Load Distribution Factors For Horizontally Curved Composite Concrete-Steel Girder Bridges

Lecturer Dr. Rafa'a Mahmood Abbas **Zainab Saadi Qassem**
rafaamaa@yahoo.com
Department of Civil Engineering - University of Baghdad

ABSTRACT

This paper focuses on Load distribution factors for horizontally curved composite concrete-steel girder bridges. The finite-element analysis software"SAP2000" is used to examine the key parameters that can influence the distribution factors for horizontally curved composite steel girders. A parametric study is conducted to study the load distribution characteristics of such bridge system due to dead loading and AASHTO truck loading using finite elements method. The key parameters considered in this study are: span-to-radius of curvature ratio, span length, number of girders, girders spacing, number of lanes, and truck loading conditions.

The results have shown that the curvature is the most critical factor which plays an important role in the design of curved girders in horizontally curved composite bridges. Span length, number of girders and girder spacing generally affect the values of the moment distribution factors. Moreover, present study reveals that AASHTO Guide criterion to treat curved bridges with limited curvature as straight one is conservative. Based on the data generated from the parametric study, sets of empirical equations are developed for the moment distribution factors for straight and curved steel I-girder bridges when subjected to the AASHTO truck loading and due to dead loading.

KEYWORDS: Composite Bridges, AASHTO Loading, Load Distribution Factors, Horizontally Curved Bridges, Finite Element Analysis, Curved I-Girders, Warping Stresses.

معاملات توزيع الأحمال على الجسور المركبة المنحنية في المستوى الأفقي

م. د. رافع محمود عباس **زينب سعدي قاسم**
rafaamaa@yahoo.com
قسم الهندسة المدنية - جامعة بغداد

الخلاصة:

يهدف هذا البحث لدراسة السلوك الإنشائي للجسور المركبة بسيطة الإسناد والمنحنية في المستوى الأفقي. حيثُ يهدف البحث لتحديد معاملات توزيع الأحمال الحية والأحمال الميتة على تلك الجسور المركبة. أن المواصفة الأمريكية للجسور المنحنية لا تعطي قيم أو صيغ رياضية لمعاملات توزيع الأحمال على الأعتاب الفولاذية لتلك الجسور وإنما تكتفي فقط بإعطاء صيغة مبسطة لتحليل تلك الجسور عندما تكون قيمة التقوس لها بسيطة وذلك بإهمال تاثير التقوس واحتساب معاملات توزيع الأحمال فيها كما في الجسور المستقيمة.

تم استعمال طريقة العناصر المحددة لتحليل نموذج ثلاثي الأبعاد لسطح الجسر والعتبات الفولاذية المقوسة. تم استعمال برنامج (SAP 2000) لعمل موديل ثلاثي الأبعاد للجسر المركب ودراسة تأثير عدد من العوامل المؤثرة على معاملات توزيع أحمال العجلات والأحمال الميتة لتلك الجسور. إن العوامل التي تمت دراستها في هذا البحث تشمل: درجة التقوس، طول الجسر، عدد الاعتاب الفولاذية، مسافة توزيع الأعتاب الفولاذية، عدد الممرات لسطح الجسر وعدد وطبيعة الممرات المحملة بالمركبات. بينت النتائج من هذه الدراسة إن درجة التقوس للمسقط الأفقي لسطح الجسر لها دور كبير في تحديد معاملات توزيع العزوم في الأعتاب المقوسة وانه كلما زادت درجة التقوس ازدادت تلك المعاملات. كما وان طول الجسر وعدد الأعتاب ومسافة توزيعها لها دور في تحديد تلك المعاملات. واعتماداً على النتائج النظرية التي تم التوصل إليها في هذه الدراسة تم تطوير عدد من المعادلات الرياضية المبسطة التي تساعد المصمم للجسور المركبة المنحنية على تحديد معاملات توزيع العزوم في الأعتاب الفولاذية وبطريقة مشابهة لمعاملات الجسور المستقيمة

كلمات المفتاح: تحليل العناصر المحددة، الجسور المركبة، الجسور المنحنية في المستوي الافقي، العتبات المقوسة، معاملات توزيع الاحمال، اجهادات الالتواء، احمال الجسور.

INTRODUCTION

During recent years, there is a trend toward the design and construction of horizontally curved highway bridges to accommodate higher volumes of traffic within geographical constrains. Due to its geometry, simple presence of curvature in curved bridges produces non uniform torsion and consequently, lateral bending moment (warping or bi-moment) in the girder flanges as shown in **Fig.1**. The simple presence of curvature in curved steel girders complicates, to a great extent, their behavior and design considerations over those of straight girders. **Fig. 2** shows typical cross-section of a four-girder bridge. It consists of a concrete deck slab supported over steel I-girders. Cross-bracings as well as top and bottom chords are used at equal intervals between bridge support lines to stabilize the girders during construction and enhance its structural integrity.

In designing highway bridges, dead loading and live loading are imposed on bridges and used in the design of bridges**.** In the bridge design codes, the live load is the standard truck loading with concentrated wheel loads. Both longitudinal and lateral position of truck wheel loads is of great importance when calculating moment in the girders. Therefore, the truck load must be positioned longitudinally and transversely in a certain manner to produce maximum positive and negative bending moments, shear and deflection in the girders. Bridge design codes define lateral distribution factor that specify the fraction of each wheel load that must be applied to each girder and allows each girder to be designed as straight girder. For this reason, load distribution factor is of fundamental importance in bridge design.

BACKGROUND

The first treatment of the analysis of curved beams is presented in 1843 by Barré de Saint Venant as referred by Zureik (1998, 1999). McManus et al. (1969) present the first survey of the most published works related to horizontally curved bridges. His bibliography list contained 202 references.

Serious studies pertaining to the analysis and design of horizontally curved bridges begun only in 1969 when the Federal Highway Administration (FHWA) in the United States formed the Consortium of University Research Teams (CURT). This team consists of Carnegie Mellon University, University of Pennsylvania, University of Rhode Island, and Syracuse University, whose research efforts, along with those at University of Maryland, resulted in the initial development of working Stress Design (WSD) or Allowable Stress Design (ASD) criteria and tentative design specifications.

The American Society of Civil Engineers (ASCE) and the AASHTO Task Committee on flexural members (1977) compile the results of most of the research efforts prior to 1976 and presented a set of recommendations pertaining to the design of curved I-girder bridges. The CURT research activity is followed by the development of Load Factor Design (LFD) criteria adopted by AASHTO to go along with the ASD criteria. These provisions appeared in the first Guide (1980) as well as the Guide (1993). It is worthwhile to mention that the AASHTO guide specification for horizontally curved highway bridges (1993) is primarily based upon research work conducted prior to 1978.

