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Section Geometry's Effect on the Behavior of Curved Continuous Box Girder Bridges

***Asala Asaad Dawood* [1)*], *Khattab Saleem Abdul-Razzaq* [2)], *Wael Shawky Abdulsahib* [1)]**

[1)] *Civil Engineering Department, University of Technology, Iraq.* [*]*Corresponding Author. Email: asalaasaad01@gmail.com*
[2)] *Civil Engineering Department, University of Diyala, Iraq.*

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ABSTRACT

Horizontal curved box bridges are considered important structures due to their high efficiency and economy. It is necessary to know their behavior in general and the effect of changing the box section in terms of shape and dimensions because of the important effect on the behavior and thus on the design. The large value of box girders' height makes behavior different compared to shallow ones, because they are subject to the behavior of deep members. A horizontally curved specimen was cast and experimentally tested. It was also numerically modeled using the finite element CSiBridge software, comparing its experimental results with the modeling results. The effect of changing cross-sectional shape, height, and width on deformation, shear, torsion, and bending moments was numerically studied. The shape of rectangular section was changed to a clipped, trapezoidal, and circular shape besides changing the section height and width. From the finite element results, it is clear that the circular shape is the most efficient shape, because it provides an equal distribution of stresses around the center, which makes it more efficient in resisting shear and torsion. Increasing the height by 100% and 200% leads deflection to decrease by 75% and 86%, respectively. In addition, increasing the width by 15%-32%, increases the section's resistance to bending by 15%-46%, making the box girder more rigid. Increasing the height led to the direct transfer of stresses from the loading to the supporting points, and thus the deflection and bending moments decreased, accompanied by an increase in shear forces. Increasing the overall width of the girder means that there is more zone for shear stresses to distribute.

Keywords: Box girder, CSiBridge software, Concrete, Shear, Torsion.

INTRODUCTION

Box girders with a horizontal curvature are used in turns, overpasses, and bridges. When compared to segmental box girder bridges, continuous horizontal curved box girder bridges are more efficient and cost-effective. Development, population density, and the scarcity of available land for building have all contributed to the growing significance of curved bridges (AASHTO, 2017; Sayhood et al., 2014; Ng et al., 1993). Torsional moments happen in a horizontally curved beam, because, in contrast to a straight girder, the neutral and centroidal axes of the girder do not coincide (Ali & Hemzah, 2014). In deep members, stresses do not vary linearly from the neutral axis because of the great depth (Abdul-Razzaq et al., 2023a; Abdul-Razzaq et al., 2023b). The cross sectional deflection throughout the width of straight concrete girders is constant when there is no torsion present. Conversely, eccentrically loaded straight and curved concrete girders experience torsion that results in twisting. Consequently, the girder width causes the cross section's deflection to vary, usually with the biggest deflection at the section's extreme inner or outer edge (Song et al., 2017; Dawood et al., 2023; Shen et al., 2019; Song et al., 2021).

The cross section of a box girder can be trapezoidal or rectangular. It might have a single, double, or multiple cell structure (Hadi et al., 2021). In addition to their great flexural rigidity, low material content, and relative light weight, concrete box bridges have notably higher torsional stiffness when compared to open section girder bridges (Al-Attar et al., 2019; Hii & Al-Mahaidi, 2006). Due to their attractive architectural shape, high performance efficiency, and relatively low cost, box girder bridges are now widely used. The region's geography and the bridge's intended use determine how curvaceous the curve should be. While some of them are straight, others have a slight curve to them. Additionally, there are bridges with extremely steep curves. Bridges are subjected to a variety of loads, and their locations shift throughout time, causing them to exhibit varying behaviours (Sennah & Kennedy, 2001; Alhamaidah, 2017).

On contemporary curving bridges at multi-level urban interchanges, continuous span layouts are frequently utilized due to their dependability and cost-effectiveness. Beautiful structures can be achieved with bridges that are horizontally curved and have continuous girders at a constant depth. Horizontally curved bridges often have comparable overall costs to alternative structural choices for curved road alignments. For example, limitations on the cantilever overhang, the number of expansion joints, and bearing characteristics, as well as the usage of kinked girders and/or a series of straight short span chords, may be implemented as a result of the substructure's cost savings (Nakai & Yoo, 1988).

