Parametric Study of The Structural Behavior of Horizontally Curved Bridge Deck

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Abstract: This paper investigates the impact of the following parameters on the structural behavior of horizontally curved bridge decks: 1- the analytical modeling methods; 2- the radius of curvature; 3- the number of internal cross girders and 4- the thickness of the deck slab. The results of the different analytical modeling technique are compared to experimental results by conducting a load test on a curved bridge deck physical model at the structural lab of the American University in Cairo. The remaining parameters of this study are investigated using a typical curved concrete slab-girder bridge deck which is commonly used in real projects. The impact of these parameters on the structural behavior of the deck is addressed by the change in straining actions and the deflection of the main girders of the bridges.

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1- Introduction

Curved bridges are very common due to their aesthetics and to comply with the need of such bridge geometrics in high way intersections. Some earlier trials were made to facilitate the design of simple types of curved bridges before the development of computer methods, [1-6]. Unfortunately these trials were very limited and did not cover most of the conditions of the bridges such as the rigidity of the supports andthe different rigidities of the bridge deck.

More rigorous analysis methods using special developed computer programs were introduced using finite difference, finite element, virtual work methods, [7-9]. Due to the great advances in computer programs, more advanced techniques using finite elements, and grillage analysis are recently widely used among the professional engineers, [10-12].

In this paper the impact of the following parameters on the structural behavior of horizontally curved bridge decks is introduced:

A- The analytical modeling methods:

The accuracy of the most common analytical modeling technique is investigated.

B- The radius of curvature:

Different radii of curvaturefrom 100m to 10000meters are applied to a typical curved concrete slab-girder bridge deck which is commonly used in real projects

C- The number of internal cross girders:

The impact of the number of internal cross girders on the lateral distribution of the traffic loads is investigated using the same typical curved deck. Different cases are used starting from the case of no cross girders to 3 cross girders

D- The thickness of Deck slab:

Different thickness of the deck slab are used to study the impact of this parameter on the structural behavior of curved bridges.

The impact of these parameters on the structural behavior of the deck is addressed by the change in the straining actions and the deflection of the main girders of the bridges.

2. Study The Impact Of Different Parameters:

2.A- Investigation of Analytical Modeling Methods:

The accuracy of the most common analytical modeling technique is investigated. The different analytical methods used in this study are: a- shell elements representing the deck slab on frame elements representing the girders; b- grillage method c- solid finite element method. The results of these three analytical methods are compared to experimental results by conducting a load test on a curved bridge deck physical model at the structural lab of the American university in cairo as a part of a long research for curved bridges directed by the author.

2.A.1Description of The Physical Model

A curved model used for this study consists of a composite deck with three identical simply supported I girders, MG1, MG2 and MG3, W16x15.in the curved model, the radii of curvature (R =6.36, 5.76, and 5.16 m). The cross girders were fabricated as cross frames with an L 30x30x3. Grade 52 steel is used for all the steel sections. Composite action between the slab and the steel I girders is provided by 50 x 13mm studs. The deck slab is 60 mm thick reinforced concrete with reinforcement 8 mm diam.@150mm in the short direction and 6mm diam. @ 125mm in the long direction. The concrete strength is 25 MPa.The tests were conducted on this model twice: a- without intermediate cross girders; b- with three interior cross frames. Figures 1 to 3show the details of the deck model considered in this study with the loading points P1=2.5 Ton at MG1 and MG3and P2=5 Ton at MG2.