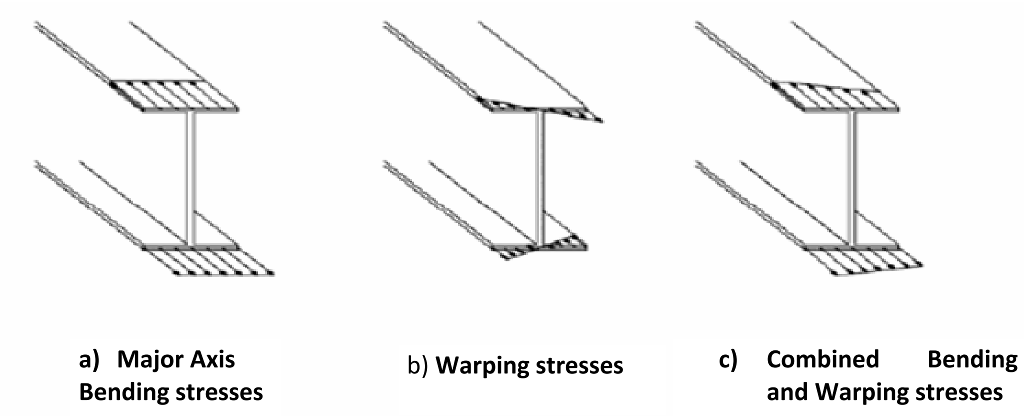

a) Major Axis Bending stresses
b) Warping stresses
c) Combined Bending and Warping stresses

Fig. 1: Normal Stresses Distribution in Curved I-Girder Flanges

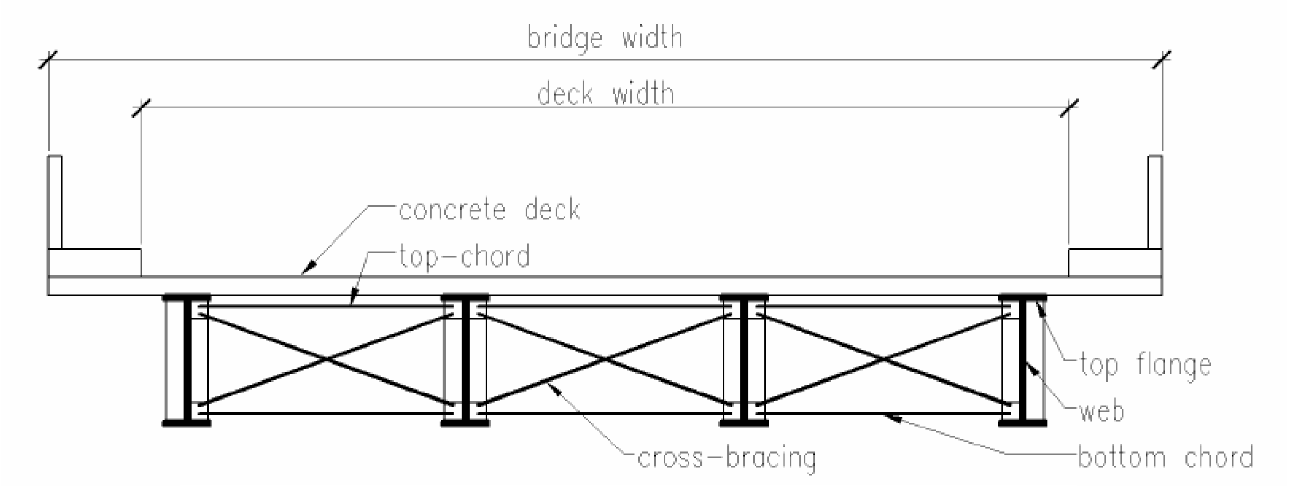


Fig. 2: Typical Cross Section of Concrete Deck I-Girder Bridge

OBJECTIVES

The objectives of this study are:

1. Identifying the key parameters that influence the lateral distribution of loads in straight and horizontally curved composite concrete-steel bridges and calculating the load distribution factors,
2. Providing accurate database that can be used for developing simplified design method for horizontally curved composite concrete-steel bridges, and
3. Developing simplified formulas for moment distribution factors for straight and horizontally curved composite concrete-steel bridges when subjected to AASHTO truck loading as well as dead loading.

BRIDGE MODEL CONFIGURATIONS

102 simply supported straight and curved composite concrete-steel girder bridge prototypes are considered for finite-element analysis in this study. Several major parameters are considered as follows:

1. Span length **(L)**: 15, 25, and 35 m,
2. Girder spacing **(S)**: 2, 2.5, and 3 m,
3. Number of girders **(N)**: 3, 4, and 5, and
4. Span-to-radius of curvature ratio **(L/R)**: 0.0, 0.1, 0.2, & 0.3 for span L=15 m; 0.0, 0.1, 0.3,

Other bridge configurations are listed as below:

- The deck slab thickness is taken as 225 mm,
- The deck slab width (Wc) is taken equal to the total bridge width minus 1.0 m to consider the parapet thickness,
- The depth of the girder webs is taken (1/20) of the centre line span,
- The girder web thickness is considered equal to 16 mm,
- The over-hanging slab length is considered equal to half the girders spacing, and
- The bottom and top steel flanges width and thickness are maintained 300 mm, and 20 mm, respectively.

Table 1 shown below summarizes the straight bridge configurations considered in this study.

Table 1: Bridge Configurations Considered in the Parametric Study

Bridge Width (m)	**Deck Width,Wc (m)**	**Number of Girders**	**Girder Spacing (m)**	**Number of Lanes**
7.5	6.5	3	2.5	2-lanes
9	8	3	3	2-lanes
8	7	4	2	2-lanes
10	9	4	2.5	2-lanes
12	11	4	3	3-lanes
10	9	5	2	2-lanes
12.5	11.5	5	2.5	3-lanes
15	14	5	3	4-lanes

X-type cross-bracings with top and bottom chords are utilized in this study as shown in **Fig. 2**. These bracings are spaced at equal intervals between the support lines and are made of single steel angles having dimensions (150x150x25) mm. The equal intervals spacing between these cross-bracings are based on **equation A**, which is developed by Davidson et al. (1996) to reduce and limit the warping-to-bending stress ratio.

$$S_{max} = L\left[-Ln\left(\frac{Rb_f}{2000L^2}\right)\right]^{-1.52} \qquad \text{(A)}$$

Where: (L) is span length, (R) radius of curvature, (b_f) flange width.

The study is based on the following assumptions:

1. The reinforced concrete slab deck has composite action with the top steel flange of the girders (shear interaction);
2. The bridges are simply-supported;
3. All materials are elastic and homogenous;
4. The effect of road super elevation, and curbs are ignored; and
5. Bridges have constant radii of curvature between support lines.

Regarding the first assumption, Wassef (2004) concludes that bridge composite action is accurately achieved when the shear connector studs are modeled in the finite element analysis using shell element rather than frame elements. Hence, the latter is ignored in this study and shell elements are adopted to represent the shear connectors in the finite element models.

The modulus of elasticity of concrete material is taken 28 GPa with Poisson's ratio of 0.20 while they are 200 GPa and 0.30, respectively, for structural steel material.

FINITE ELEMENTS MODELING

To analyze all the above mentioned composite bridge models and to determine their structural behavior, a three-dimensional finite-element model is used.

The composite bridge is divided into concrete deck slab, top steel flange, steel web, bottom steel flange, and the cross-bracings. In this study, four-node shell elements with six degrees of freedom at each node are used to model the concrete deck slab, the top and bottom girder flanges, and finally the girder web. Whereas, frame elements, pinned at both ends, are used to model the cross-bracings with the top and bottom chords.

Based on previous work on finite-element modeling, four vertical shell elements are used in each web, and another four are used horizontally for the deck slabs between the webs, whereas two shell elements are used for the over hanged deck slab, and for the upper and lower steel flanges. **Fig.3** shows a finite-element discretization of the four-girder cross section.

BOUNDARY CONDITIONS

In modeling the bridge supports in this study, the lower nodes of the web ends are restrained against translation in such way to simulate temperature-free bridge superstructure. The interior support at the right end of the bridge is restrained against movements in all direction. The middle supports and the exterior support at the same right end of the bridge are restrained against the vertical movement and against the movement in y-direction.