Fu and DeWolf (2002) examined causes and patterns of the cracking of a multi-span reinforced concrete bridge with a non-prismatic three-cell box cross-section and a curved alignment. To determine the causes of cracking, the investigation entailed closely observing how the bridge behaves under varied loading conditions. Because of the curvature of the bridge, the analysis takes into account the intricate relationships between bending moments, shear forces, and torsional effects. The findings shed important light on how curved RC box girder bridges behave structurally and emphasize how crucial it is to take these aspects into account during construction and maintenance in order to guarantee longevity and avoid cracking.

Khalafalla and Sennah (2014) compared internal forces between straight and curved concrete bridges under dead loads using the finite element method (FEM). The findings have shown that curvature lowers the fundamental flexural frequency while increasing flexural stresses, vertical deflection, and supporting reaction. Additionally, the Canadian Highway Bridge Design Code and AASHTO-LRFD curvature limitations understate the structural response, resulting in unsafe design. An empirical formula was created with safety margins of 5% and 10%, with 5% being suggested as being more realistic in engineering practice.

Xiang and Xu (2014) developed a 3D solid element cracking model to analyze the continuous curved concrete box girder bridge from cracking to failure. It was investigated how the arrangement of reinforced bars, curvature radii, and support types affected the cracking behavior. The findings demonstrated that the embedded reinforcement model could be used to properly estimate the non-linear cracking behavior, and the anticipated crack distribution agreed with the findings of the on-site tests. By choosing the right bearing pattern, logically modifying the pre-eccentricity, and raising the longitudinal reinforcement ratio, the mechanical behavior may be improved. Particularly for bridges with short radii, it is advised that the main reinforcement ratio of RC curved box girder bridges be greater than that of straight bridges with the inclusion of torsional bars.

Song et al. (2018) investigated the effects of bearing eccentricity and curvature radius on the choice of overturning axis. Based on theoretical analysis supported by model bridge experiments, the study came to the conclusion that, depending on the curvature radius and bearing eccentricity, the overturning axis can be successfully identified by connecting either the outermost bearings at the abutments or the bearings at the central piers. This indicates that every bearing is located on the inner side of this axis, with the exception of the two on the overturning axis. The line joining the two adjacent outermost bearings is usually used to define the overturning axis for curving bridges with several spans and either single-column or double-column piers.

Agarwal et al. (2023) used finite element modeling with CSiBridge software to investigate the design forces in simply supported single-cell reinforced concrete curving box-girder bridges. Their study emphasized the impacts of vertical loads on the structure, including dead load and live load, and validated its methodology using an existing specimen. In this work, the effects of curve angle and span on bending moment, shear force, torsional moment, and vertical deflection in bridge girders are investigated. Findings showed that the influence on forces and deflections is negligible for curve angles up to 12°, meaning that these bridges can be treated in the same way as straight bridges.

Using a scaled model, Cao et al. (2024) examined the long-term deformation behaviour of a pre-stressed concrete continuous box-girder bridge with a considerable span. The bridge deformed most quickly during the first three months of the 558-day trial, reaching 60%-70% of its overall distortion before stabilizing. Due to a negative bending moment, the mid-span section first displayed a reverse arch. However, as the internal forces re-organized, the camber eventually vanished. To take into consideration the cracking effects in force re-distribution, a modified damage coefficient was created. The research used bending performance testing to create a long-term deflection calculation method that, with a maximum error of less than 15%, closely matched experimental results. This study offered important new information for evaluating the safety of these kinds of bridge constructions.

It is often necessary to vary the cross-sectional dimensions longitudinally for aesthetic and design purposes. The bridge's planar geometry could be curved or straight. A bridge may occasionally have both straight and curved portions (Choudhury & Scordelis, 1988). Vehicle-bridge interaction is a topic that has drawn a lot of attention in the field of civil engineering. A special emphasis is placed on vibrations that could compromise the strength of the structure and the passengers' safety and comfort (Nallasivam & Talukdar, 2007; Hodson, 2012). CSiBridge is one of the greatest programmes available for analyzing geometrical objects. Computers and Structures, Inc., an American company, was behind its creation. With the CSiBridge programme, engineers can easily construct complex bridge geometry, boundary conditions, and load scenarios (Sali, 2017).

