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Load Distribution Factors for Horizontally Curved Concrete Box Girder Bridges

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ABSTRACT

In this study, a 3-D finite element model was used for the analysis of the horizontally curved bridge slab built monolithically with box girders. A parametric study was carried out to calculate the load distribution factors for horizontally curved reinforced concrete box girder bridges based on (AASHTO 1996) live loads by using F.E.M by SAP 2000 (Structural Analysis Program). The parameters considered in this study were: span-to-radius curvature ratio, span length, number of longitudinal girders, girder spacing and number of lanes. The analysis of the bridge was done for the case of full live loads and partial live loads.

Keywords: AASHTO Horizontally Curved Reinforced Concrete Box-Girder Bridge, Load Distribution Factors.

معاملات توزيع الأحمال على الجسور الخرسانية الصندوقية المقطع المنحنية في المستوى الأفقي

الخلاصة

في هذه الدراسة تم استخدام نموذج العناصر المحددة ثلاثية الابعاد في تحليل سقوف الجسور المنحنيه في المستوى الافقي ككتله واحده مع الروافد الصندوقيه. باستخدام طريقة العناصر المحددة تم دراسة العوامل المؤثرة في حساب معامل توزيع الاحمال الحية المسلطة على الجسور المنحنيه في المستوى الافقي ذات الروافد الخرسانيهالمسلحه بالاعتماد على المواصفات (AASHTO 1996) بواسطة برنامج SAP 2000 (برنامج التحليل الانشائي) . ان المتغيرات التي تم اعتمادها في الدراسة هي نسبة الانحناء بالنسبة لفضاء الجسر ، فضاءالجسر،عدد الروافد الطولية ، المسافة التي تفصل بين الروافد بالاضافة الى عدد ممرات السير. اجري التحليل لحالات التحميل بالاحمال الحية الكاملة والجزئية.

INTRODUCTION

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In recent years, concrete box girder bridges have become a popular solution for medium and long span bridges in modern highways and even in railway bridges. This type of bridges is aesthetically pleasing and less vulnerable to environmental conditions compared to open-section Bridges. Accordingly, maintenance costs could be significantly reduced throughout the life of the structure [1].

Box girders have more advantages due to:

i. Their high torsional stiffness which allows freedom in the selection of both the supports and bridge alignment.
ii. The possibility of utilizing the space inside the box girder.

The use of multiple box girders can lead to considerable economy due to their superb torsional stiffness that may be 100 to more than 1000 times that of comparable I-girders [2].

Box-girder bridges are suitable for railroads as well as highways. Railroad structures carry heavier live loads than highway structures. Dynamic loads caused by live loads are a critical issue for bridges, and box-girder bridges have more resistance to vibration effects than classical bridges. Curved box girders are widely used for modern highway bridges and interchanges in large urban areas.

RESEARCH SIGNIFICANCE

This study aims to investigate moment distribution factor (MDF) and deflection distribution factor (DDF) for horizontally curved cast in place reinforced concrete box girder bridges, while AASHTO calculates the MDF and DDF for straight girder bridges only.

AASHTO defines the distribution factor as the ratio of the moment obtained from the bridge system to the moment obtained from a single girder loaded by one truck wheel load.

CONCRETE BRIDGE CONFIGURATIONS

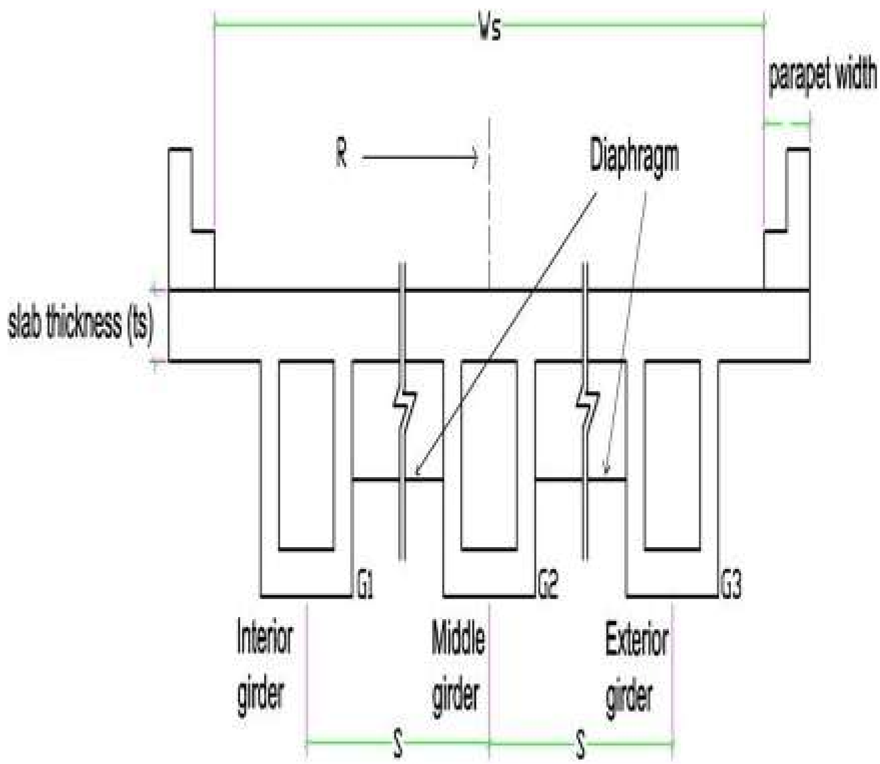
Figure(1) shows the details of the typical concrete box girder bridge'sconfiguration used in this study. Diaphragms are provided between box cells as shown in the Figure. These diaphragms are spaced at equal intervals between the support lines and are made of reinforced concrete to connect the cell boxes. The spacing between these diaphragms is based on limitation of (AASHTO 1996 specification 8.12.3) [3]. Typical plan of straight and curved girders with the distribution of the transverse diaphragms are shown in the Figure (2). The study is based on the following assumptions:

- The reinforced concrete deck slab and reinforced concrete box girders behave in full interaction.
- The bridges are simply-supported.
- All materials arelinearly elastic and homogeneous.
- The effect of road super-elevation and curbs can be neglected.
- Curved bridges have constant radius of curvature between support lines.
- The study does not include the effect of cyclic and fatigue loading.
- The effect of friction force between deck slab and girders is neglected.