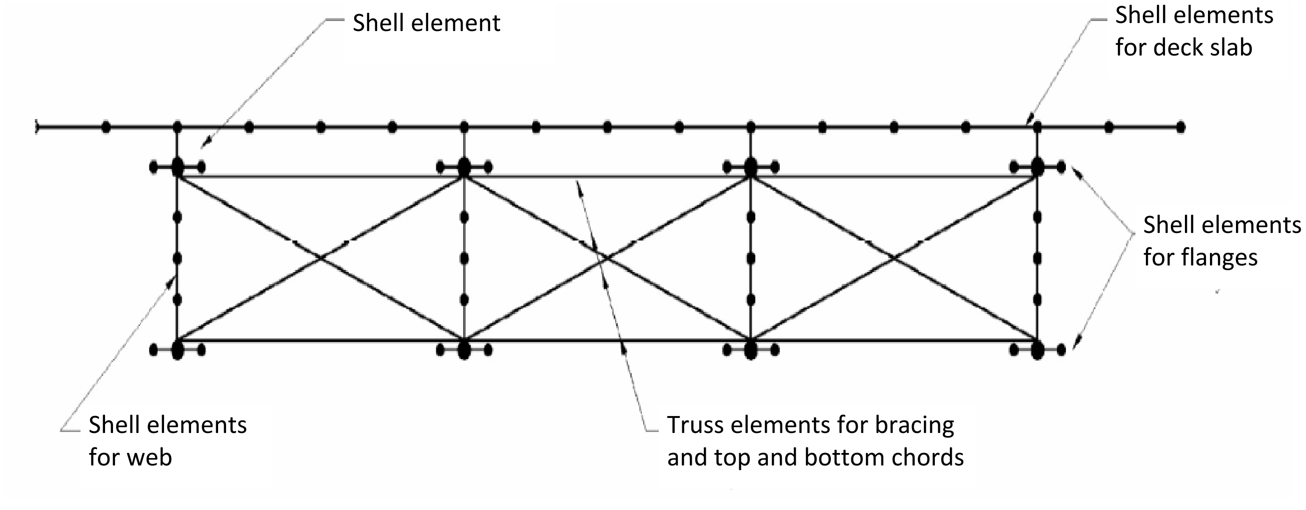


Fig. 3: Finite Element Discretization of the Bridge Cross-section

On the other end of the bridge (left end), all the supports are restrained only against vertical movement, except for the interior support which in addition to the vertical restraining, it is restrained in x-direction (towards the bridge transverse direction).

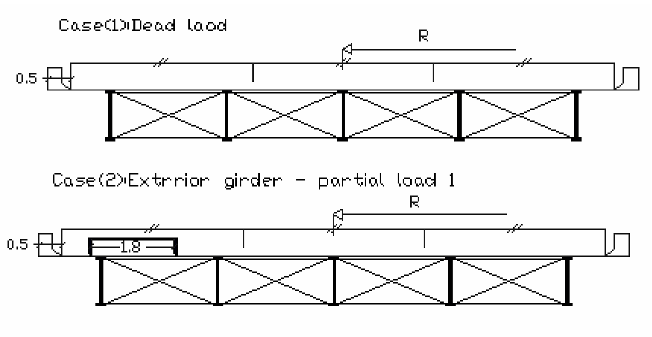
BRIDGE LOADING

The loading conditions considered herein include dead load and AASHTO truck loading case.

For the longitudinal position of truck loading, three different AASHTO (HS-20) truck loading configurations are employed, namely: Level 1, Level 2, and Level 3 trucks. The Level 1 truck is used for bridges with span of 15 m, Level 2 truck is considered in case of 25m span bridges and Level 3 truck is considered in case of 35m span bridges. In these loading levels, the longitudinal truck loading position on the bridge prototype is applied in such a way to produce maximum midspan longitudinal stresses.

For the transverse truck loading position across the bridge deck, different bridge configurations are considered in this study which includes two-lane, three-lane and four-lane bridges. Three different sets of loading cases are considered in this study based on the number of design lanes. **Fig. 4** shows one set of schematic diagrams of the loading cases considered in determining the structural response of the exterior, middle, and interior girders for three lane loading.

The exterior girder in this study is the one which is far away from the centre of curvature in the bridge and the internal girder is the closest girder to the centre of bridge curvature.



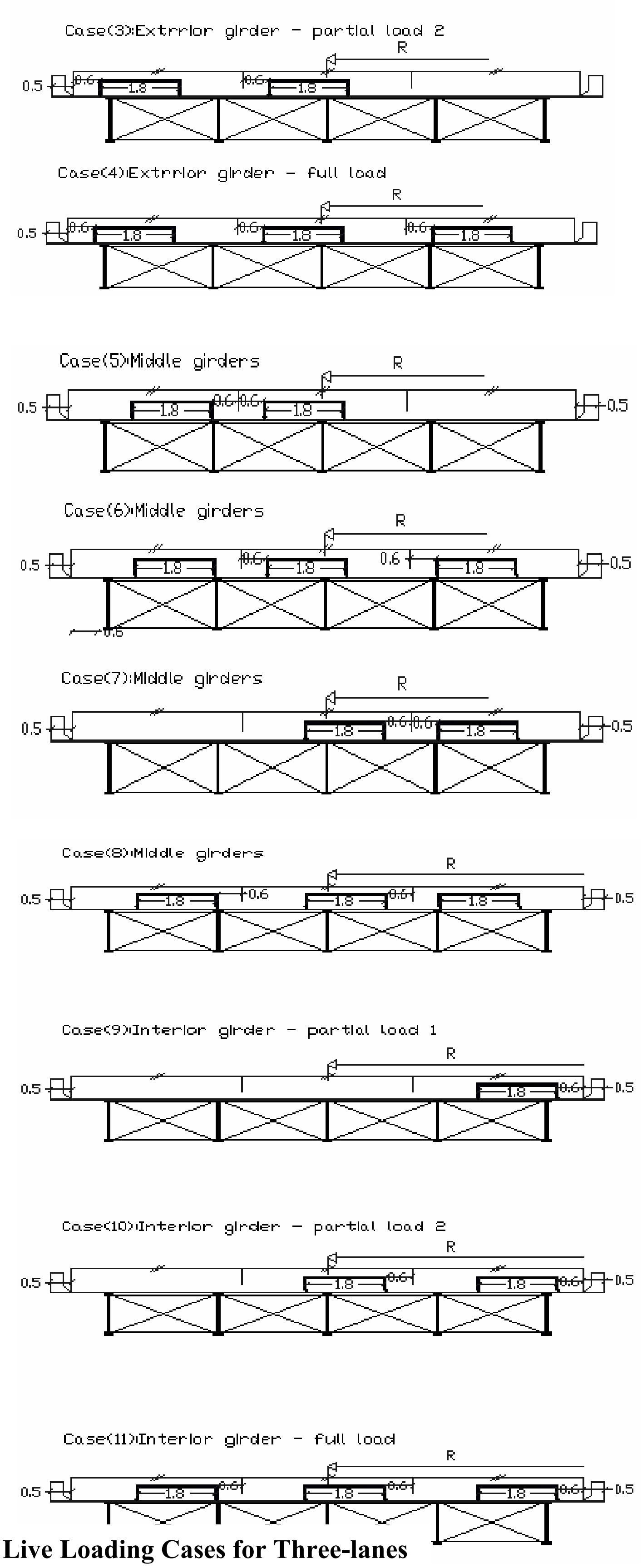


Fig. 4: AASHTO (HS20) Truck Live Loading Cases for Three-lanes Bridge

MOMENT DISTRIBUTION FACTORS

To determine the moment distribution factor (MDF) for curved girder, the maximum flexural stresses, $(\sigma_{\text{straight}})_{\text{truck}}$, $(\sigma_{\text{straight}})_{DL}$ are calculated for a straight simply supported beam subjected to AASHTO truck loading, and dead load, respectively.