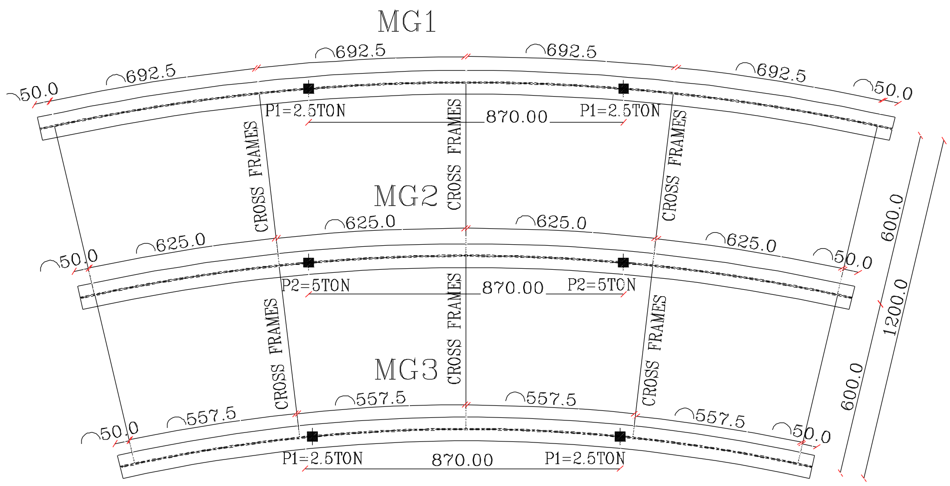
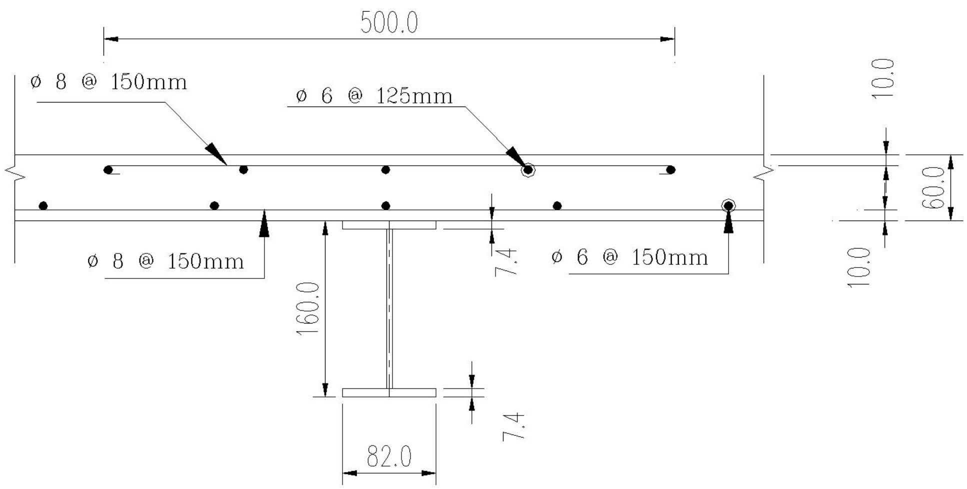


Figure 1: Plan of the physical model



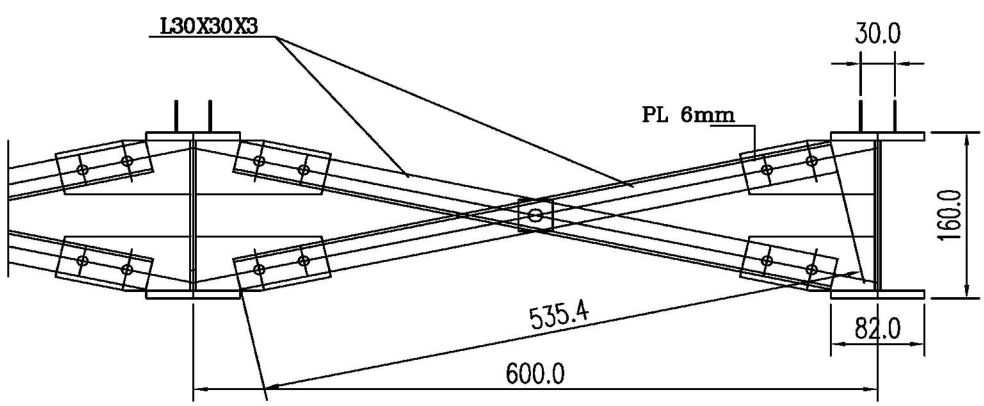


Figure 3: Details of the cross frames

2.A.2 Analytical Study of The Physical Model:

This model was solved analytically by three different modeling techniques:

1- Shell slab and frame elements:

The slab was modeled as weightless 50mm x50 mm plate elements overframe elements representing the main composite I-girders.The cross frames were connected to the main girders by shifting the top and bottom flanges of these girders. Figure 4 illustrate the shell and frame elements.

2- Grillage modeling:

Both the longitudinal main girders are modeled with the properties of aI-section and the slab was modeled as lumped transversal grillage elements at 10cm spacing. Figure5 illustrates the grillage elements for the experimental model.

Each of the above mentioned models prepared by SAP2000, [10].

3-Solid elements:

A 3-D model was prepared using ANSYS software,[11]. The bridge deck was modeled using solid elements as shown in figure 6. This modeling technique is considered the most accurate technique for researchers where all elements are modeled exactly as in real case.

The details of the above mentioned three techniques are explained in Hambly, [12].