Other bridge configurations are listed below: - (See Figure 4)

- The deck slab thickness (ts) is taken as 0.2 m.

- The total bridge width is taken as the deck width (Ws) plus 1.0 m to consider the parapet width of 0.5m on each side of the bridge.
- Link element is modeled to represent the connection between deck slab and box cells (vertical reinforcement) to provide full interaction between them and designed so that the behavior is full interaction (slip very small).
- The depth of the box girder is taken as (0.06 times of bridge span) [3].
- The girder web thickness and bottom flange thickness is considered equal to 0.15m [3].
- Depth to Width ratio is taken forstability and rigidity.
- Dimensions of diaphragms are taken as a ratio from box girder geometry to increase the stability, torsion resistance and easy work before casting.
- Numbers of diaphragms are taken according to AASHTO 1996 requirements (8.12.3 and 9.10.3.3) [3].



Where:

Ws: Deck width.(Road way)
R: Radius of curvature.
S: Girders spacing (center-to-center).
G: Girder**.**

Figure (1) Cross-Section of Concrete Box-girder Bridge.

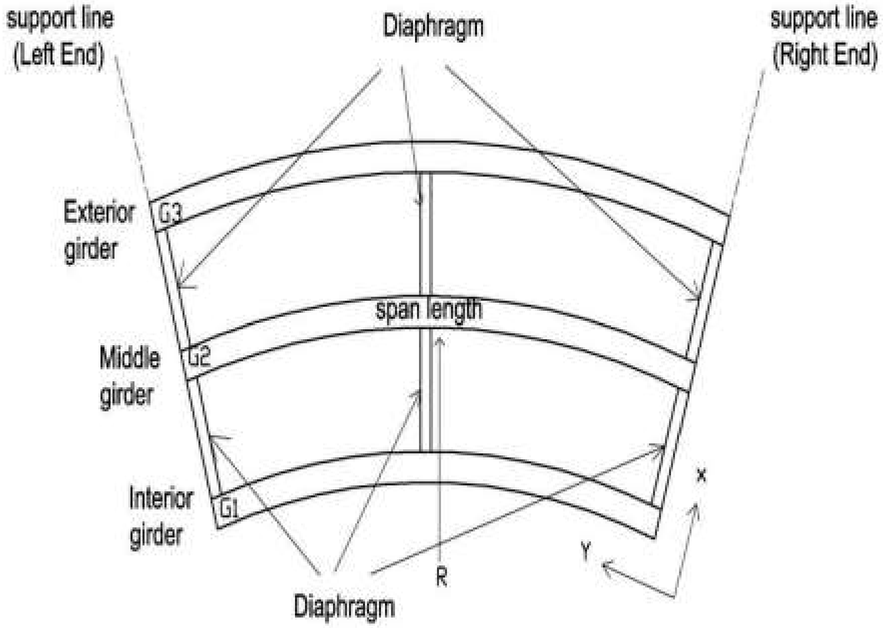


Figure (2) Plan of Concrete Girder Arrangement.

8 simply supported straight and 36 simply supported horizontally curved concrete slab-on-concrete Box girder bridge prototypes are considered for finite-element analysis in this parametric study. Several major parameters are considered as shown in Tables (1) and (2).

Table (1) Bridge Configurations as Considered in this Parametric Study.

Span of Bridge[L] (m)	Number of Girders [N]	Girder Spacing [S] (m)	Number of Lanes [n]	L/R Ratios	Bridge Width (m)	Deck Width [Ws] (m)
20	2	4	2	0,0.2,0.3,0.4	7.5	6.5
	3	4	3	0,0.2,0.3,0.4	11.5	10.5
	4	3	3	0.2,0.3,0.4	13	12
30	2	4	2	0,0.3,0.5,0.6	8	7
	3	4.5	3	0,0.3,0.5,0.6	13	12
	4	4	3	0.3,0.5,0.6	16	15
40	2	4.5	2	0,0.3,0.5,0.7	9	8
	3	5.5	3	0,0.3,0.5,0.7	16	15
	4	5.5	4	0.3,0.5,0.7	21	20
50	2	6	2	0,0.5,0.7,0.9	11.5	10.5
	3	5.5	4	0,0.5,0.7,0.9	17	16

	4	5.5	4	0.5,0.7,0.9	22	21

Table (2) Dimensions for the Boxes and Diaphragms, (See Figure 4).