Sali studied the effect of several parameters using the CSiBridge software and for one span, while the current study is for more than one span. The terminology used in the parametric definition of the bridge specimens will be recognizable to bridge engineers. The software updates models of solid, shell, and spine objects automatically as the parameters for the bridge specification change.

It is necessary to know the effect of changing the box section in terms of shape and dimensions because of its important effect on behavior and thus on design. In the current study, the effect of the box section in terms of its shape, height, and width was studied using the finite element CSiBridge software. The effect of the studied parameters on the deflection, shear, torsional moments, and bending moments along the bridge was presented. For the purpose of verifying the finite element model (FEM), a laboratory specimen was cast, tested, and then modeled numerically in the CSiBridge software. The current study can give designers an idea about the stresses that need reinforcement.

MODEL VALIDATION

The finite element model was verified by casting and testing one horizontally curved box-girder experimental specimen, and the results were compared with the FEM ones. The subtending angle of a circular arc is 114 degrees, the total length is 2000m, the height is 460m and the web width is 66m, while concrete strength is 24 MPa. The box void that extended the length of the specimen was formed by pressed cork. Two spans with one concentration load on each span were used to analyze the test specimen’s behaviour. Figure 1 shows the cross-sectional and longitudinal dimensions, while Figure 2 displays the constructed moulds and reinforcing details.

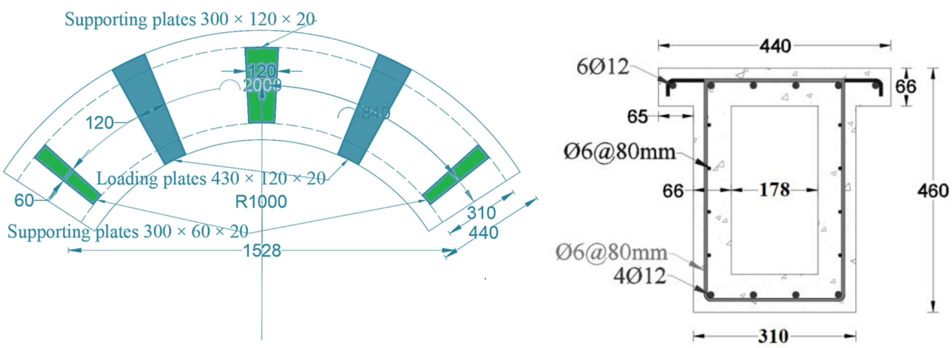

Figure 1. Cross-sectional and longitudinal dimensions of curved box girder

Figure 2. Box girder moulds and reinforcement details

A hydraulically universal testing machine with a 2000 kN capacity (AVERY) is used to test all specimens at the Structural Laboratory of the Civil Engineering Department, University of Technology, Iraq, as shown in Figure 3. By locating the load and support locations, the specimens are prepared for testing. The testing machine does not include three supports that may be positioned on a curved line to support the curved specimen of the current experiment. Consequently, a frame that was specifically manufactured had two steel I-sections joined at a 125-degree angle.

Figure 3. The loading condition, geometry and cracking patterns of box girders

Two LVDTs were positioned in the outer and inner webs at the midpoint of the specimen's span. To prevent local direct load concentration on concrete, loading areas utilize bearing plates with dimensions of 20×120×440 mm. The centre and end supports are equipped with 20×120×310 mm and 20×60×310 mm bearing plates, respectively. Neoprene rubber pads were placed between the specimen and the bearing plates to lessen the impact of any abnormalities in the concrete surface. Up until they broke, the specimens were subjected to progressively monotonic-static loading increments. When the specimen's total load began to decrease, the test was over.