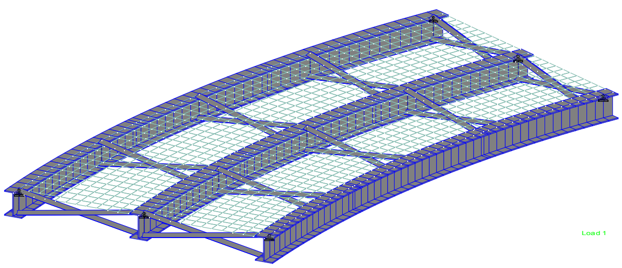


Figure 4: Shell slab and frame elements

Figure 5: Grillage model

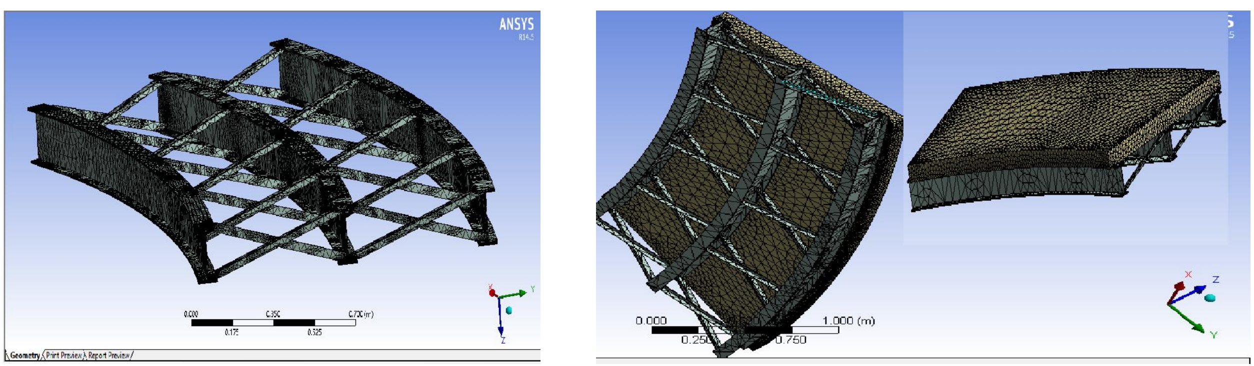


Figure 6: Solid elements

Picture 1: Assembly of the steel girders for the model with 3 cross frames

Picture 2: Adding reinforcementto the model without cross frames

Picture 3: Reinforced concrete deck

Picture 4: Loading system

2.A.3 Experimental Study

The experimental study is a part of a research outlined and directed by the author to study the behavior of curved bridges under both cyclic and static loads. In this paper, the static load results are investigated for the purpose of comparing different analytical methods. Pictures 1 to 4show part of the preparations of the models and the loading system

The data were collected from the hydraulic actuator LVDT and load cell, which provided measurements of actuator deflection and load, respectively, to be used in the data analysis. On the other hand strain gauges were attached to the top of the concrete deck. All data from the strain gauges, LVDT's, and the actuator load cell during the tests were collected through the System data acquisition system in conjunction with the computer program Strain Smart. All sensors used in the static testing were calibrated and collected using a system attached to the Strain Smart program installed on a computer. Raw data for the cyclic and static tests were filtered and transferred into a Microsoft Excel spreadsheet for data analysis.

2.A.4Comparison of The Results:

Figures 7 and 8 show the values of the deflection at the mid-span of the three girders for two cases respectively:

- Case 1: without cross frame and -Case 2: with three cross frame.

The results are shown for the three modeling methods and the experimental results

In all of the three cases the cross frames at the two ends exists. The values of deflections are in mm.The following points may conclude from the shown figures:

- The solid element method gives results very close to the experimental model as expected. Yet, it is very difficult for the design engineers to use this method in solving actual bridges, extract the results and convert these results to designs.
- The grillage methodgives results very close to the solid elements and the experimental results.

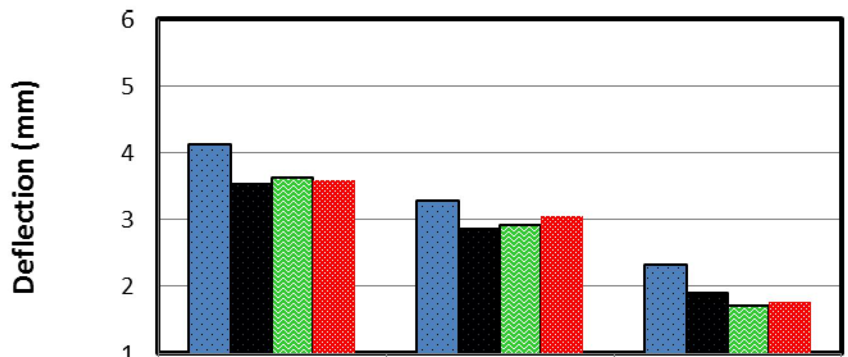
- The shell-frame element method, although it is widely used among the designers, yet it gives inaccurate results. This inaccuracy mat be attributed to the needto shift the centroid of the shell elements to be above the top surface of the beam.

