Experimental Study for Horizontally Curved Box Girder Bridges with Special Reference to the Live Load Moment Distribution Factor

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Abstract: -The main objective of this research is to study the live load moment distribution factor (MDF) for horizontally curved reinforced concrete multi-spine bridge under **AASHTO LRFD** HL-93 live load through an experimental program. This program includes three simply supported horizontally curved bridge models with a different radius of curvature and one straight model used as (Reference model). The girder support reaction under each bridge model is recorded by eight-load cell connected to weight indicator to measure the reaction increment under each load case. The moment distribution factor (MDF) was calculated according to the equilibrium method and compared with AASHTO LRFD formulas for cast in place concrete box girder. The experimental results showed that the AASHTO formula underestimates the MDF with 33% for the exterior girder (G1) for the straight model and (38%, 47%, 53%) for curved models with θ (10^0, 13.5^0, 18^0) respectively. In contrast, the AASHTO formula overestimates the MDF for interior girder (G2) with (30 %)in the case of straight model and overestimate the MDF with (44%60,69%) for (θ (10^0, 13.5^0, 18^0) respectively.

Keywords: Horizontally curved, Live load distribution factor

1. Introduction

The radius of curvature (R) can be considered as one of the most important factors that effects on the live load distribution along bridge girders [10]. Many studies were conducted to develop a new simplified equation for the live load distribution factor (LLDF) instead of the classical formula (S/D) [10].

Zokaie`s et al study [14] and National Cooperative Highway Road project NCHRP [8,9] report (12-26) established the current AASHTO LRFD live load distribution factor formulas for concrete box girder. There is no statement, which these formulas applicable for curved box girder bridge, two main fields well studied to check the applicability of these formulas as follows:- Firstly was present through field monitoring and bridge performance. This procedure includes applying an AASHTO truck on straight or curved bridge previously constructed and designed, then asses the bridge response, the results will be compared with the current ASSHTO formula to check where these equation over or underestimate the curved bridge performance Dereck J. Hudson **[**4]. Secondly; theoretical study by conducting a 3D finite element analysis using available commercial software based on serval parameters to show how these variables effect on the live load distribution along bridge girders such (span length to the radius of curvature (L/R) ; number of loaded lane (NL); the number of box (NB) and the width of the carriageway (W)). Aimad Alden Khalif [6]; Mohammed Zaki [7]

2. Experimental Program

Three horizontally curved models with radius of curvature (12.5, 16.7, and 23.3) m and angle of curvature (10^0, 13.5^0, 18^0) and one straight model used as (reference model). These four models had been designed and constructed according to AASHTO LRFD standard specification. All the bridge models have the same cross-section as shown in **Fig 1.** Each bridge model includes two separated box girder connected through deck slab and two end and intermediate diaphragms. The simply supported prototype bridge span is (24 m) scaled by (1/6) with the overall carriageway width of (8.4 m) scaled to (1.4 m), the details of tested bridge models are listed in **Table 1**.The overall mold formed by CNC machine depend on Auto-CAD drawing represent the scaled down models dimension. The models construct into two stages. First includes the re-bar stage for bottom slab; End and intermediate diaphragm reinforcement; fixing vertical web reinforcement and finally casting the bottom slab as shown in **Fig 2**. The second stage includes fixing the longitudinal web reinforcement; forming box section; deck slab reinforcement and finally casting the web and deck slab together as shown in **Fig 3.**

3. Test procedure

3.1 Partially Loaded Lane (One Lane)

Include applied the design truck (I) or the design tandem (IV) at the external lane to find the maximum effect on the exterior girder (G1) as shown in Fig 5 Finally, one design truck will applied on the internal lane (II) to find the distribution factor for interior girder (G2) from this load All load cases are applied in the longitudinal direction according to Barre's Theorem for simply supported spans as shown in Fig 5 for the scaled design truck and Fig 6 in case of design tandem

3.2 Full Loaded Lane (Two Lanes) Two-design truck (III) applied on both lanes to find the maximum effect on the interior girder as shown in Fig 7