Through the crack behavior in the experimental specimen, which is characterized by its large value of height, it is clear that the stress transfer occurred directly from the load application to the support. This leads to a decrease in deflection due to the dominance of shear forces over bending forces; increasing the specimen's load capacity, as shown in Figure 4. Shear cracks appeared first in the outer web, then in the inner web, followed by flexural cracks. The specimen test continued until shear failure occurred between the load and the intermediate support. The load-deflection behavior was characterized by being linear in most of the loading stages due to the dominance of shear forces. Due to the presence of horizontal curvature, torsional moments appear, thus adding to the conventional bending and shear moments. The torsional moments make the deflection in the outer web greater than in the inner web, which generates a twist angle. The model was examined and it was found that there is consistency between the experimental and numerical results, as shown in Table 1. This is significant, since designers really use this software to analyze and build bridges. There is agreement in the deflection in terms of general trend and values, as shown in Figure 5, which displays the shear and torsional moments; the comparison also took into account the positive bending moments in the middle of the span and the negative bending moments at the supports.

Table 1. Model validation

	Current work			(Hashim & Ali, 2022)		
	Experimental	**CSiBridge**	**Experimental / CSiBridge**	**Experimental**	**CSiBridge**	**Experimental / CSiBridge**
Max. deflection (mm)	4.85	5.24	0.92	16.75	12.4	1.35
Max. shear (kN)	480	445	1.08	142.45	145	0.98
Max. torsion (kN.m)	20	22	0.91	20	18	1.11
Max. moment +ve (kN.m)	69	87	0.79	48.84	55.6	0.88
Max. moment -ve (kN.m)	138	115	1.20	97.68	86.3	1.13

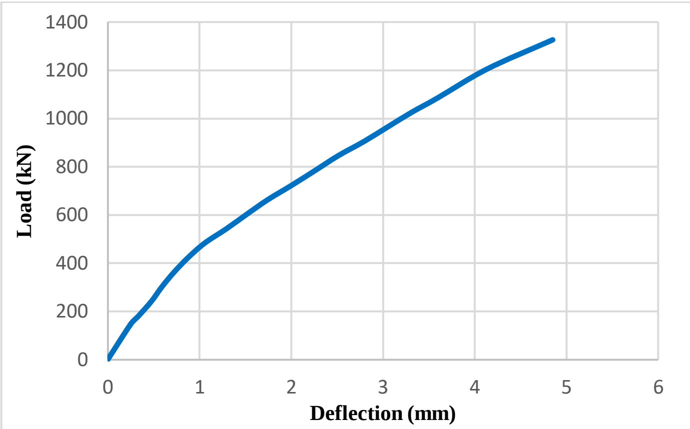

Figure 4. Load-deflection response curve of the experimental specimen

In addition to the current study conducted here, a previous study (Hashim & Ali, 2022) was modeled with the CSiBridge software for verification. A specimen with a radius of 1.15 meters that is horizontally curved and shaped like a semi-circle provides the validation. The specimen's cross-sectional measurements are as follows: the top flange width is 360 mm, the width is 250 mm, and the overall depth is 250 mm. The ends of each beam extended 50 mm beyond the support's centerlines. Two-point loads were placed on these beams at the 45° angle in the centre of each span.

FINITE ELEMENT MODELING

Single-cell box girder cross-section with two lanes is presented in Figure 6, for a bridge with three equal spans of 120 m total length and a web width of 0.5 m. The horizontal curvature has 200-m radii, the other dimensions and parameters are shown in Table 2. CSiBridge software, version 23.3.1, is used to model the bridge using FEM method as an area object with a size of 1.2 sub-mesh.

Using the CSiBridge finite element software allows for flexibility in varying any of the influencing parameters and quickly, easily, and affordably determining the results of this modification. Software called CSiBridge is dedicated to the analysis and design of bridges, regardless of their construction or material requirements. Because this software contains pre-built sections that can be altered in terms of cell number, web inclination, web size, flange, and other factors, working with box bridges is made easier. The CSiBridge software facilitates the determination of deflection, shear forces, bending, and torsional moments along the whole span of the bridge.