The cross frames result in a better load distribution between the main girders and less deflection at the outer main girder.

2.B. The Impact of The Radius of Curvature:

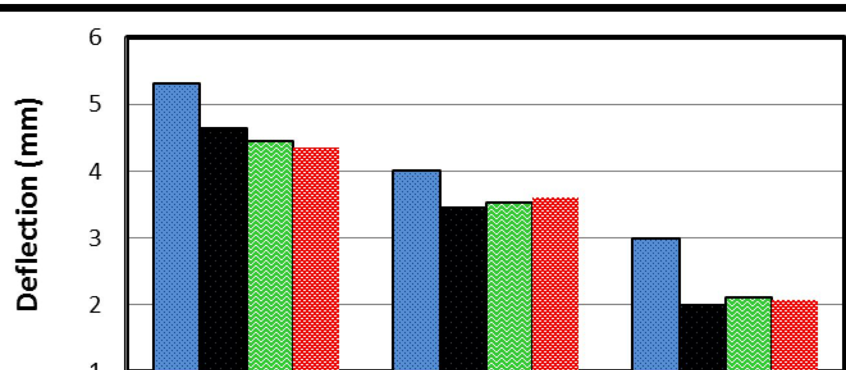
The followings parts of the parametric study is done using a commonly used curved concrete slab-girder bridge deck. Figure 9 shows a plan and a section of the typical curved slab- girder bridge deck used in many bridges. Figure 10A shows the load configuration used in the following parts of the study to provide the maximum straining actions at MG1. This load configuration conforms to the Egyptian code ECP201-2012.

Figure 10B shows the grillage system used for this study.



	M.G1	M.G2	M.G3
SHELL	4.135014	3.301876	2.345
GRILLAGE	3.552744	2.878968	1.923
SOLID	3.65064	2.925951	1.732
EXP.	3.6087072	3.06918	1.777577

Figure 7: Comparison of the deflection at mid-span; without intermediate cross frames



	M.G1	M.G2	M.G3
SHELL	5.3013	4.012	2.984
GRIL.	4.632	3.452	1.987
SOLID	4.452	3.521	2.103
EXP.	4.34784	3.6108	2.06695

Figure 8: Comparison of the deflection at mid-span; with 3 intermediate cross frames.

The shown deck in figure 9 was solved for different radii of curvature for a constant slab thickness Ts=200mm without interior cross girderes.

Figure 11 shows the change in the deflection at the mid span of the main girders MG1 to MG4. As shown in this figure, by increasing the radius R, the deflection decreases for the outer girder MG1 and increase for the inner girder MG4 up to R =1000 meters. The deflection after this limit is almost steady.

Figure 12 shows the change in the bending moment, B.M., at the mid span of the main girders MG1 to MG4. As shown in this figure, by increasing the radius R, the bending moment decreases for the outer girder MG1 and increase for the inner girder MG4 up to R =800 meters

Figure 13 shows the change in the torsional moment, T.M, at the two ends of each main girders. As shown in this figure, by increasing the radius R, the torque decreases for the outer girder MG1 and increase for the inner girder MG4 up to R =800 meters. The patterns of change for the three above results are almost the same.

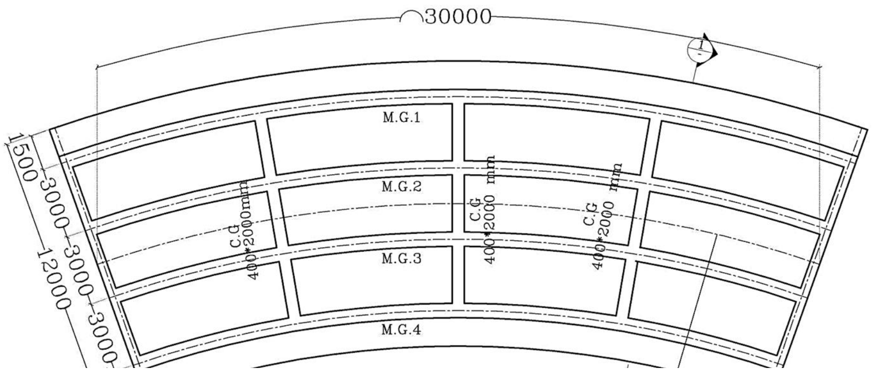


Figure 9A: Details of the curved deck used in the parametric study.