The span of the straight simply supported girder is taken as the curved length of the bridge centerline. From the finite-element modeling, the maximum longitudinal moment stresses along the bottom flange for dead load, fully loaded lanes, and partially loaded lanes are calculated. Consequently, the moment distribution factors (MDF) were calculated as follows:

FOR EXTERIOR GIRDERS:

$$(MDF)_{DLext}=(\sigma_{FE.ext})_{DL}/(\sigma_{\text{Straight}})_{DL} \quad (1)$$

$$(MDF)_{FL.ext}=(\sigma_{FE.ext})_{FL} x N/((\sigma_{\text{Straight}})_{\text{truck}} x n) \quad (2)$$

$$(MDF)_{PL.\ ext} = (\sigma_{FE.ext})_{PL} \text{ x } N \text{ x } RL' / ((\sigma_{\text{Straight}})_{\text{truck}} \text{ x } \text{x}RL) \quad (3)$$

FOR MIDDLE GIRDERS:

$$(MDF)_{DL.mid}=(\sigma_{FE.mid})_{DL}/(\sigma_{\text{Straight}})_{DL} \quad (4)$$

$$(MDF)_{FL.mid}=(\sigma_{FL.mid})_{FL} x N/((\sigma_{\text{Straight}})_{\text{truck}} \times n) \quad (5)$$

FOR INTERIOR GIRDERS:

$$(MDF)_{DL.int}=(\sigma_{FE.int})_{DL}/(\sigma_{\text{Straight}})_{DL} \quad (6)$$

$$(MDF)_{FL.int}=(\sigma_{FE.int})_{FL} x N/((\sigma_{\text{Straight}})_{\text{Truck}} x n) \quad (7)$$

$$(MDF)_{PL.int}= (\sigma_{FE.int})_{PL} \text{ x } N \text{ x } RL' / ((\sigma_{\text{Straight}})_{\text{truck}} \text{ x } n \text{ x } RL) \quad (8)$$

Where $(MDF)_{DL}$, $(MDF)_{FL}$, and $(MDF)_{PL}$ are the moment distribution factors for dead load, fully loaded lanes, and partially loaded lanes, respectively. And the symbols ext, mid, and int. refer to the exterior, middle, and interior girders, respectively. $(\sigma_{FE.\ ext})_{DL}$, $(\sigma_{FE.\ ext})_{FL}$, and $(\sigma_{FE.\ ext})_{PL}$ are the maximum longitudinal stresses which are the greater at bottom flange, found from the finite-element analysis for the exterior girder due to dead load, fully loaded lanes, and partially loaded lanes , respectively.

In the same criteria, $(\sigma_{FE.mid})_{DL}$, $(\sigma_{FE.mid})_{FL}$, $(\sigma_{FE.int})_{DL}$, $(\sigma_{FE.int})_{FL}$, and $(\sigma_{FE.int})_{PL}$ are the maximum stresses which are the greater of the flange stresses for the middle and interior girders under the same above types of loading. While RL, RL′, n, and N are defined as:

n: number of design lanes, as listed in **Table 2**,

RL: multi-lane factor based on the number of the design lanes; as shown in **Table 3**,

RL′: multi-lane factor based on the number of the loaded lanes; as shown in **Table 3**, and

N: number of girders.

Table 2: Number of Design Lanes

Deck Width, Wc	Number of Design Lanes, N
Over 6.0 m to 10.0 m incl.	2
Over 10.0 m to 13.5 m incl.	3
Over 13.5 m to 17.0 m incl.	4

Table 3: Modification Factors for Multilane Loading

Number of Loaded Design Lanes	Modification Factor
1 or 2	1
3	0.90
4 or more	0.75

PARAMETRIC STUDY

A parametric study is conducted to study the load distribution characteristics of the curved composite bridge system due to dead loading and AASHTO truck loading and to examine the key parameters that can influence the distribution factors for horizontally curved composite steel girders.

The key parameters considered in this study are:

- Span-to-radius of curvature ratio,
- Span length,
- Number of girders,
- Girders spacing,
- Number of lanes, and
- Truck loading conditions.

Results from the parametric study are presented herein below

EFFECT OF CURVATURE

Fig. 5 shows the variation in the moment distribution factors for the exterior, middle and interior girders of the three-lane, four-girder bridge with the increase in the span-to-radius of curvature (L/R) ratio due to dead load. Whereas, **Fig. 6** shows the moment distribution factors for the exterior, middle and interior girders for the same bridge with the increase in the span-to-radius of curvature (L/R) ratio due to fully-loaded lanes with AASHTO truck loading.

It can be observed that the moment distribution factors for the exterior and middle girder increases with the increase in span-to-radius of curvature ratio. It can also be noticed that the rate of increase of the moment distribution factor generally increases with the increase in span length. Whereas, the moment distribution factor for the interior girder increases with increase of curvature up to a certain value of L/R ratio, after which the moment distribution factor decreases with the increase in curvature.

These figures reveal that curvature of the bridge is one of the most significant parameters affecting the distribution of moments between the longitudinal girders.

It should be noted AASHTO Guide, 2003 states that curved bridges can be treated as straight ones if the span-to-radius of curvature ratio is less than 0.06 radians. While, the AASHTO-LRFD, 2004 specifications state that a curved bridge can be treated as a straight one in structural design if the central angle is less than 3° (≈ 0.05 radians) for bridge cross-section made of three or four girders and 4°(≈ 0.07 radians) if the number of girders is 5 or more.

It is evident from the results presented in **Figs. 5 and 6** that the limitation specified by AASHTO guide 2003 and AASHTO-LRFD, 2004 is in a good agreement with the results from this parametric study for simply supported composite concrete bridges with small L/R ratio. It is evident that AASHTO Guide criterion (Guide, 2003) to treat curved bridges as straight one is conservative.

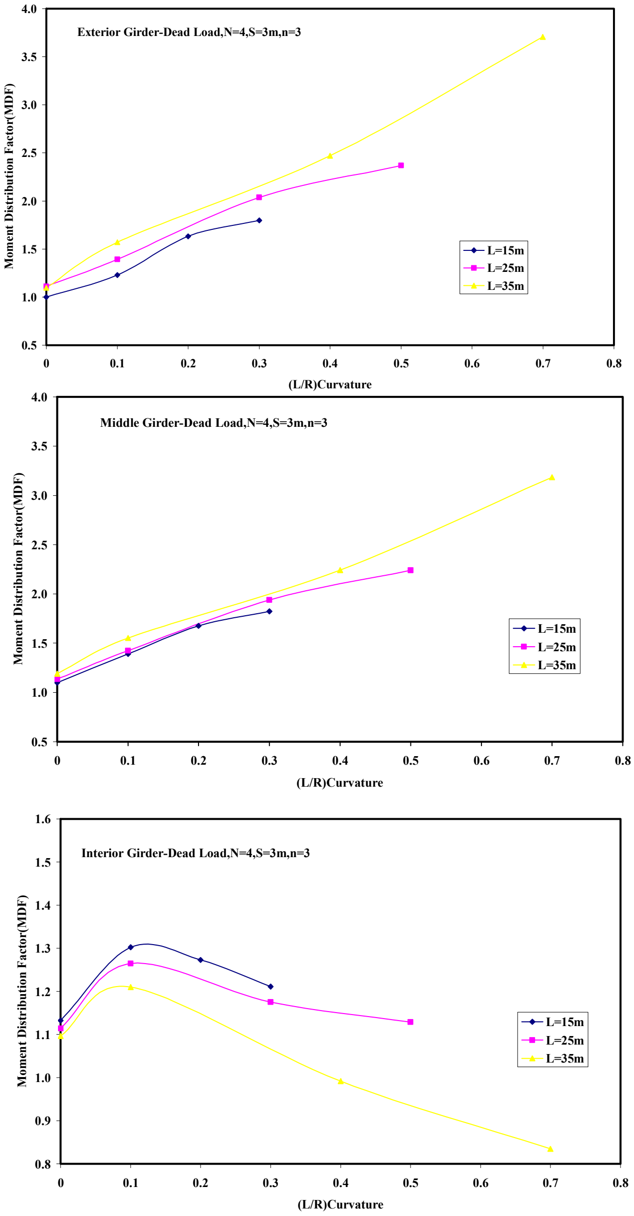


Fig.5: Effect of Bridge Curvature on moment distribution factors due to dead loading