Span of Bridge(m)	Box Depth [H] (m)	Box Width [B] (m)	Diaphragm Depth (m)	(Depth/Width) Of Diaphragm
20	1.2	1.5	0.6	2
30	1.8	2	0.9	
40	2.4	2.5	1.2	
50	3	3.5	1.5	

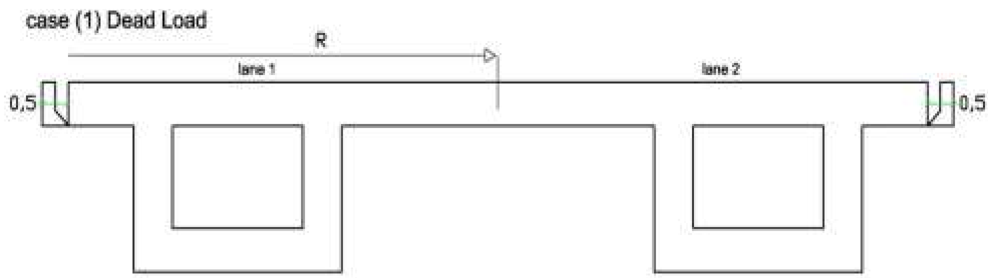
BRIDGE LOADING

According to AASHTO 1996[3], the highway live loadings on the roadways of bridges or incidental structures shall consist of standard trucks or lane loads that are equivalent to truck trains. Two systems of loading are provided, the H loading and the HS loading. The HS loading is heavier than the corresponding H loading.

Each lane load will consist of uniform load per linear meter of traffic lane combined with a single concentrated load (or two concentrated loads in the case of continuous spans), so placed on the span as to produce maximum stress. The concentrated and uniform loads will be considered as uniformly distributed over a three meter width on a line normal to the centerline of the lane.

For truck loading there are four standard classes of highway loading: H20, H15, HS20, and HS15. Loading H15 is 75 percent of loading H20. If there is a need to other than the above loadings it should be designed. They shall be obtained by proportionately changing the weights shown for both the standard truck and the corresponding lane loads. The H loading consists of a two-axel truck or the corresponding lane loading. The H loading is designated H followed by a number indicating the gross weight in tons of the standard truck. The HS loading consists of a tractor truck with semi-trailer or the corresponding lane loading.

The loading conditions considered herein include dead load case and truck loading case. Figure (3) shows schematic diagrams of the loading cases for two-lanes bridge considered in determining the structural response of the interior girder, middle girder, and exterior girder.



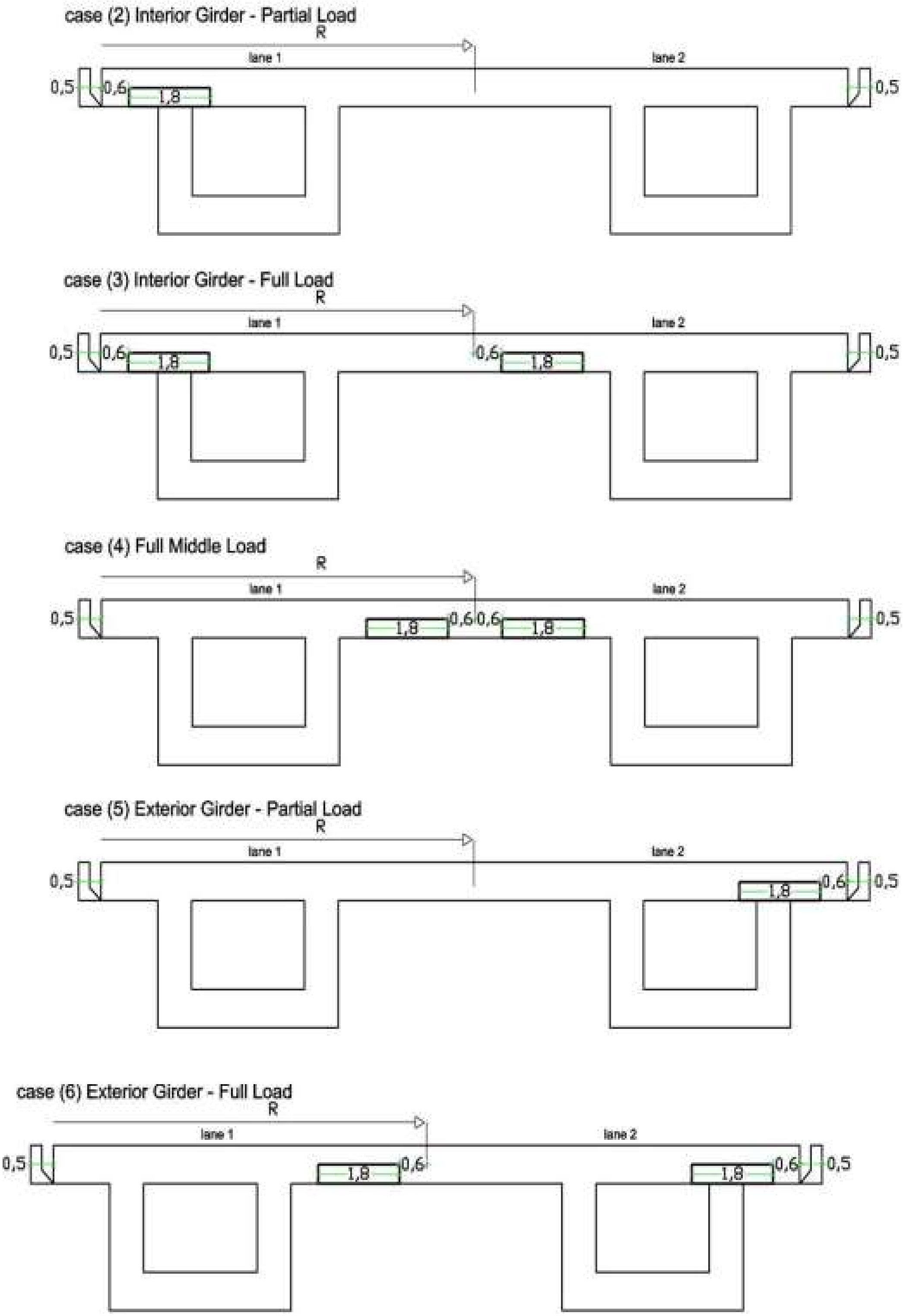


Figure (3) Live loading cases for two-lanes bridge Boundary Conditions.