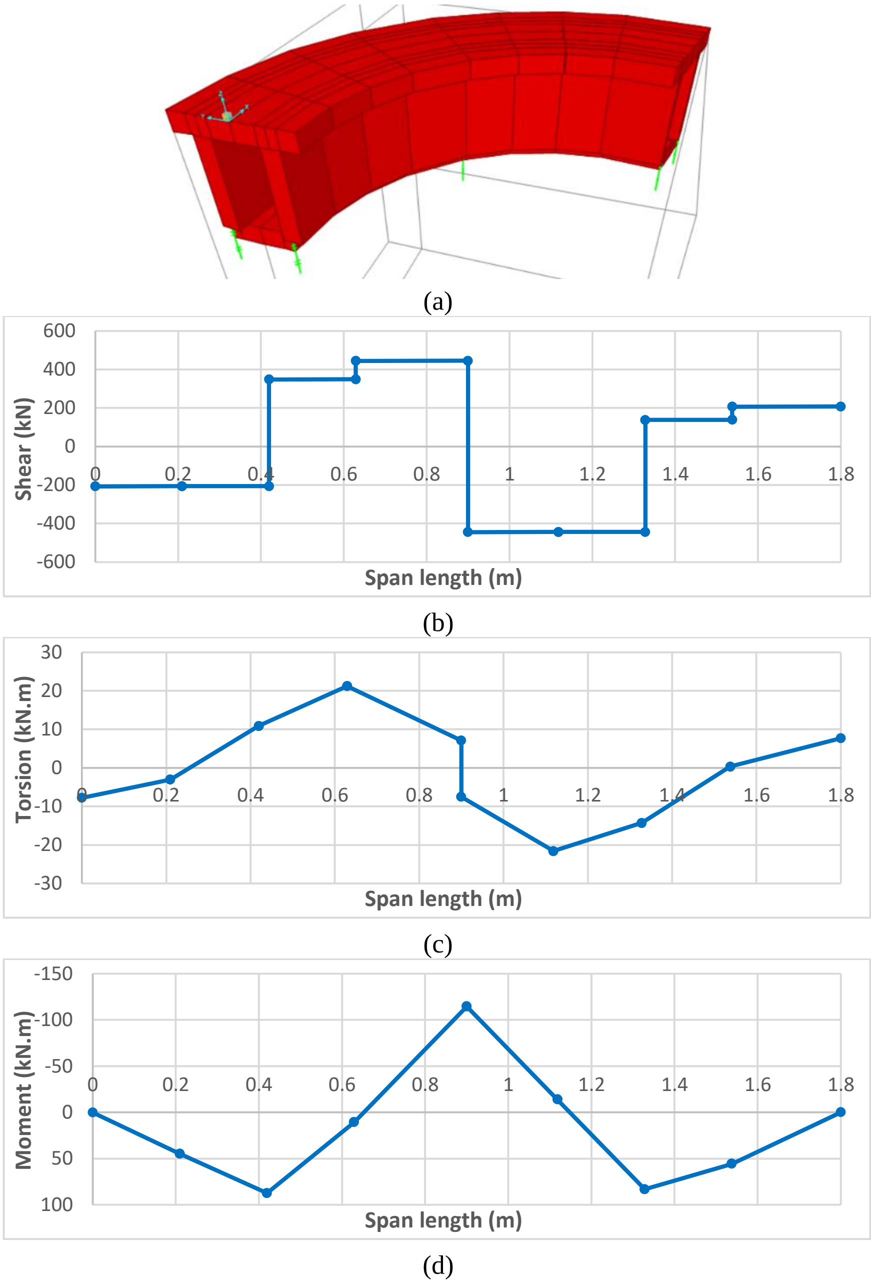

Figure 5. FE model of the experimental model; (a) 3D modeling (b) shear (c) torsion and (d) bending moment