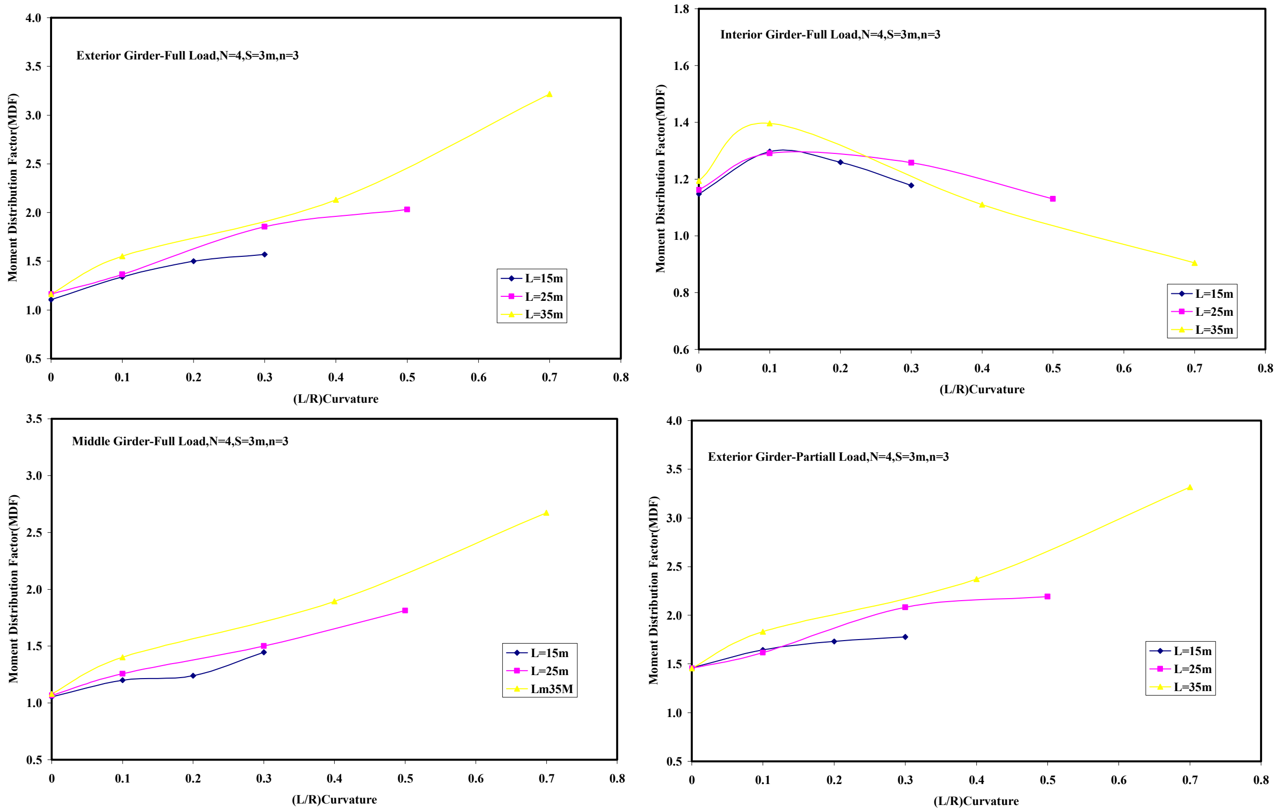


Fig.6: Effect of Bridge Curvature on moment distribution factors due to AASHTO Truck loading

EFFECT OF SPAN LENGTH

Fig. 7 shows result for the effect of bridge span length on the moment distribution factors for the external girders of two-lane five-girder bridges due to dead load and fully-loaded lanes, respectively.

It can be observed that the effect of the span length on the moment distribution factors is insignificant for straight bridges with L/R=0. However, for curved bridges, the moment distribution factor of the exterior girder is observed to increase with the increase in the span length as shown in this figure.

EFFECT OF NUMBER OF LONGITUDINAL GIRDERS

To study the effect of number of girders on the moment distribution factors, a bridge with 2.5m girder spacing and 35m span length is considered. **Figs. 8 and 9** show the effect of number of longitudinal girders on the moment distribution factors due to dead load, fully-loaded lanes, respectively, for the exterior, middle and interior girders

Generally, In case of dead load, there is insignificant change in the moment distribution factor for the exterior and interior girders with the increase in number of girders for any investigated curvature ratios. Whereas, moment distribution factor for the middle girder increases with the increase in the number of girders especially for larger curvature ratios.

For the case of fully loaded lanes, it can be observed that the moment distribution factor for the exterior and interior girders increases with the increase of number of girders. It can also be noticed that the rate of increase of the moment distribution factor generally higher for the interior girder. Whereas, moment distribution factor for the middle girder generally increases with the increase in the number of girders especially for larger curvature ratios.