*Where:*is a truck load

In the bridge supports modeling in this study, the center nodes of the lower flange of box girder 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 directions. 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 (towards the bridge longitudinal direction). 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 transversedirection) [4].

CALCULATION OF THE MOMENT DISTRIBUTION FACTORS

To determine the moment distribution factor (MDF) for a 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 maximumlongitudinal 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 Canadian Highway Bridge Design Code (CHBDC) [4] as follows:

For Exterior girders:

$$(MDF)_{DLe}=(\sigma_{FEe})_{DL}/(\sigma_{Str})_{DL} \quad \ldots(1)$$

$$(MDF)_{FL.e}=(\sigma_{FE.e})_{FL}*N/\ ((\sigma_{Stt})_{LL} * n) \quad \ldots(2)$$

$$(MDF)_{PLe} =(\sigma_{FE.e})_{PL}* N * ML'/((\sigma_{Str})_{LL}* n * ML) \quad \ldots(3)$$

For Middle girders:

$$(MDF)_{DL.m}=(\sigma_{FE.m})_{DL}/(\sigma_{Str})_{DL} \quad \ldots(4)$$

$$(MDF)_{FL.m}=(\sigma_{FL.m})_{FL}*N/\ ((\sigma_{Strt})_{LL} * n) \quad \ldots(5)$$

For Interior girders:

$$(MDF)_{DL.i}=(\sigma_{FE.i})_{DL}/(\sigma_{Strt})_{DL} \quad \ldots(6)$$

$$(MDF)_{FL.i}=(\sigma_{FE.i})_{FL}*N/\ ((\sigma_{Strt})_{LL} * n) \quad \ldots(7)$$

$$(MDF)_{PL.i}=(\sigma_{FE.i})_{PL}*N*ML' / ((\sigma_{Strt})_{LL} * n* ML) \quad \ldots(8)$$

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 letters e, m, and irefer to the exterior, middle, and interior girders, respectively. $(\sigma_{FE.\ e})_{DL}$, $(\sigma_{FE.\ e})_{FL}$, and $(\sigma_{FE.\ e})_{PL}$ are the maximum longitudinal stresses which are the greater at bottom flange points 1 and 3, as shown in Figure (4) which are found

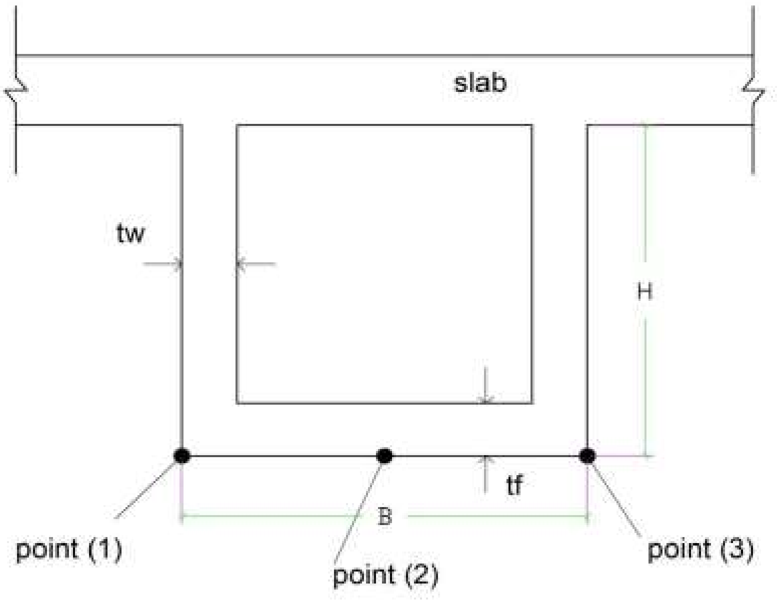
from the finite-element analysis for the exterior girder due to dead load, fully loaded lanes, and partially loaded lanes , respectively. In the same criteria, $(\sigma_{FE.m})_{DL}$, $(\sigma_{FE.m})_{FL}$, $(\sigma_{FE.i})_{DL}$, $(\sigma_{FE.i})_{FL}$, and $(\sigma_{FE.i})_{PL}$ are the maximum stresses which are the greater of points 1 and 3 but for the middle and interior girders under the same above types of loading, while ML, ML′, n, and N are defined as:
n: number of design lanes,
ML: multi-lane factor based on the number of the design lanes; as shown in Table 3,
ML′: multi-lane factor based on the number of the loaded lanes; as shown in Table 4,
N: number of girders.

Table (3) Number of Design Lanes [4].

Width of Design Lane	ML
Over 6.0 m to 10.0 m included	2
Over 10.0 m to 13.5 m included	3
Over 13.5 m	4

Table (4) Modification Factors for Multilane Loading [4]

Number of Loaded Design Lanes	Modification Factor (ML′)
1 or 2	1
3	0.85
4 or more	0.75



Where:
H: Depth of Box Girder.
B: Width of Box Girder.
tw: Thickness of box girder web.
tf: Thickness of box girder flange.

Figure (4) - Cross-Section of Box Girder.