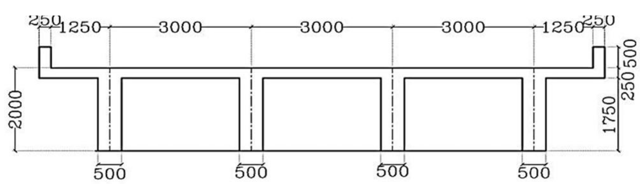


Figure 9B: Cross section 1-1

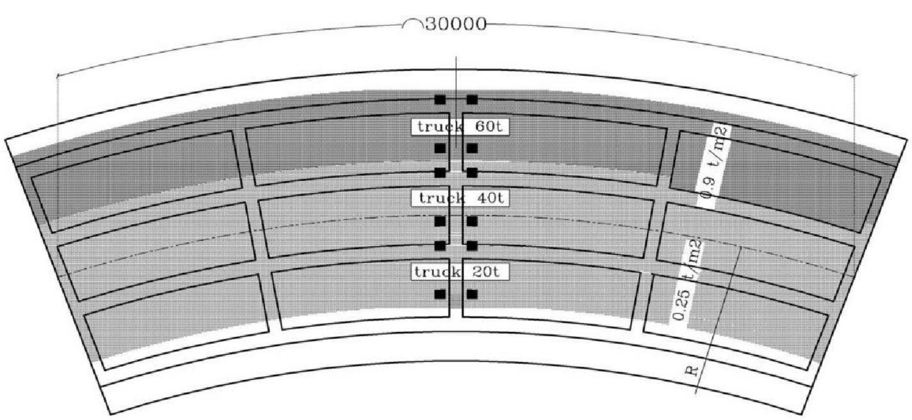


Figure 9: Details of the curved deck used in the parametric study.

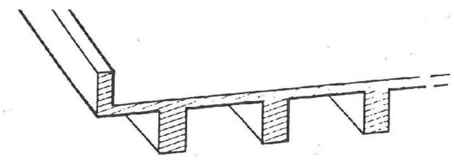


Fig 10A. a- real section

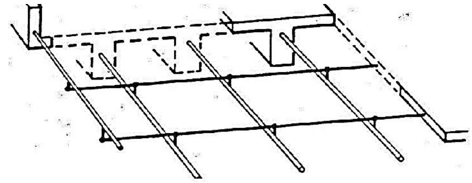
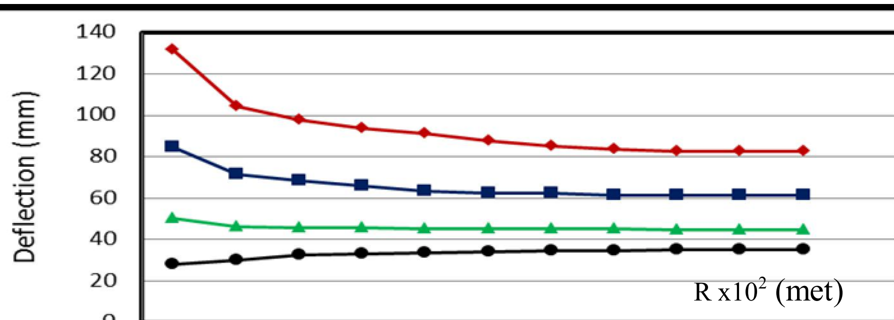


Fig 10B. b- longitudinal grillage for main girders and lumped transversal grillages for the slab spaced at 1 met.

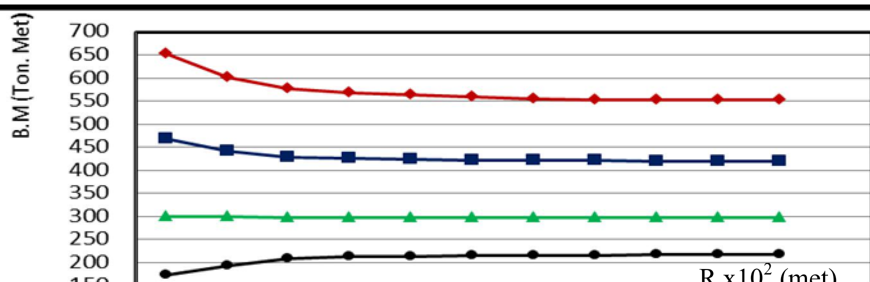
Figure 10A: Load configuration to obtain maximum bending moment on MG1 according to ECP201-2012
Figure 10B. The grillage system used for this study.

