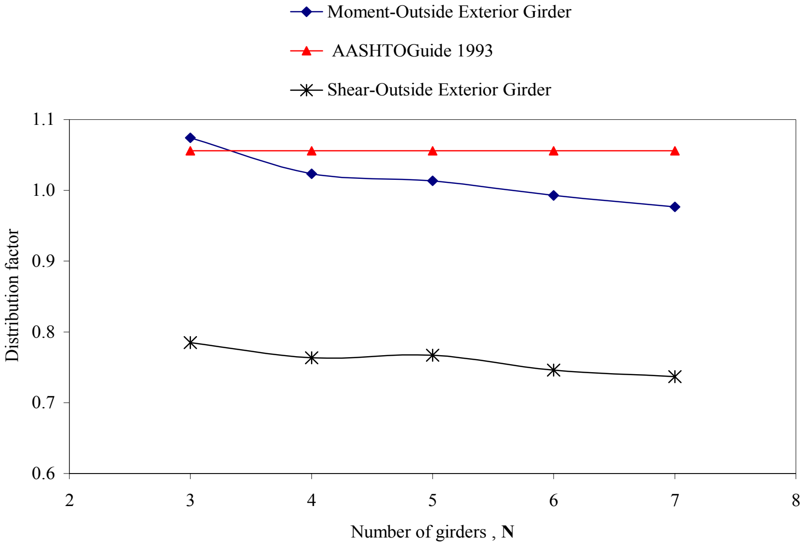

Figure 7 Effect of number of girders on moment and shear distribution

Effect of Girder Torsional Inertia, J

To study the effect of girder torsional inertia on moment and shear distribution factors, girder flange width and web height were varied to keep the parameter K_g at very small variation. The results are plotted in Figure 7. From this figure, it can be seen that torsional stiffness has negligible effect on moment and shear distribution factors, although it is important in resisting torsion in curved bridges.

Effect of Distance between Center of Exterior Girder and Inside Edge of Traffic Barrier or Curb (overhang), d_e

The overhang length was varied between -0.5 m and 1.5 m. Figure 8 shows the results for parameter d_e. As expected, exterior girder load distribution is sensitive to truckload position on the bridge. Outside exterior girder moment and shear distribution factor have a linear relation with parameter d_e. However, AASHTO *Guide Commentary*

(1993) formula ignores the effect of this key parameter. As a matter of fact, the results of AASHTO *Guide Commentary* (1993) are too conservative for d_e less than 3 ft and unconservative for d_e greater than 3 ft for outside exterior girder for multiple-lane loading.

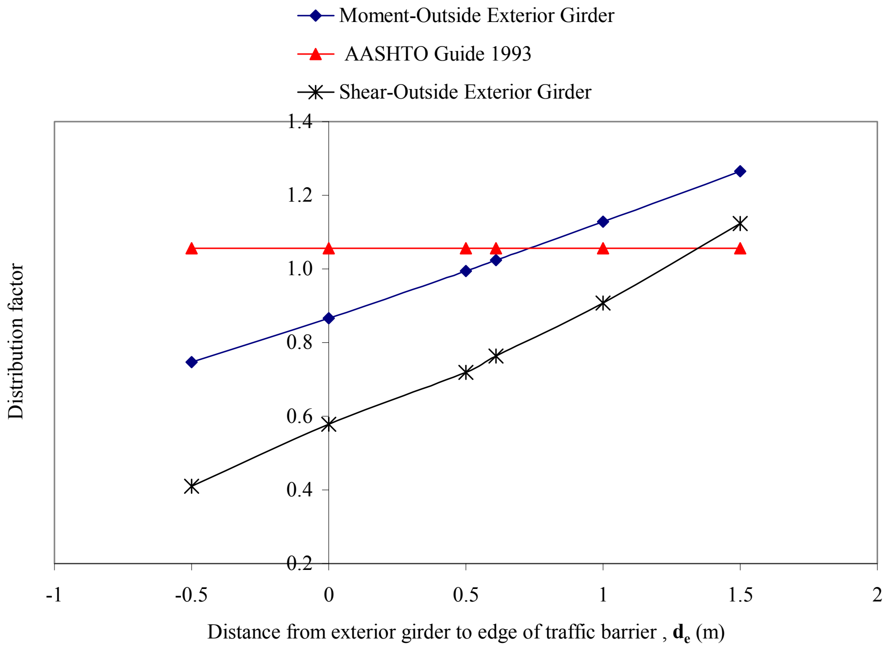

Figure 8 Effect of distance between center of exterior girder and inside edge of traffic barrier on moment and shear distribution

Effect of Cross Frame Spacing, S_c

Cross frame spacing was varied between 3m and 12m. When cross frame spacing changes, numbers of cross frames in each span vary while keeping the span length constant; the results show that cross frame spacing has negligible effect on moment and shear distribution factors.