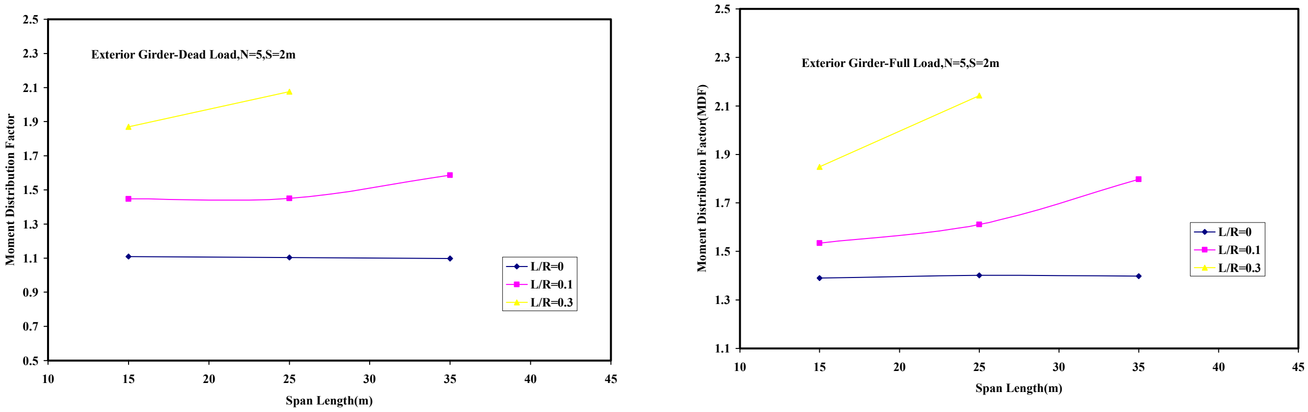


Fig.7: Effect of Bridge Span Length on moment distribution factors

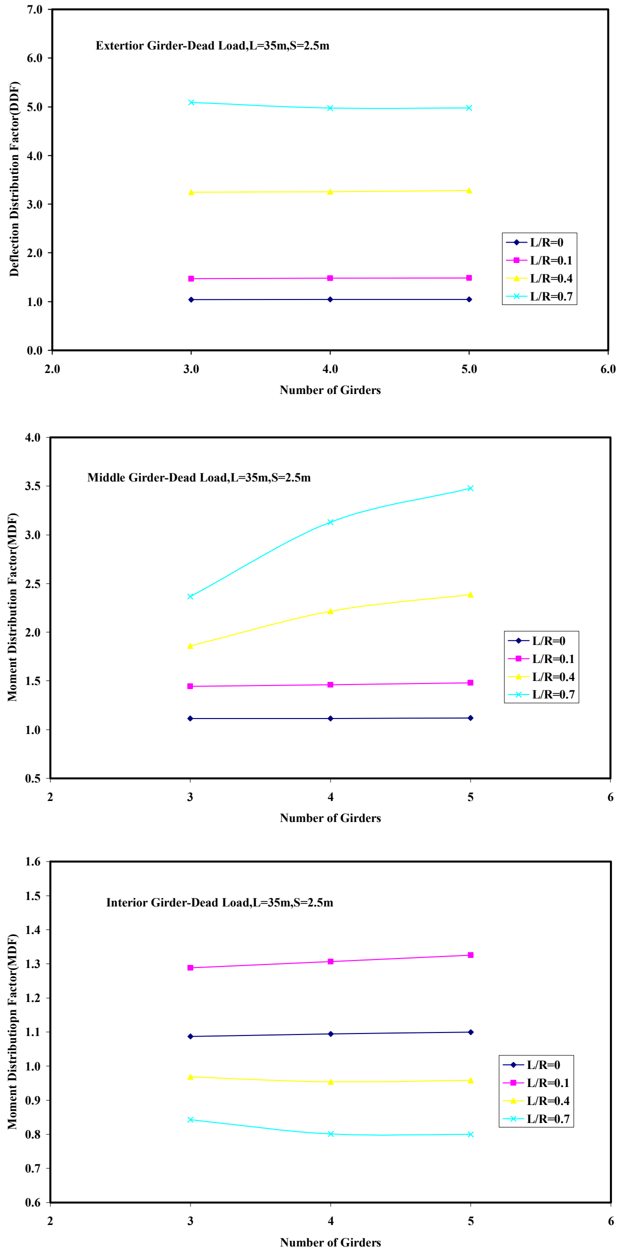


Fig.8: Effect of Number of Girders on moment distribution factors Due to Dead loading

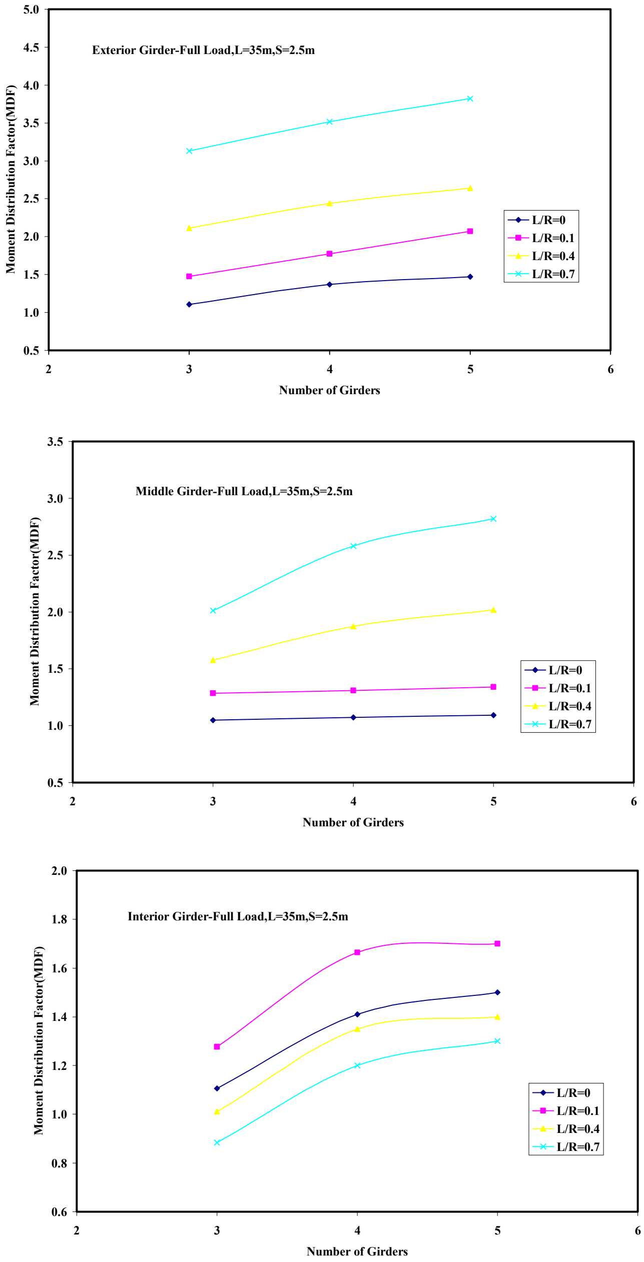


Fig.9: Effect of Number of Girders on moment distribution factors Due to Live loading

EFFECT OF SPACING OF GIRDERS

Figs. 10 and 11 show the effect of the spacing of the longitudinal girders on moment distribution factors for the exterior, middle and interior girders of two-lane curved bridges of 15m span and having 4 girders due to dead load and fully-loaded lanes, respectively.

Generally, it can be observed that the moment distribution factors for all girders increases with the increase in girder spacing for AASHTO truck live loading **(Fig. 11)** especially for the exterior and interior girders. While, the moment distribution factors are almost unchanged with the increase in girder spacing in the case of dead load as shown in **Fig. 10**.

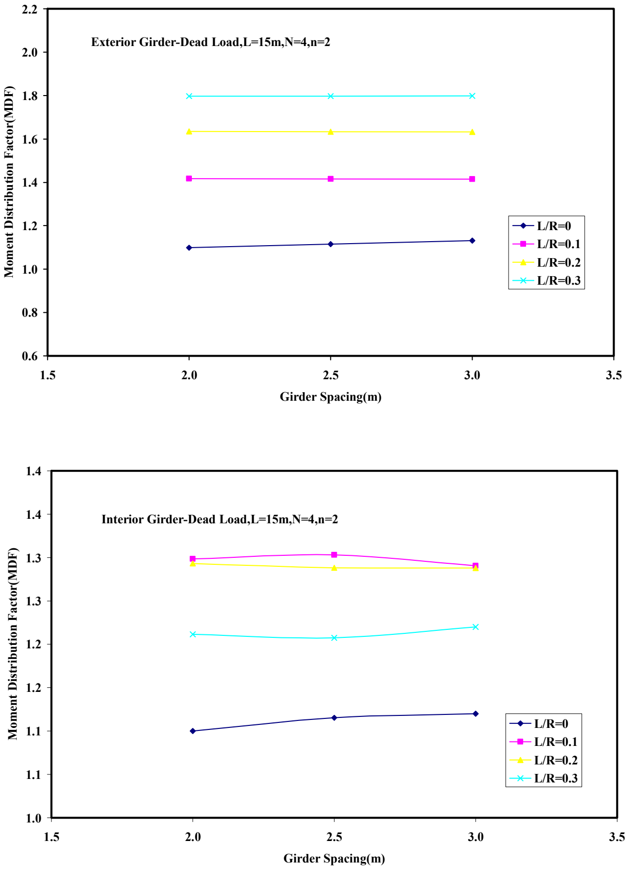


Fig. 10: Effect of Girders Spacing on moment distribution factors Due to Dead loading

EFFECT OF NUMBER OF LANES

Figs. 12 and 13 show the relationship between the moment distribution factors and the number of lanes for the exterior and interior girders of a bridge with five girders, 2 m girder spacing and 15m span length due to fully loaded lanes and partially loaded lanes, respectively.

It is observed that in the full loading case as the number of lanes increases, the moment distribution factors decreases. Hence, for the exterior girder shown in **Fig. 12,** as the number of lanes increases from 2 to 4 lanes the moment distribution factor decreases from 1.83 to 1.59 for L/R=0.3.

For partially loaded lanes no general trend is observed as shown in **Fig. 13**. But, generally the moment distribution factors increases for the exterior girder as the number of bridge lanes is increased.