Figure 10. The grillage system used for this study.



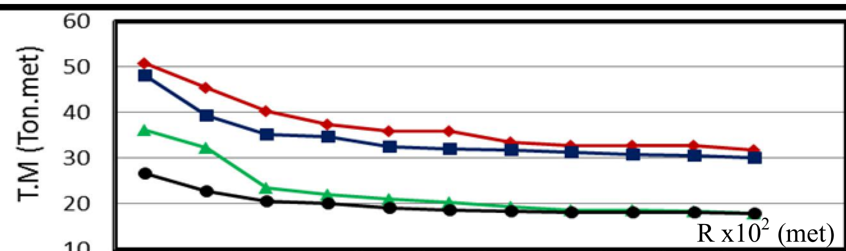
	1	2	4	6	8	10	20	40	60	80	100
MG1	132	104	97.8	93.7	91.2	87.8	85.4	83.7	82.9	82.9	82.9
MG2	84.9	71.6	68.6	66	63.5	62.3	62.3	61.7	61.7	61.7	61.7
MG3	50.4	46.1	45.7	45.7	45.4	45.4	45.4	45.4	45	45	45
MG4	28.3	30.3	32.5	32.9	33.7	33.9	34.7	34.8	35	35	35

Figure 11: Deflection vs. Radius of Curvature



	1	2	4	6	8	10	20	40	60	80	100
MG1	652	601	578	568	564	558	555	553	553	553	553
MG2	469	442	427	425	423	421	421	421	419	419	419
MG3	300	298	297	297	297	297	297	297	297	297	296
MG4	173	193	209	212	214	214	215	216	217	217	217

Figure 12: Bending moment vs. Radius of Curvature



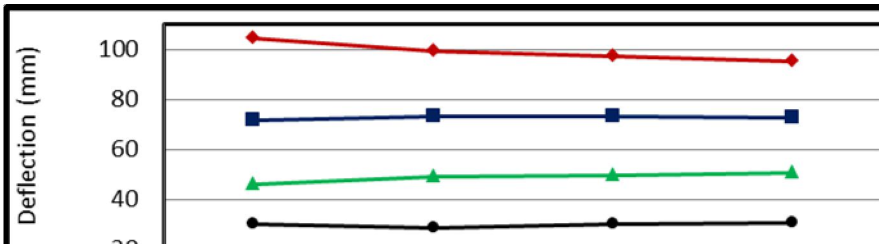
	1	2	4	6	8	10	20	40	60	80	100
MG1	50.9	45.3	40.4	37.5	35.9	35.9	33.4	32.8	32.8	32.8	31.8
MG2	48.1	39.2	35.3	34.7	32.6	32	31.7	31.4	30.8	30.5	30.2
MG3	36.1	32.2	23.4	22.1	21.1	20.3	19.3	18.7	18.7	18.5	18
MG4	26.8	22.8	20.6	20	19.2	18.6	18.4	18.1	18.1	18.1	17.9

Figure 13: Torsional moment vs. Radius of Curvature

From these figures, it is clear that the curved deck carries larger bending moments than the straight deck in addition to the torque. It is also clear that for this specific typical case, R may be ignored for the values more than1000 meters.

2.C.The Impactof The Number of Interior Cross Girders:

The deckshown in figure 9 was solved for different cases of interior cross girders: 1- No cross girder (NO-C.G); 2- One cross girder, (1-C.G); 3- Two cross girders, (2-C.G) and d- Three cross girders, (3-C.G). The slab thickness is 200mm and the radius of curvature 200meters.



	NO C.G.	1 C.G	2 C.G	3 C.G
MG1	104.4	99.2	97.1	95.4
MG2	71.6	73.2	73	72.5
MG3	46.1	48.9	49.5	50.7
MG4	30.3	28.5	30.3	30.9

Figure 14: Deflection vs. Number of Cross Girders

Figure 14 shows the change in the deflection at mid-span of the main.The deflection of MG1, with the longest span, decreased by 9.5% for the 3-C.G compared to NO-C.G. The change in the deflection of other girders is not noticeable.

Figure 15 shows the change in the mid-span bending moment. The moment of MG1 changed by 8.5% for the 3- C.G compared to NO C.G.