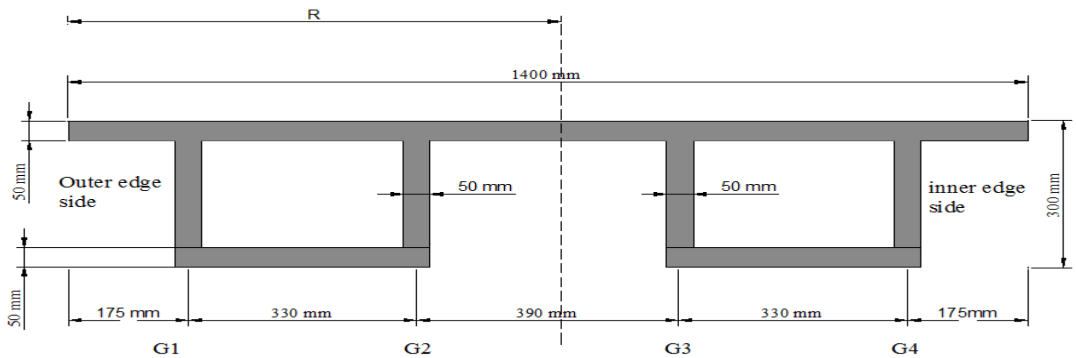

Fig. 1 Bridge models cross section

Table. 1 Dimension and properties of tested bridge models

Bridge Models	Central Span (m)	Radius of Curvature (m)	Angle of Curvature (degree)	(L/R)	Girders arch length (L_{as}) in m			
					G1	**G2**	**G3**	**G4**
BGS	4.0	0	0	0	4.000	4.000	4.000	4.000
BGC R12.5	4.0	12.5	18	0.31	4.170	4.07	3.95	3.85
BGC R16.7	4.0	16.7	13.5	0.23	4.13	4.05	3.96	3.89
BGC23.3	4.0	23.3	10	0.171	4.10	4.04	4.03	3.95

Fig. 3 Second stage of BGC R 23.3 construction

Fig. 2 First stage of BGC R12.5 construction

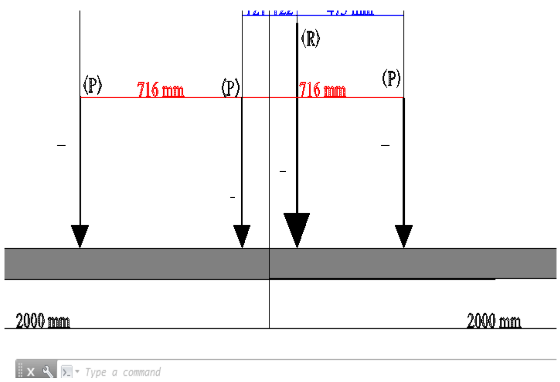

Fig. 5 section at mid span; Long direction for load case (I, II,III); axle location of scaled design truck

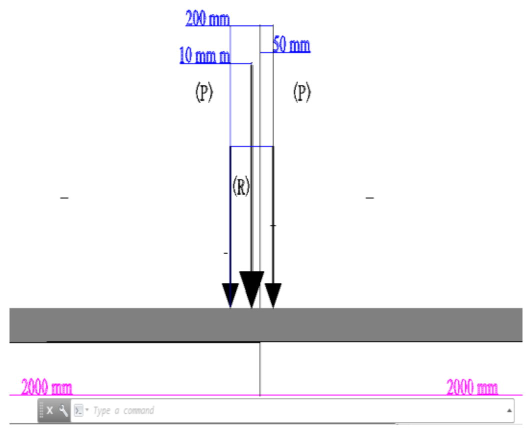

Fig. 6 Section at mid span; Long direction for load case (IV); axle location of scaled design tandem

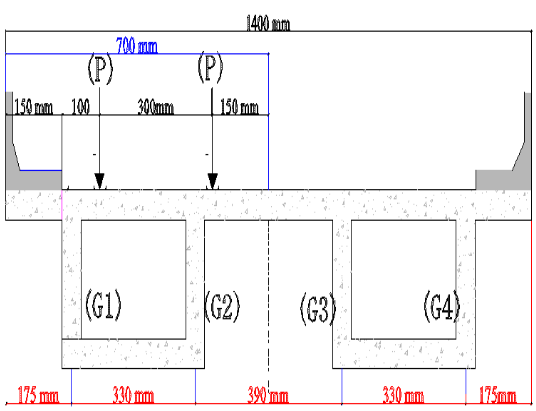

Fig. 4 Load case (I, II,IV) in the transverse direction (model)