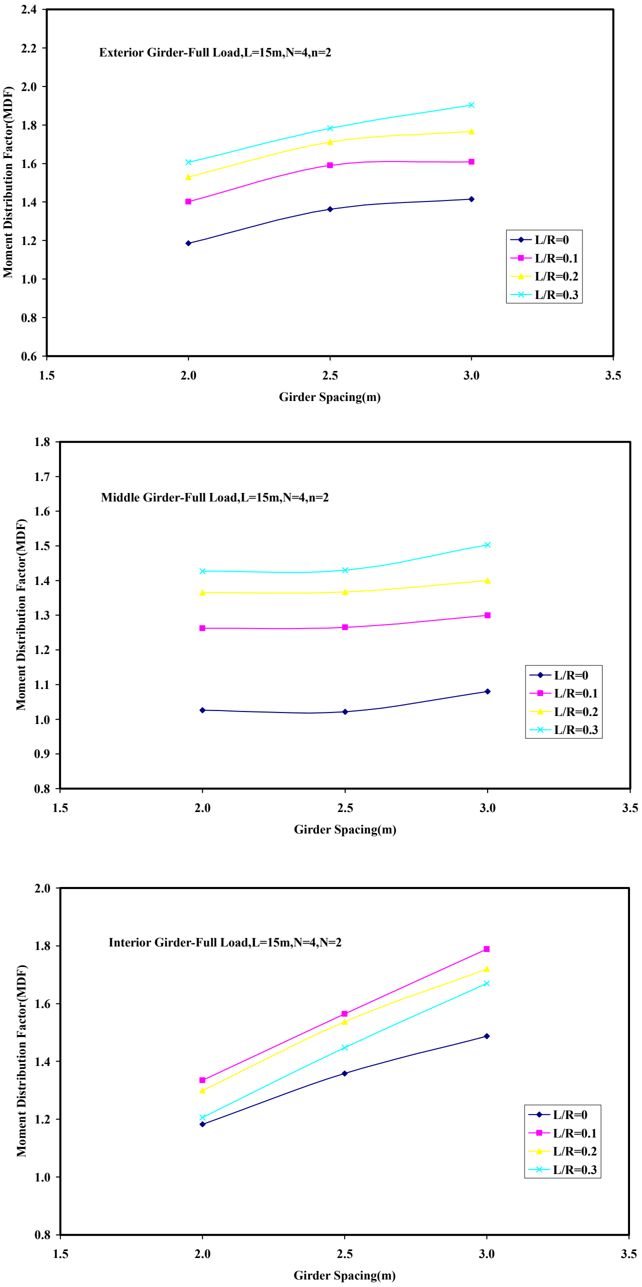


Fig. 11: Effect of Girders Spacing on moment distribution factors Due to Truck loading

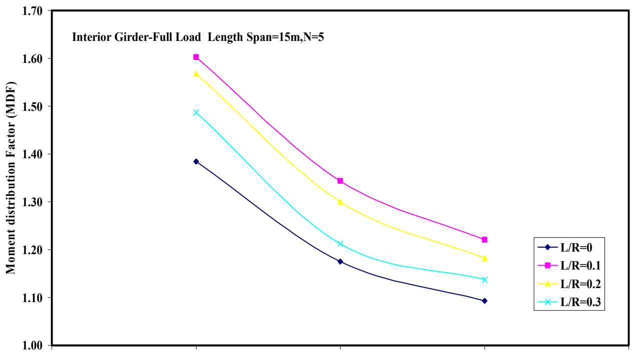


Fig. 12: Effect of Number of Lanes on moment distribution factors Due to Fully loaded Lanes

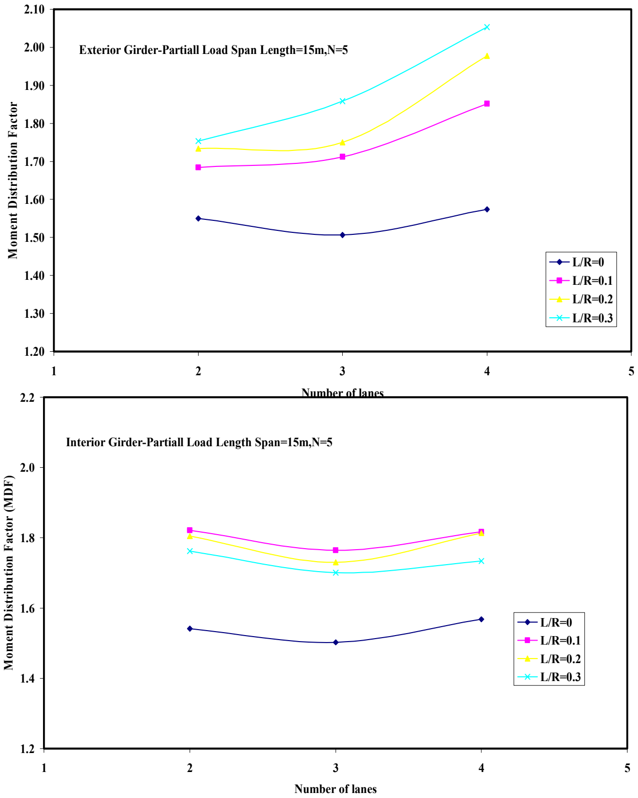


Fig. 13: Effect of Number of Lanes on moment distribution factors Due to partially loaded

EFFECT OF LOADING CONDITION

It is important to examine the effect of number of loaded lanes on the moment distribution factor to establish the critical cases that produce extreme values of moment distribution factors. Accordingly, two loading cases are considered; fully loaded lanes with truck loading and partially loaded lanes with truck loading.

Figs. 14 and 15 show the relationship between results obtained from the case of fully loaded lanes and the case that provides the maximum moment distribution factor of all the partially loaded cases for the exterior and interior girders, respectively. It is worthwhile to mention that these plotted values are for all bridges of 35m and 15m spans regardless of number of lanes, or number of girders or girders spacing.

It can be observed from the above Figures that sometimes with partially loaded lanes are almost half of the live load of the fully loaded lanes, still they can provide extreme design values especially for the interior girder

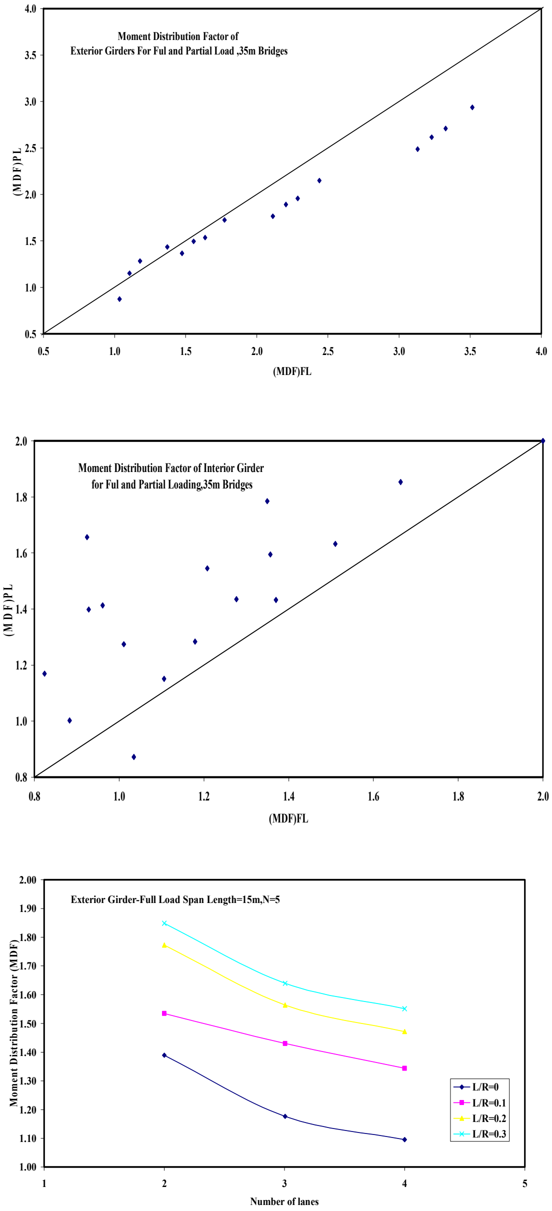


Fig. 14: Effect of loading condition on the moment distribution factor for the 35m span bridges