CALCULATION OF THE DEFLECTION DISTRIBUTION FACTORS

To determine the deflection distribution factor (DDF) for a curved girder, the mid-span deflection, $(\delta_{Straight})_{truck}$, $(\delta_{Straight})_{DL}$ are calculated for a straight simply supported girder subjected to AASHTO truck loading, and dead load, respectively. Similar to the above MDF cases, the span of the straight simply supported girder is taken as the curved length of the bridge centerline. The deflection values of the idealized girder due to truck loading and dead load are calculated using SAP2000 software [5]. From the finite-element modeling, the mid-span deflection values at the middle of the bottom flange due to dead load, fully loaded lanes, and partially loaded lanes are determined. Consequently, the deflection distribution factors (DDF) were calculated as Canadian Highway Bridge Design Code (CHBDC) [4] as follows:

For exterior girders:

$$(DDF)_{DL.e} = (\delta_{FE.e})_{DL} / (\delta_{Strt})_{DL} \quad \ldots(9)$$

$$(DDF)_{FL.e} = (\delta_{FE.e})_{FL} * N / ((\delta_{Strt})_{LL} * n) \quad \ldots(10)$$

$$(DDF)_{PL.e} = (\delta_{FE.e})_{PL} * N * ML' / ((\delta_{Strt})_{LL} * n * M L) \quad \ldots(11)$$

For middle girders:

$$(DDF)_{DL.m} = (\delta_{FE.m})_{DL} / (\delta_{Strt})_{DL} \quad \ldots(12)$$

$$(DDF)_{FL.m} = (\delta_{FE.m})_{FL} * N / ((\delta_{Strt})_{LL} * n) \quad \ldots(13)$$

For interior girders:

$$(DDF)_{DL.i} = (\delta_{FE.i})_{DL} / (\delta_{Strt})_{DL} \quad \ldots(14)$$

$$(DDF)_{FL.i} = (\delta_{FE.i})_{FL} * N / ((\delta_{Strt})_{LL} * n) \quad \ldots(15)$$

$$(DDF)_{PL.i} = (\delta_{FE.i})_{PL} * N * ML' / ((\delta_{Strt})_{LL} * n * M L) \quad \ldots(16)$$

Where $(DDF)_{DL}$, $(DDF)_{FL}$, and $(DDF)_{PL}$, are the deflection distribution factors for dead load, fully loaded lanes, and partially loaded lanes, respectively. And the letters e, m, and i refer to the exterior, middle, and interior girders, respectively. $(\delta_{FE.e})_{DL}$, $(\delta_{FE.e})_{FL}$, and $(\delta_{FE.e})_{PL}$ are the deflections at point 2, refer to Figure (4), which are found from finite-element analysis for the exterior girder due to dead load, fully loaded lanes, and partially loaded lanes, respectively. In the same manner, $(\delta_{FE.m})_{DL}$, and $(\delta_{FE.m})_{FL}$, $(\delta_{FE.i})_{DL}$, $(\delta_{FE.i})_{FL}$, and $(\delta_{FE.i})_{PL}$ are the finite element deflections for the middle and interior girders under the same above types of loading. While ML, ML′, n, and N are defined as before.

GEOMETRIC MODELING

A three-dimensional finite-element model was developed to simulate each bridge considered in this study. Three-dimensional shell elements were selected to model the reinforced concrete deck slab, reinforced concrete webs and reinforced concrete flanges. The arrangements of elements in the transverse and longitudinal directions were selected to accurately simulate the actual structure geometric configurations.

SAP2000 [5] has a three-or four-node formulations for shell elements. The formulation combines the membrane and plate-bending behavior. The shell element used in this study is a homogeneous one. The element 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. The element has six degrees of freedom at each node, namely: three displacements (U1, U2, U3) and three rotations (ϕ1, ϕ2, ϕ3). Four-point numerical full integration formulation is used for the shell stiffness. Internal forces, moments, and stresses are evaluated at the 2x2 Gauss integration points and then extrapolated to the nodes representing the element. Therefore, the four-node elements were used to model the plate components of the bridges studied.

RESULTS &DISCUSSION

The truck live load data shown in Table (5) is considered and taken from AASHTO - 1996 [3] for analysis and design. The geometry of each element of concrete bridge is calculated and a preliminary design is made. Materials properties are assumed but including the requirements of AASHTO [3] - Table [6].

Table (5) Types of Loading.

Type of loading	Values
Dead load	Self weight for members + weight of 100mm thick asphalt.
Live load	HS 20 - 44

Table (6) Material Properties.

Concrete	Values
E_C	23500 MPa
f_c'	25 MPa
γ_c	24kN/m³
ν	0.2

Where:

E_C: Modulus of elasticity for concrete.
f_c': Cylinder compressive strength of concrete.
γ_c: Weight per unit volume of concrete.
ν:Poissons's ratio of concrete.

Moment Distribution Factor

Effect of Curvature:

The results of the current parametric study reveal that curvature of the bridge is one of the most significant parameters affecting the distribution of moments between the longitudinal girders. The curvature ratio (L/R) is up to (0.4) for span length (20 m), up to (0.6) for span length equal to (30 m), up to (0.7) for span length equal to (40 m) and up to (0.9) for span length equal to (50 m). MDF of curved girders is less than that of straight girders. As curvature ratio increases for curved girders, MDF increases because when the curvature (R) decreases, the stresses concentration decreases.Figure (5) below shows the variation in the moment distribution factor for the interior girder of two, three and four-lanes bridge with two, three, and four girders, with the increase in the span-to radius of curvature ratio (L/R) due to partially-loaded lanes and fully-loaded lanes with live loading.