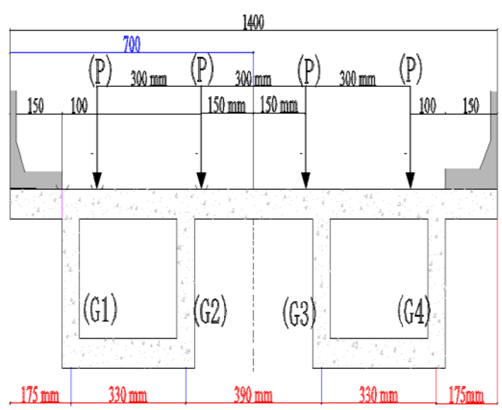

Fig. 7 Load case (III) in the transverse direction (model)

4. Instrumentation

Eight load cells of 5 Ton capacity were used one under each girder for the left and right sides of bridge models to measure the support reaction under each loading stages as shown in Fig 8. The reading from these load cells were recorded by a weight indicator connected to each load cell separately and calibrated

5. HL-93 Live Load

HL-93 is a type of theoretical vehicular loading proposed by AASHTO" in 1993 and it's a combination of three different loads as follows:-

A-HL-93 Design Truck (formerly, HS20-44 Truck)

B-HL-93 Design Tandem (formerly, Alternate Military)

C-Design Lane Load

Even the experimental program covers all the load combinations (A+C, B+C). But the study includes only the effect of the loading (A,B) separately to get a good understanding of wheel load distribution along curved bridge girder, the details of AASHTO design vehicles are given below:-

A-**Design Truck** consists of three axles, front and two rear axles with front axle weighing 8kip (35 kN) and two rear axles weighing 32kip (145 kN). The distance is 14 ft (4.3m) between front and rear truck axle and that of two rear axles can be varied between 14' (4.3m) to 30 ft (9.0m) to obtain the max design force. The tire-to-tire distance in any axle is 6 ft (1.8m). As shown in **Fig. 9.**

B- **Design Tandem** consists of twin axles spaced 4 ft. (1.2m) apart, weight of each axle is 25kip (110 kN). The distance between the tires in an axle is 6 ft (1.8m). As shown in in **Fig. 10**

C- The design **Lane Load** applied as uniformly distributed load of a magnitude (9.3 kN/m) along the longitudinal direction and across the lane width in the transverse direction.

The design truck was modeled based on real truck dimensions with the same scale factor that used for bridge cross section (1/6). The equivalent design truck and the design Tandem was modeled using two IPN-220 steel beam connect together with steel channel to ensure that the center of truck resultant coincide with point load application as shown in Fig 11 The total trucks scaled load is given in Table 2 according simulation requirement that given by **Harry** and **Gajanan [5]** . The load applied using manual hydraulic jack load and load cell Tons as shown in Fig (12 to 15)

Fig.8 Load cell under bridge girder

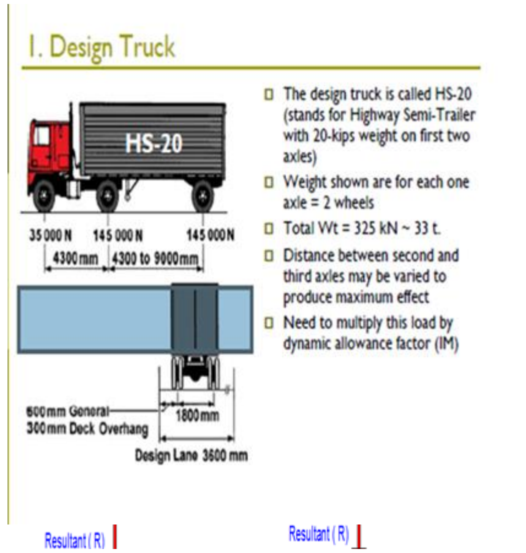

Fig. 9 HL-93 design Truck [3]

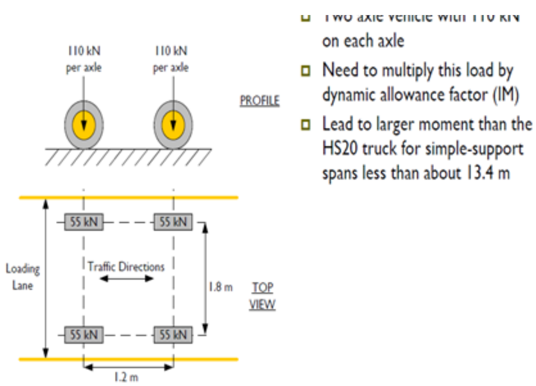

Fig.10 HL-93 Design tandem [3]