Effect of Girder Longitudinal Stiffness, K_g

Since girder dimensions instead of girder cross section properties were required as input to the program, only girder web height was varied in parameter longitudinal stiffness K_g. This was done to keep the parameter torsional inertia at very small variation. The effect of K_g on moment and shear distribution factors is shown in Figure 9. From this figure, it can be seen that moment distribution varies slightly with the variation of parameter K_g and the effect of K_g on shear distribution is negligible.

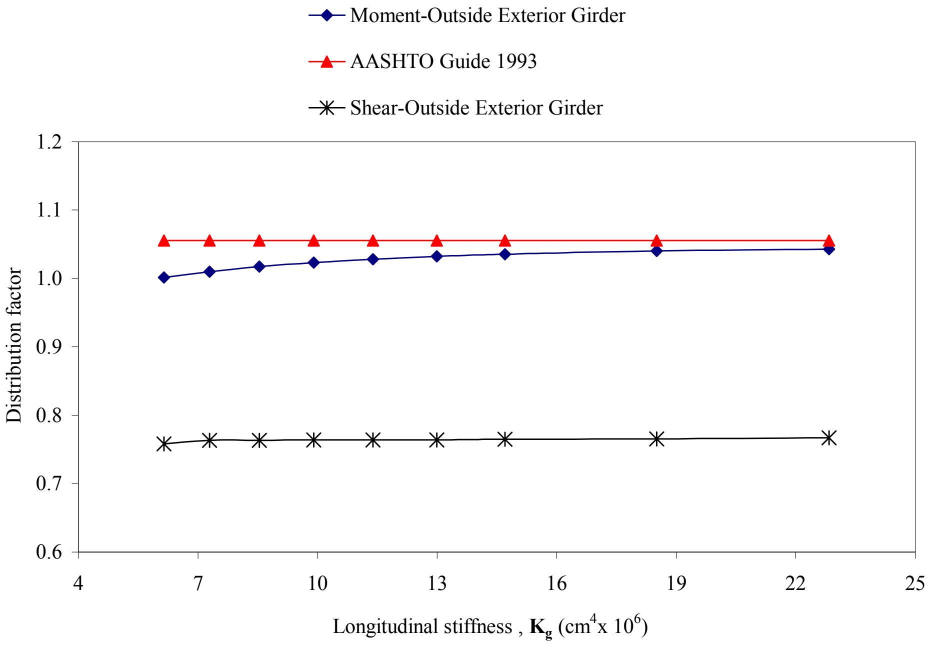

Figure 9 Effect of longitudinal stiffness on moment and shear distribution

SUMMARY AND CONCLUSIONS

In this study, the effect of various bridge parameters on moment and shear distribution factors was investigated. The parameters considered in the study were: radius of curvature, girder spacing, span length, slab thickness, girder longitudinal stiffness, girder torsional inertia, number of girders, distance from center of exterior girder and inside edge of traffic barrier, and cross frame spacing. The variations of these parameters were based on the statistical analysis of the real bridge data collected. A parametric study was carried out using the selected F.E. model to calculate the lateral load distribution factors based on AASHTO live loads. The F.E.M results were compared with values obtained from AASHTO (1993) *Guide Commentary* formula. The following conclusions can be drawn from the results of this study:

- The 3-D dimensional modeling of curved steel I-girder bridges provides a better understanding of the overall bridge superstructure behavior.
- This study showed that the outside exterior girder moment always had the most maximum value and two-lane loading would generally produce maximum girder response.
- The parametric study showed that for variable bridge width:
  - -Radius of curvature, span length, girder spacing, and distance from center of exterior girder and inside edge of traffic barrier had significant effect on distribution factors.
  - -Slab thickness, number of girders and longitudinal stiffness had slight effect.
  - -Effect of cross frame spacing and girder torsional inertia could be neglected.
- It was found that the distribution factors of outside exterior girder positive moment obtained from AASHTO (1993) *Guide Commentary* were

unconservative in some cases and conservative in other cases compared with the results of FEM analysis.

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