The case of 2- C.G reduced the bending for MG1 and MG4 but not as much as the case of either 1- C.G or 3- C.G. Another worthy observation that the effect of one cross girder is almost equal to the effect of using three cross girders on the bending moment.

Figure 16 show the change in the torsional moment at the ends of the girders. As shown in this figure, adding one cross girder at the middle changes the results remarkably and two or three cross girders will result in the same change of adding one cross girder.

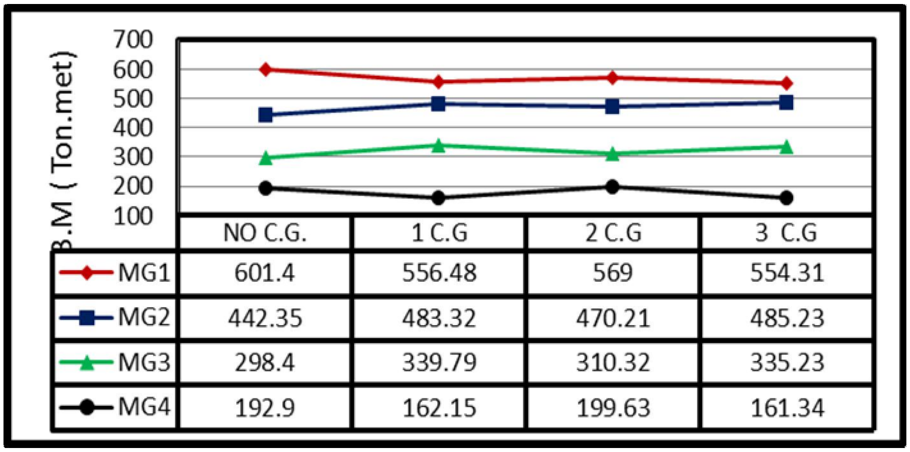


Figure 15: Bending Moment vs. Number of Cross Girders

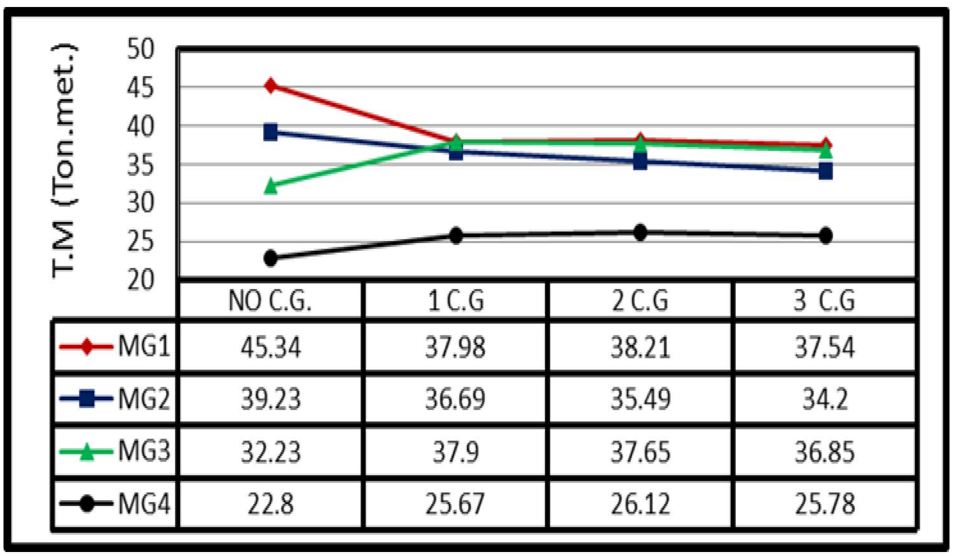
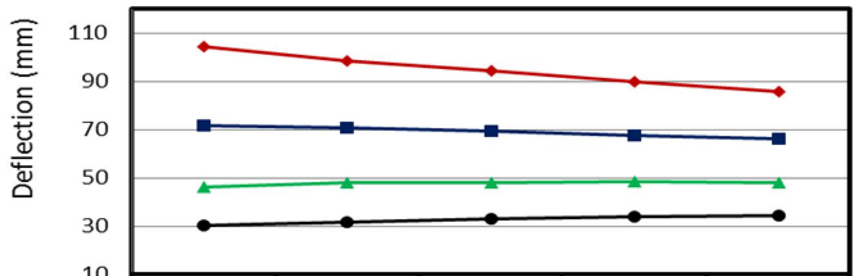