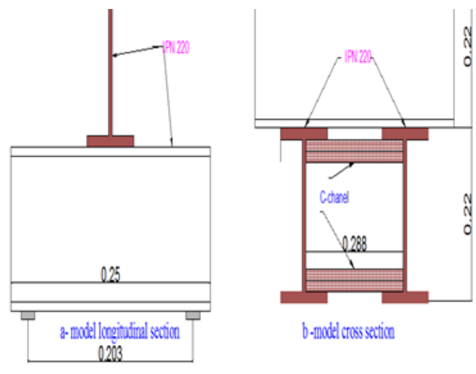

Fig.11 Scaled design tandem

Table. 2 Similitude Requirements (Harry and Gajanan)

Type of Truck	Total wheel load (R)	Concentrated load, Q S^2_L=1/36
design truck	325 kN	9 kN
Design tandem	220 kN	6.1kN

6. Experimental Results

The moment distribution load factors (MDF) can be computed from static quilibrium, depend on the values of girders support reaction when the load at mid span using equation below

$$(MDF)_i = \frac{P_i}{\sum_1^n P_j/N} \qquad (1)$$

Where P_i and P_j are the reaction force from the static equilibrium that record by a load cell and weight indicator. n is the number of the girders in the cross section and N is the number of loaded lanes. The MDF from experimental result can be classified into-

4.1. MDF due dead load effect

The girder reaction under the effect of model self-weight was listed in Table 3 and by applying Eq (1) , the MDF due

dead load effect are listed in Table 4

4.2 MDF due live load effect

The same procedure that mentioned in section 6.1 will be applied for the live load effect. The MDF result will be classified according to the mid span load cases and can be categorized as follow:-

A-MDF for load case (I)

One design truck applied at the exterior lane (outer side) as shown in Fig 12, the girder reaction due to load case (I) is given in Table 5, by using Eq 1 the MDF are listed in Table 6

B-MDF for load case (II)

One design truck applied on the interior lane as shown in Fig 13, the girder reaction result are given in Table 7 while the MDF listed in Table 8

C- MDF for load (III)

Tow design Truck applied on both lanes lane as shown in Fig 14 and the reaction result are given in Table 9, the MDF are listed in Table 10

D- MDF for load case (IV)

The design tandem applied on the external lane as shown in Fig 15 and the reaction are given in Table 11.The result of MDF are given in Table 6.12

Fig.12 Design truck at the exterior lane load case (I) for model BGC

Fig.14 Load case (III) in the transverse direction (model) BGS

Fig. 13 Design truck at the internal lane load case (II) for model BGC R12.5

Fig.15 Design tandem at the external lane load case (IV) for model BGS

Table. 3 (Left + Right) Girder support reaction under self-weight effect (N)

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5
G1	4900	6900	5900	5450
G2	4400	5000	4750	4700
G3	4400	5300	5100	5050
G4	4850	3000	3400	3800

Table. 4 MDF result from equilibrium method under self-weight effect

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5
G1	0.275	0.275	0.286	0.3
G2	0.23	0.23	0.247	0.24
G3	0.23	0.23	0.26	0.26
G4	0.261	0.261	0.2	0.17

Table. 5 (Left + Right) Girder support reaction under load case (I) (N) (one design truck at exterior outer lane)

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5
G1	6000	6500	7500	8500
G2	2500	2500	2500	2000
G3	1500	2000	1000	1500
G4	0.0	-1000	-1000	-2000

Table. 6 MDF result from equilibrium method under load case (I) (one design truck at exterior outer lane)

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5

G1	**0.6**	**0.65**	**0.75**	**0.85**
G2	0.25	0.25	0.25	0.2
G3	0.15	0.2	0.1	0.15
G4	0	-	-	-

(-) mean negative reaction (support will upload) and the dead load will keep it position

Note:- The maximum critical MDF are shown in bold colure.