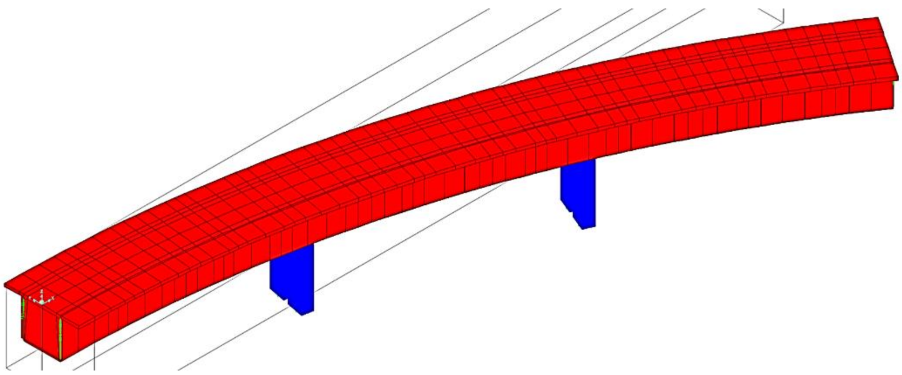

Figure 6. Finite element modeling using CSiBridge software

Table 2. Specimen details

<table>
<tr><th>specimen No.</th><th>Section shape</th><th>Height, m</th><th>Width, m</th><th>Web & flange width, m</th><th>Cantilever flange width, m</th></tr>
<tr><td>1</td><td>Rectangular</td><td rowspan="4">7</td><td rowspan="10">13</td><td rowspan="13">0.5</td><td rowspan="13">3</td></tr>
<tr><td>2</td><td>Clipped</td></tr>
<tr><td>3</td><td>Trapezoidal</td></tr>
<tr><td>4</td><td>Circular</td></tr>
<tr><td>5</td><td rowspan="9">Rectangular</td><td>2</td></tr>
<tr><td>6</td><td>4</td></tr>
<tr><td>7</td><td>8</td></tr>
<tr><td>8</td><td>10</td></tr>
<tr><td>9</td><td>12</td></tr>
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<tr><td>11</td><td>15</td></tr>
<tr><td>12</td><td>17</td></tr>
<tr><td>13</td><td>19</td></tr>
</table>

Using concrete at 4000 psi (27.6 MPa), the main super-structure and transverse cross section of the bridge were represented, as shown in Table 3. Apart from the piers in the middle, the sub-structure is represented by the abutments at both ends and the commencement of the bridge. Material modeling is a crucial element in ensuring the accuracy of structural analysis, as the physical and mechanical properties of the materials used affect the overall performance of the system. In the current research work, the CSiBridge software used relies on non-linear material modeling, which allows the evaluation of the effect of stresses and deformations without direct user intervention, taking into account the relationship between stress and strain according to the approved standards. Elastic-plastic-behavior models are implemented to analyze the effect of loading, in addition to including shrinkage and creep properties that affect the material response over time. The software also processes material parameters based on experimental results and numerical simulation models, ensuring that expectations are consistent with the actual performance of the structure without the need for manual adjustment by the user.

Table 3. Material properties

Compressive strength (*f'c*), MPa	Modulus of elasticity (*Ec*), MPa	Poisson`s ratio (*v*)	Light-weight concrete factor	Shear modulus (*G*), MPa
27.5	24855.6	0.2	1	10356.3

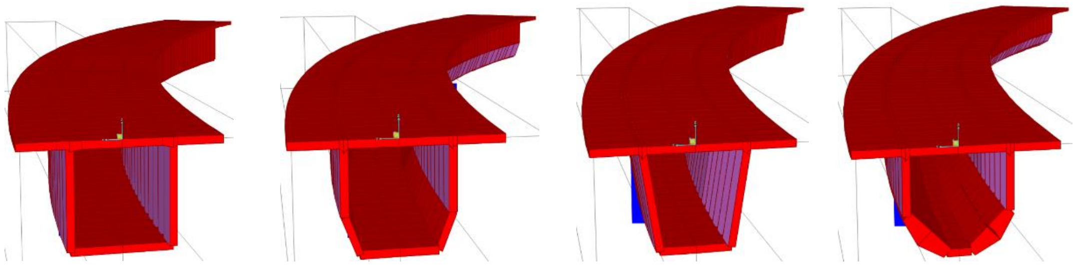
Self-weight and concentrated dead load of 900 kN at mid-spans are the applied loads. The deflection, shear, torsion and bending moment behavior along its length was examined and analyzed. The software finite element approach accurately captured the nature of the supports. Consequently, the first support at the abutment and median support are the roller, and the last one is a pinned.