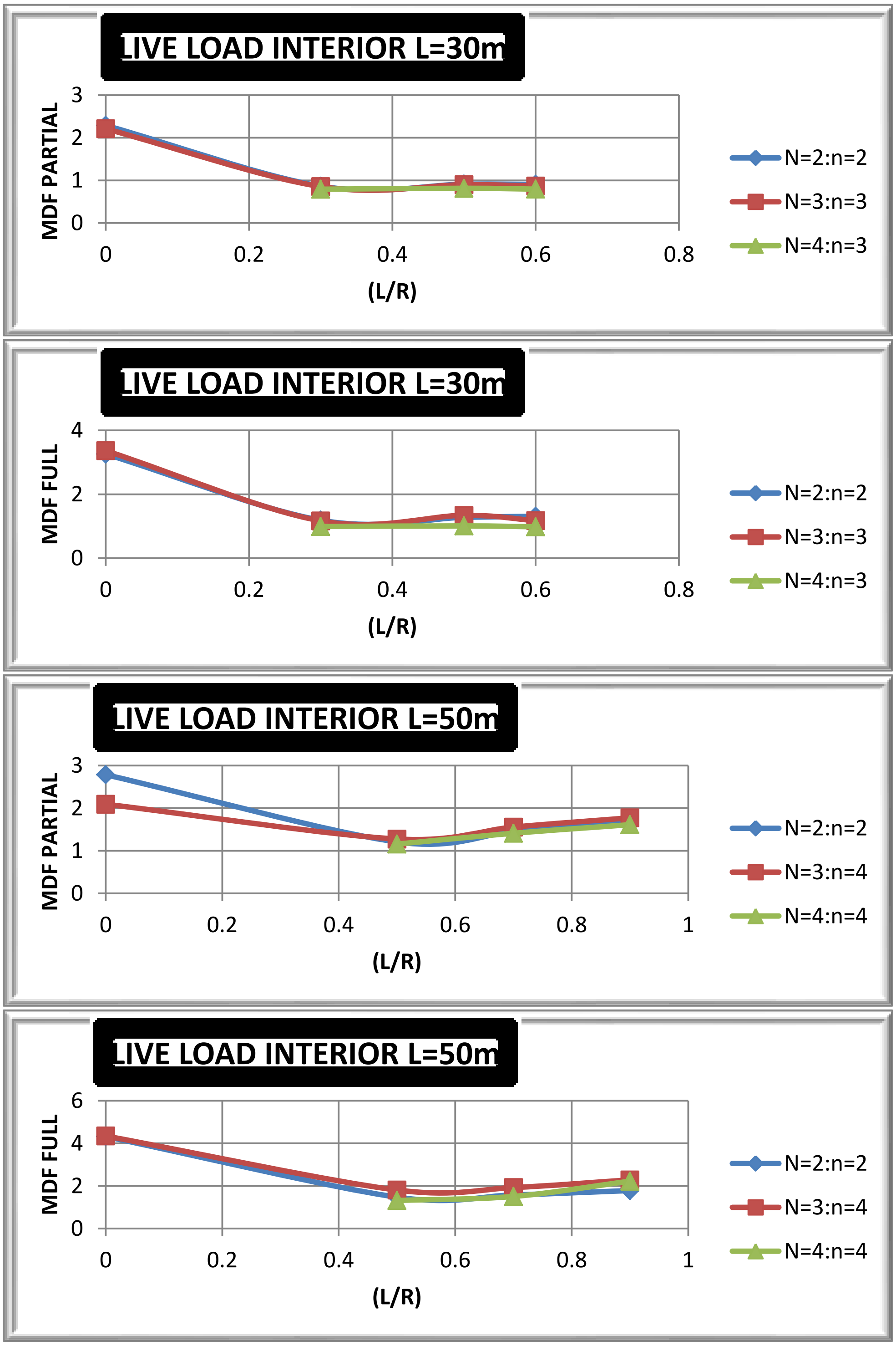


Figure (5) Effect of Curvature on the Moment Distribution Factor for the Interior Girder due to Live Load.

EFFECT OF SPAN LENGTH

The results for the effect of bridge span length on the moment distribution factors for the exterior and interior girders of two-lanes, two girders due to dead load, live load (as interior, middle and exterior) for partially and fully loaded lanes are shown in the Figure (6). It can be observed that the moment distribution factor generally increases when the length increases. As the length of the span increases, the overall depth of box girders increases then the moment of inertia increases. When the moment of inertia increases the stress decreases then the MDF increases.Figure (6) below shows the selected results for the effect of bridge span length on the moment distribution factors for the interior girders of two-lanes, two girders due to partially-loaded lanes and fully-loaded lanes with live loading.