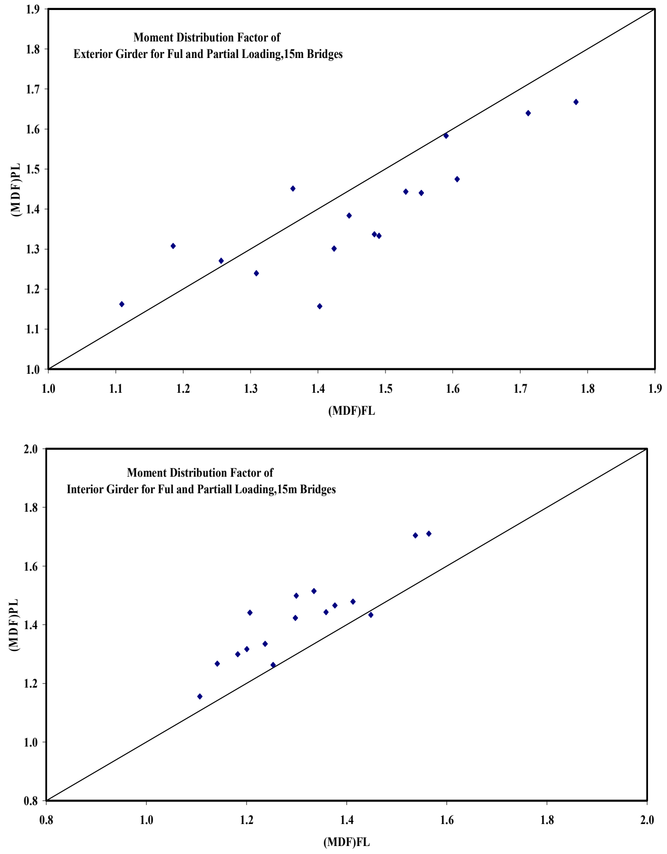


Fig. 15: Effect of loading condition on the moment distribution factor for the 15m span

PROPOSED MOMENT DISTRIBUTION FACTOR EQUATIONS

The current parametric study provides a database for the moment distribution factors for straight and horizontally curved composite concrete-steel bridges. This database can be used to develop expressions for the moment distribution factors for such bridges.

The general equations for load distribution factor for exterior, middle and interior girders for straight and curved I-girder bridges due truck loading and dead loading are presented herein below.

Two equations are proposed for each girder. Equations A includes the three major parameters that affect load distribution factors, as indicated by the correlation matrices. Whereas, equations B includes the six parameters investigated in this study.

Equation B is intended to represent simple relation with the minimum number of variables that may yield sufficiently accurate load distribution factor results. Whereas, Equation B is intended to represent the most general relation that may yield the most accurate load distribution factor results to be used for final analysis and design of curved bridge girders.

TRUCK LOADING

$$(MDF)_{EXT} = 1.11 + .025L + 3.862L/R - .116X \tag{9.A}$$

$$(MDF)_{EXT} = .124 + .025L + .243N + .297S + 3.925L/R - .119X - .323n \tag{9.B}$$

$$(MDF)_{MID} = .969 + .019L + 3.071L/R - .088X \tag{10.A}$$

$$(MDF)_{MID} = .567 + .018L + .087N + .018S + 3.032L/R - .088X - .003n \tag{10.B}$$

$$(MDF)_{INT} = .7 \times (MDF)_{EXT} \tag{11}$$

DEAD LOAD

$$(MDF)_{EXT} = .914 + .025L + 4.347L/R - .1X \tag{12.A}$$

$$(MDF)_{EXT} = .661 + .025L + .03N + .069S + 4.351L/R - .1X - .017n \tag{12.B}$$

$$(MDF)_{MID} = 1.19 + .015L + 3.812L/R - .096n \tag{13.A}$$

$$(MDF)_{MID} = .595 + .014L + .114N + .053S + 3.764L/R - .093X + .000n \tag{13.B}$$

$$(MDF)_{INT} = 0.75(MDF)_{EXT} \tag{14}$$

CONCLUTIONS

Based on the results from the parametric study, the following conclusions are drawn:

1- Curvature is the most critical factor which plays an important role in the design of curved girders in composite bridges. Moment distribution factors increase with the increase in bridge curvature,

2- Span length, number of girders and girders spacing generally affect the values of the moment distribution factors .In general, the increase in the number of girders, girders spacing, and span length results in an increase in the moment distribution factor,

3- The developed sets of empirical expressions for moment distribution factors can be used to obtain the MDF for such bridges.

4- Study reveals that fully loaded lane cases govern the extreme values of the moment distribution factors. Nevertheless, partially loaded lane cases sometimes provide the design value.

5- Results from this study have shown that AASHTO Guide and AASHTO-LRFD criterion to treat curved bridges with small specified amount of curvature as straight ones is safe and conservative.

REFERENCES

- American Association for State Highway and Transportation Officials, AASHTO. 2004. **AASHTO-LRFD Bridge Design Specifications**. Washington, D.C.
- American Association for State Highway and Transportation Officials, AASHTO. 2003. **Guide Specification for Horizontally Curved Highway Bridges**. Washington, D.C.
- American Association of State Highway and Transportation Officials, AASHTO. 1996. **Standard Specifications for Highway Bridges**. Washington, D.C.
- American Association for State Highway and Transportation Officials, AASHTO. 1993. **Guide Specification for Horizontally Curved Highway Bridges**. Washington, D.C.
- Davidson, J. S., Keller, M.A. and Yoo, C.H., "**Cross-frame Spacing and Parametric Effects in Horizontally Curved I-Girder Bridges**", ASCE Journal of Structural Engineering, 122(9): 1089-1096, 1996.
- Qassem, Z.S. , "**Load Distribution Factors for Horizontally Curved Composite Concrete-Steel Girder Bridges**", M.Sc. thesis, Civil Engineering Dept., University of Baghdad, 2004.
- McManus, P.F., Nasir, G.A. and Culver, C. G., "**Horizontally Curved Girders – State of the Art**", Journal of Structural Division. ASCE, 95(ST5): 853-870, 1969.
- Wassef J., "**Simplified Design Method of Curved Concrete slab-on-steel I-girder Bridges**", M.Sc. thesis, Civil Engineering Dept., Ryerson University, Toronto, Ont., Canada, 2004.
- Zuerick, A. and Naqib, R., "**Horizontally Curved Steel I-Girders State-of-the-Art Analysis Methods**", Journal of Bridge Engineering, 4 (1): 38-47, 1999.
- Zureick, A., Linzell, D., Leon, R. and Burrell J., "**Curved steel I-girder bridges: Experimental and analytical studies**". Engineering Structures, 22(2), Elsevier Science Ltd., 180-190, 1998.

NOTATION

L	centre line span of a simply supported bridge
n	number of design lanes
N	number of girders
R	radius of curvature of the centre span of the curved bridge
R L	multi-lane factor
Wc	width of design lane
$(\sigma_{simple})_{DL}$	mid-span stress in bottom flange fibres, for a straight simply supported girder subjected to dead load
$(\sigma_{simple})_{truck}$	mid-span stress in bottom flange fibres, for a straight simply supported girder subjected to AASHTO truck loading
$(MDF)_{DL\ ext}$	the moment distribution factor of exterior girder for dead load case
$(MDF)_{FL\ ext}$	the moment distribution factor of exterior girder for full load case
$(MDF)_{PL\ ext}$	the moment distribution factor of exterior girder for partial load case
$(MDF)_{DL\ mid}$	the moment distribution factor of middle girder for dead load case
$(MDF)_{FL\ mid}$	the moment distribution factor of middle girder for full load case
$(MDF)_{DL\ int}$	the moment distribution factor of interior girder for dead load case
$(MDF)_{FL\ int}$	the moment distribution factor of interior girder for full load case
$(MDF)_{PL\ int}$	the moment distribution factor of interior girder for partial load case