NUMERICAL RESULTS

Several parameters were studied to investigate the box behavior including the section shape, height and width. Deflection, shear and torsional moments were determined in addition to positive and negative bending moments, as shown in Table 4.

Table 4. Results of specimens

Specimen No.	Section shape	Height, m	Width, m	Deflection, mm	Max. Shear, kN	Max. Torsional Moment, kN.m	Max. +ve Bending Moment, kN.m	Max. -ve Bending Moment, kN.m
1	Rectangular	7	13	5.587	10919	3626	63197	72509
2	Clipped			5.523	10300	3683	59756	68457
3	Trapezoidal			5.514	10242	4037	58821	68890
4	Circular			5.438	12353	4391	71026	81480
5	Rectangular	2		48.844	7308	2590	41545	50246
6		4		12.227	8760	2969	50073	59462
7		6		6.693	10202	3394	58779	68256
8		8		4.896	11634	3869	67654	76673
9		10		4.150	13059	4388	76667	84772
10		12		3.824	14479	4950	85762	92678
11		7		5.587	10919	3626	63197	72509
12			15	5.874	12329	3481	72450	79950
13			17	6.240	13721	3531	82028	86661
14			19	6.471	15076	3656	92245	91899

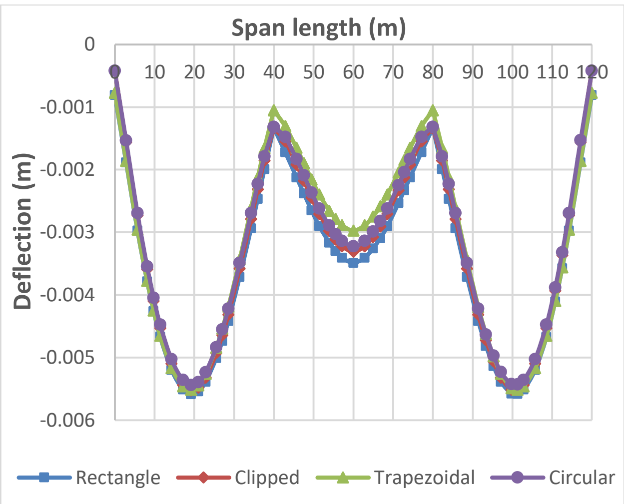


a. Rectangular b. Clipped c. Trapezoidal d. Circular

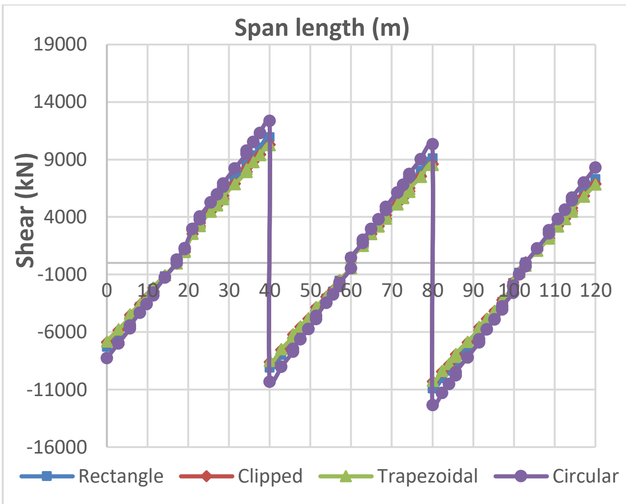
Figure 7. Cross-section shapes of box girder