Table. 7 (Left + Right) Girder support reaction under load case (II) (N) (one design truck at internal inner lane)

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5
G1	-	1000	1500	2500
G2	-	1500	2000	1500
G3	-	3000	2500	2500
G4	-	4500	4000	4000

Table. 8 MDF result from equilibrium method under load case (II) one design truck at internal inner lane)

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5
G1	0.75	0.1	0.15	0.2
G2	0.45	0.15	0.2	0.15
G3	0.4	0.3	0.25	0.25
G4	0.4	0.45	0.4	0.4

Table. 9 (Left + Right) Girder support reaction under load case (III) (N) two design truck applied an both lane)

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5
G1	6500	7500	8500	9500
G2	5000	4500	4000	4000
G3	4500	4000	4000	3500
G4	4000	4000	3500	3000

Table. 10 MDF result from equilibrium method under load case (III) (two lane)

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5
G1	**0.65**	**0.75**	**0.85**	**0.95**
G2	**0.5**	**0.45**	**0.4**	**0.4**
G3	0.45	0.4	0.4	0.35
G4	0.4	0.4	0.35	0.3

Note: - The maximum critical MDF are shown in bold colure

Table. 4.9 (Left + Right) Girder support reaction under load case (IV) (N) one design tandem at exterior outer lane)

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5
G1	4200	4900	5150	5600
G2	2100	1400	1750	1570
G3	700	1040	750	1040
G4	0.0	-300	-850	-1040

Table. 4.10 MDF result from equilibrium method under load case (IV) one design tandem at exterior outer lane)

Girder	BGS	BGC R23.3	BGC R16.7	BGC R12.5
G1	0.6	0.67	0.742	0.822
G2	0.3	0.239	0.257	0.248
G3	0.1	0.133	0.1	0.070
G4	0.0	-	-	-

(-) Mean negative reaction (support will upload) and the dead load will keep it position

7. Moment Distribution Factors according to AASHTO LRFD[1]

A- MDF Exterior girder

Based on the equation in AASHTO SI unit, listed **Table 4.6.2.2.2d-1[1]** for cast in place concrete box girder to predict the moment distribution factor for one or two loaded lane or more which equal to:-

$$ge = \frac{We}{4300} \qquad (2)$$

We = half the web spacing, plus the total overhang spacing [ft. (mm)], and from Fig 4

We= (1.05+1.98/2)=2.040 m=2040 mm

so the MDF for one lane or two or multiple box girder

$$G1 = 2040/4300 \approx 0.48$$

B-MDF FOR interior girder

Case 1: One Design Lane Loaded

$$\text{DF} = \left(1.75 + \frac{S}{1100}\right)\left(\frac{300}{L}\right)^{0.35}\left(\frac{1}{NC}\right)^{0.45}$$

Where

S:- distance betwwn bidge girder (center to center mm)

L:- span length (mm)

NC:-number of box

$$= \left(1.75 + \frac{1980}{1100}\right)\left(\frac{300}{24000}\right)^{0.35}\left(\frac{1}{2}\right)^{0.45} = 0.561\ lane/web$$

Case 2: Two or more design lanes load

$$\text{DF} = \left(\frac{13}{NC}\right)^{0.3}\left(\frac{S}{430}\right)\left(\frac{1}{L}\right)^{0.25} = 0.681$$

The MDF for G2 = 0.681

Note: the multiple presence lane factor are include in this equation

8. Rigid Method [8]

According to ASHHTO section C4.6.2.2.2d-1, the rigid method equation is

$$g_{moment}^{SE} = \left(\frac{N_L}{N_b}\right) + \frac{X_{ext}\sum_{truck} e_t}{\sum_{N_b} x_i^2}$$

Nb = number of beams/girders in the bridge cross section, *NL* = number of lanes loaded, *xi* = location of beam *i* in the cross section, *ext* = location of truck/lane in the cross section X_{ext} X_{ext} = location of the exterior girder of interest

According to figure 2.6 the moment distribution factor

$$MDF = \frac{1}{4} + \frac{3150\times1800}{2(3150^2+1170^2)} = 0.501$$

MDF for (I) = 1.2 *(*0.57*)* = 0.601

The multiple presence factor is *m* = 1.2,

for all the load cases, the maximum MDF for the exterior girder and interior girder will be chose which have the maximum value from Tables 6.3 to 6.10 as shown in Table 9.1 to 9.3