Figure 16: Torsional Moment vs. Number of Cross Girders

2.D.Effect of the Slab Thickness (Ts):

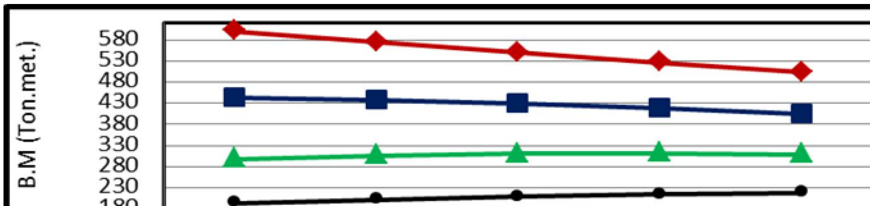
The deckshown in figure 9 was solved for different various slab thicknesses from 200mm to 400 mm. The following figures 17,18 and 19 show the effect of the slab thickness on the deflection, bending moment and torsional moment respectively.The radius of curvature is 200 met without cross girders.

Fgure 17 illustrates that the change in the deflection of MG1 is remarkable, about 22% between Ts=200 and Ts=400mm. The decrease in MG2 is not as much as MG1. The deflection at MG4 has decreased. These changes may be attributed to better transversal distribution of traffic loads among the main girders.The same observations are shown in figures 18 and 19 for the bending moment and torsion.



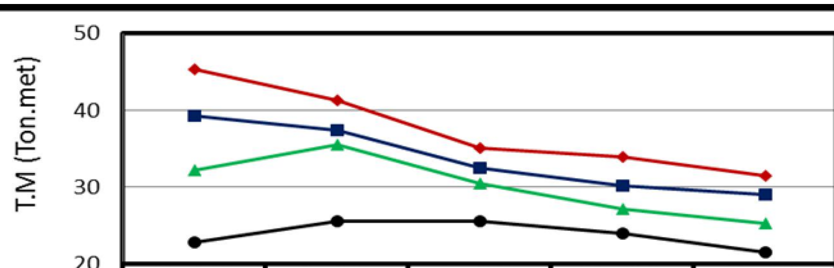
	Ts=200	Ts=250	Ts=300	Ts=350	Ts=400
MG1	104.4	98.3	94.2	89.8	85.6
MG2	71.6	71	69.6	67.8	66.1
MG3	46.1	48.1	48.1	48.7	48.2
MG4	30.3	31.7	32.9	33.8	34.6

Figure 17: Deflection vs. Slab Thickness



	Ts=200	Ts=250	Ts=300	Ts=350	Ts=400
MG1	601.4	574.24	550.31	526.61	502.33
MG2	442.35	436.76	427.99	417.1	404.23
MG3	298.4	306.43	310.36	311.1	309
MG4	192.9	201.84	208.86	214.45	218.45

Figure 18: Bending Moment vs. Slab Thickness



	Ts=200	Ts=250	Ts=300	Ts=350	Ts=400
MG1	45.34	41.23	35.14	33.99	31.51
MG2	39.23	37.33	32.46	30.23	29.05
MG3	32.23	35.56	30.44	27.13	25.23
MG4	22.8	25.5	25.56	24	21.6

Figure 19: Torsional Moment vs Slab Thickness

3- Summary and Conclusions:

The impact of the following parameters on the structural behavior of horizontally curved bridge decks is introduced:

1- The accuracy of the most common analytical modeling technique compared to experimental results; 2- the change in the radius of curvature; 3- the number of internal cross girdersand 4- the thickness of deck slab.

The experimental part was conducted at the American University in Cairo as a part of a long project related to cyrved bridge deck and directed by the author

The conclusions of this stydy are as follows:

- Solid element solution is the most accurate modeling technique for curved bridges, yet, it is appropriate for researches only due to the complications in forming a model and extracting design values by design engineers.
- The grillage modeling technique is accurate and more appropriate for design purposes.
- The shell-frame modeling technique needs to adjust the section properties to consider shifted centroids of both the beam and the slab elements to get accurate results.
- The bending moment in curved deck is larger than the bending moment in straight decks due to the effect of torsional moment
- By increasing the radius of curvature the bending moment and torsional moment descreases
- Radius of curvature more than 1000 meter, may be ignored for preliminary designs
- The intermediate cross girders shall be added to horizontally curved bridges to help in redistributing the loads among the main girders resulting in less deformation and straining actions at the outer longer girders
- Bigger deck slab thicknesses help in controlling the transversal load distribution among the main girders and decrease the deflection and the straining actions for outside girders with longer spans.

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