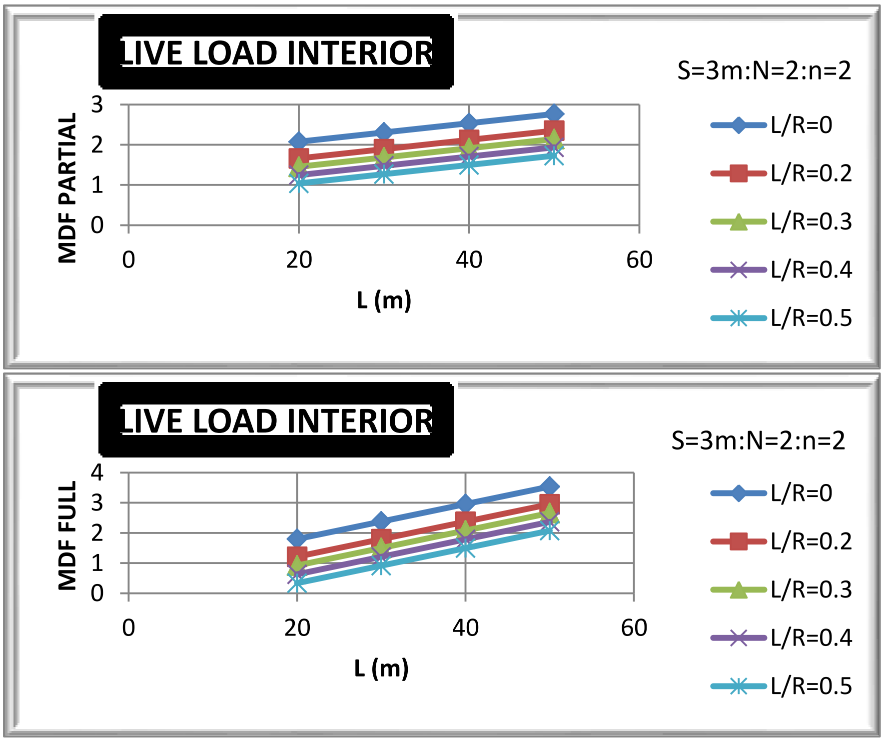


Figure (6) Effect of Span Length on the Moment Distribution Factor for theInterior Girder due to Live Load.

DEFLECTION DISTRIBUTION FACTOR

Effect of Curvature:

The effect of curvature of the bridge on the central deflection occurs on each girder and reflects the deflection distribution factor for each model is shown in the Figure (7). The curvature ratio (L/R)of the present study is up to (0.4) for span length (20 m), up to (0.6) for span length equal to (30 m), up to (0.7) for span length equal to (40 m) and up to (0.9) for span length equal to (50 m). DDF of curved girders is less than that of straight girders. As the curvature ratio increases for curved girders, DDF increases because when the curvature (R) decreases, the deflection for each girder increases.Figure(7) below shows the effect of curvature on the deflection distribution factors for the interior and middle girders of two ,three and four-lanes curved bridges with two, three and four girders for the live load cases.

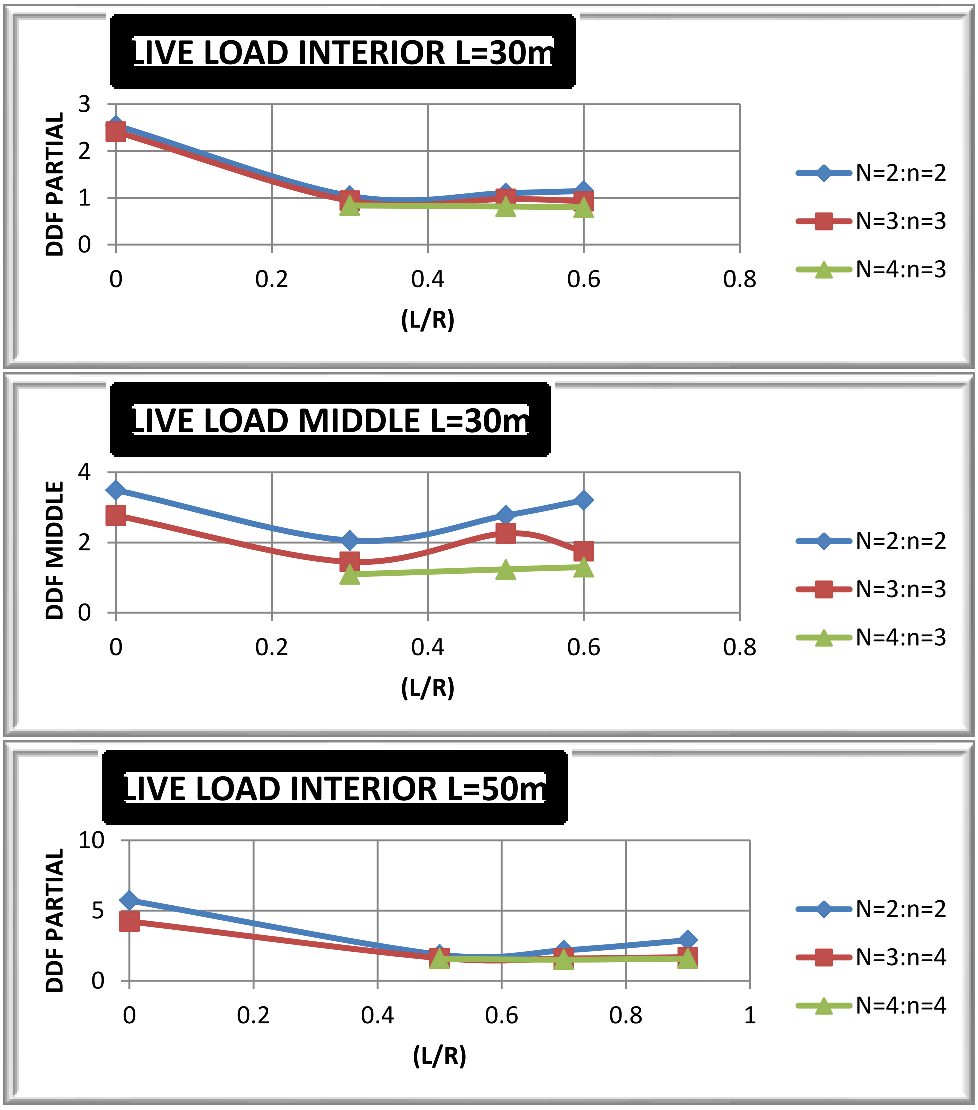


Figure (7) Effect of Curvature on the Deflection Distribution Factor for the Interior and Middle Girder due to Live Load-To be continued.