9. Result Discussion

The AASHTO formula underestimate the MDF distribution factor for the exterior girder (G1). For the straight model with (33%) under load case (I) and (26%) for load case (III). the rigid method also under estimate the MDF for the exterior girder with (17%) for load case I and 23% for load CASE III Straight model. when the curvature increase the rigid method cannot predict the MDF for curved model. The AASHTO formula under estimate the MDF for the exterior girder of the curved models with (038%, 47%, 53%) for θ (10^0, 13.5^0, 18^0) respectively in case of load case (I) as shown in Table 11. While under load case (III) the ASSHTO formula underestimate the MDF for curved models with (36 %, 44,50%)for θ (10^0, 13.5^0, 18^0) respectively for the exterior girders (G1)as shown in Table 12, the MDF comparison are shown in Fig 16 and 17 . According to section 3.2. The load case (III) can considered as the controlled load design for the value of MDF for interior girder (G2). It's can be notice from Table 13 that the ASHTO LRFD overestimate the MDF for straight model with (30%) and (44 %,60 69%) for all curved bridges model θ (10^0, 13.5^0, 18^0) .

Table. 11 MDF comparison for exterior girder under effect of load case (I)

Model	Girder	ASSHTO method	Model EXP*	Rigid method	ASSHTO/Exp	Rigid/Exp
BGS	G1	0.48	0.72	0.6	0.67	0.83
BGC1	G1	0.48	0.78	0.6	0.62	0.77

BGC2	G1	0.48	0.9	0.6	0.53	0.67
BGC3	G1	0.48	1.02	0.6	0.47	0.59

ASSHTO METHOD section 7
*Model EXP "based on equation below and Table 6.3, only one case will be calculated to verify Table 9.1 result.

$$DF(EX\ lane) = (P1/\sum \frac{P}{no\ of\ lane}) * lane\ factor(\ multible\ presence\ factor)$$

$(6000/\ (6000 + 2500 + 1500 + 0.0)/1) \times 1.2\ = 0.6 \times 1.2 = 0.72$
1.2= $multible\ presence\ factor\ (\mu)\ for\ one\ lane$
Rigid method section 9

Table. 12 MDF comparison for exterior girder under effect of load case (III)

model	Girder	AASHTO method	Model Exp*	Rigid method	ASSHTO/Exp	Rigid/Exp
BGS	G1	0.48*	0.65	0.5	0.74	0.77
BGC1	G1	0.48	0.75	0.5	0.64	0.67
BGC2	G1	0.48	0.85	0.5	0.56	0.59
BGC3	G1	0.48	0.95	0.5	0.5	0.59

ASSHTO METHOD section 7
Model Expo Reference Table 6.7
$(6500/\ (6500 + 5000 + 4500 + 4000)/2)\ \times 1 =\ 0.65 \times 1 = 0.65$
1.2= $Multible\ presence\ factor\ (\mu)\ for\ two\ lane$
Rigid method section 8

Table. 13 MDF comparison for interior girder under effect of load case (III)

model	Girder	AASHTO	Model EXP	AASHTO/EXP1.
BGS	G2	0.648*	0.5*	1.3
BGC1	G2	0.648	0.45	1.44
BGC2	G2	0.648	0.4	1.6
BGC3	G2	0.648	0.4	1.6

* ASSHTO METHOD section 7
 * Model Exp Reference Table 6.7
$(5000/\ (6500 + 5000 + 4500 + 4000)/2)) \times 1 = 0.5$

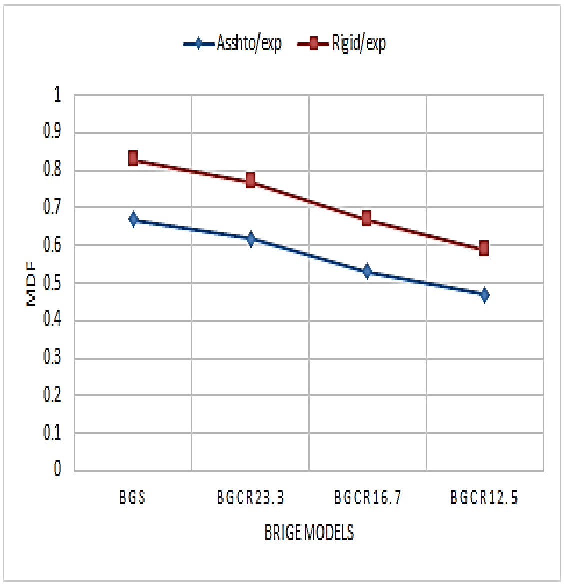

Fig.16 MDF comparison for the exterior girder under load case I

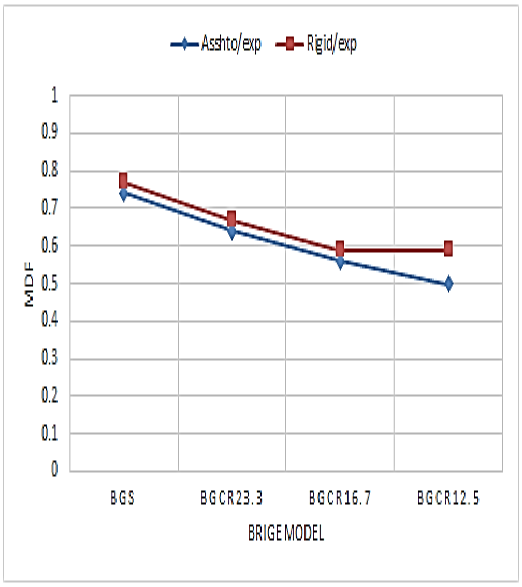

Fig.17 MDF comparison for the exterior girder under load case III

10.CONCULSION

1- The generated support reaction for both left and right girder under HL-93 live load is equal to the applied loads, which mean the measuring processor is correct

2- AASHTO formula under estimate the MDF by 33 %, for the exterior girder and overestimate the MDF by (30) for the interior girder the for straight model.

3-The rigid method formulas under estimate of the design MDF by (23 %) for the exterior girder of the straight model

4-The current AASHTO LRFD formulas for multi-cell box girder under estimate the MDF for the exterior girder of the curved models with (038%, 47%, 53%) for θ (10^0, 13.5^0, 18^0) respectively in case of load case (I)

5-The current AASHTO LRFD formulas for multi-cell box girder overestimate the MDF by (44 %,60 69%) for all curved bridges model with θ (10^0, 13.5^0, 18^0) for the interior girder (G2) under load case (III) "controlled load case"

6-The (design truck) (I) is the controlled design case when its result compared with the design (tandem + lane load) (IV) (25% I/IV for straight model outer edge girder G1 and 33% I/IV for BGC R 12.5)

7- Girder tilting (uplift) was measured for curved models under external lane loaded only under load cases (I,IV) as follow:-

(-1 kN) under load case (I) and (-0.35 kn) under load case IV for each (1 Ton) for model BGC R23.3

(-1kN) under load case (I) and (-0.85 kN) under load case IV for each (1 Ton) for model BGC R16.6

(-2kN) under load case (I) and (-1 kN) under load case IV for each (1 Ton)

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دراسة عمليه للجسور الخرسانية الصندوقية المقطع والمنحنية في المستوى الافقي مع اشاره خاصه الى معاملات توزيع الانحناء للأحمال الحية

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قسم الهندسة المدنية
جامعه بغداد/ العراق

الخلاصة: -ان الهدف الرئيسي من هذا البحث هو دراسة معاملات التوزيع الخاصة بالانحناء بالنسبة للجسور الخرسانية المنحنية في المستوي الافقي تحت تأثير الاحمال الحية استنادا الى المواصفات الأمريكية القياسية لأحمال الجسور(LRFD HL-93 2012)بواسطه دراسة عملية. اشتمل المحور العملي على تصنيع وفحص أربع نماذج مصغرة بسيطة الأسناد، ثلاث نماذج بأقطار تقوس مختلفة، ونموذج بدون تقوس (مستقيم) لأغراض المقارنة. ان الدراسة العملية تضمنت اضافه خلايا تحسس للأوزان ذات قابليه (خمسه أطنان) مع قارئ اوزان لقراءة ردود الفعل المتولدة تحت الروافد في أي حالة تحميل. ان خلايا التحسس تسمح لنا باستنتاج معاملات التوزيع للأحمال الحيه تحت تأثير الانحناء عن طريق معادلات التوازن ومقارنه هذا النتائج مع المواصفات العالمية للجسور، اثبتت الدراسة العملية ان المعادلات الخاصة لحساب معاملات التوزيع في المواصفات الأمريكية تقلل من تأثير العزم المتولد على الرافدة الخارجية وبنسبه 33 % للجسور المستقيمة و تقلل بنسبه (38%, 47%, 53%) للنماذج ذات زاوية تقوس (10^0, 13.5^0, 18^0)على التوالي . بينما تضخم من تقدير العزم المتولد على الرافدة الداخلية وبنسبه 30 % للجسور المستقيمة وبنسبه (44%60,69%) للنماذج ذات نسبه ذات زاوية تقوس (10^0, 13.5^0, 18^0)