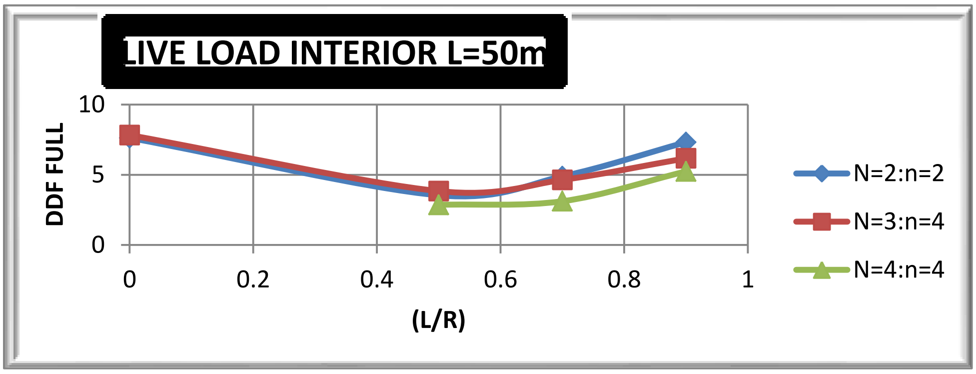


Figure (8) Effect of Curvature on the Deflection Distribution Factor for the Interior and Middle Girder due to Live Load.

Effect of Span Length:

The effect of bridge span length on the deflection distribution factors for the exterior and interior girders of two-lanes, two girders due to dead load, live load (as interior and exterior) for partial and full loaded lanes is shown in the Figure (9). It can be observed that the deflection distribution factor generally increases when the length increases (in general the central deflection increased when the span increase because of the stiffness of the bridge decrease), so that the deflection distribution factor increases. As the length of the span increases, the overall depth of box girders increases, so the moment of inertia increases then the deflection decreases and the DDF increases. Figure (10) shows selected results for the deflection distribution factors for the interior girder of two-lanes, two-girders bridge for different span lengths and degrees of curvature.

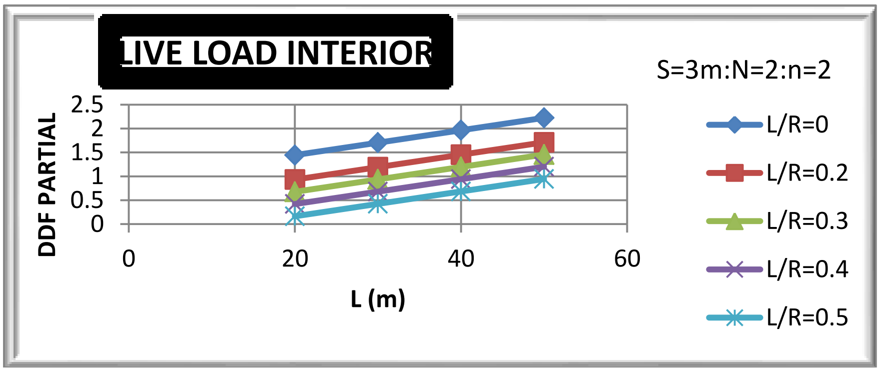


Figure (9) Effect of Span Length on the Deflection Distribution Factor for the Interior Girder due to Live Load-To be continued.

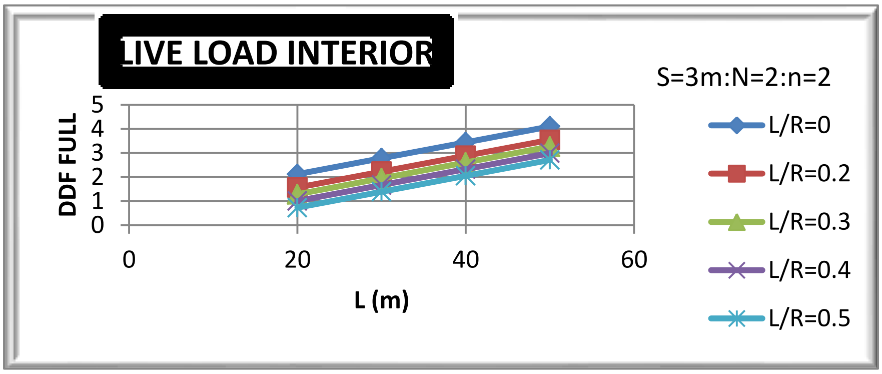


Figure (10) Effect of Span Length on the Deflection Distribution Factor for the Interior Girder due to Live Load.

CONCLUSIONS

Based on this study, the following conclusions can be made:

1) The curvature of the bridge is one of the most significant parameters affecting the distribution of moments between the longitudinal girders. The MDF of curved bridges decreases with respect to the straight girders. When the curvature ratio increases the MDF increases also. The percentage ratio of MDF is between (29% - 281%) for curvature ratio (0.2 - 0.9).
2) The effect of the span length on the moment distribution factor generally increases when the length increases. The percentage ratio of MDF is between (132% - 619%) for span length (20 - 50) m.
3) The DDF for curved girders decreases with respect to the straight girders. When the curvature ratio increases, the DDF increases also. The percentage ratio of DDF is between (22% - 277%) for curvature ratio (0.2 - 0.9).
4) The effect of the span length on the deflection distribution factor generally increases when the length increases. The percentage ratio of DDF is between (131% - 376%) for span length (20 - 50) m.

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