Effect of Section Shape

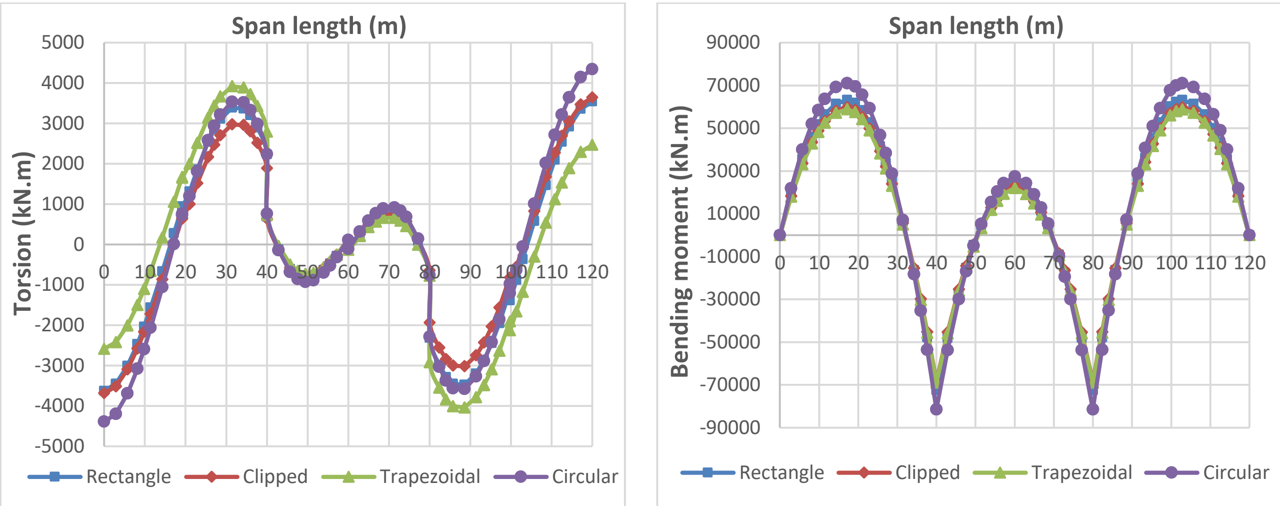
To know the effect of the cross-section shape, the various shapes that were defined by the finite element were studied, including the rectangular, clipped, trapezoidal, and circular shapes, as shown in Figure 7. By changing the shape of the section, the following results were obtained:



(a) Deflection along the span under section shape effect



(b) Vertical shear along the span under section shape effect



(c) Torsional moment along the span under section shape effect

(d) Bending moment along the span under section shape effect

Figure 8. Section shape effect

- It was found that the deflection in the rectangular section is the largest, whether in the outer or inner span, followed by the clipped section, as in Figure 8(a), while the smallest is circular in the outer span and trapezoidal in the inner span. In general, the deflection did not differ much with the different shapes of the section, because the height of the bridge is relatively large, which makes the shear deformation larger than the flexure deformation.
- It was found that the shear in the circular section is the largest, whether in the outer or inner span, followed by the rectangular one, as shown in Figure 8(b), while the smallest is the clipped section in negative shear and the trapezoid section in positive shear. Shear is affected by the dimensions of the section and the distribution of stresses. In the circular section, despite the decrease in the section, the stress distribution is more streamlined due to the lack of stress concentration sites. A rectangular section has a larger shear than a trapezoidal section and a clipped section, because the section that resists shearing is larger. The shear did not differ much according to the different shapes, which supports the possibility of changing the shape of the section and its aesthetic and economic benefits.
- It was found that the torsional moment in circular shape was the largest in the end supports and the central span, while the rectangular shape did not differ significantly from the clipped shape, and the smallest was the trapezoidal shape, as shown in Figure 8(c). As for the end span, the largest is the trapezoidal, followed by the circular and rectangular shapes, while the least is the clipped shape. The torsion in the central span is less than in the end one due to torsional moment's restriction. The maximum torsion value is near the central supports, while the values are zero in the zones of maximum moments. In resisting torsion moments, a circular section is better than a rectangular one.

The reasons are due to that:

1. The circular section provides an equal distribution of stresses around the center, making it more efficient in resisting torsion.
2. A circular section has a greater second polar moment of inertia compared to a rectangular section when comparing sections with equal dimensions. The second polar moment expresses the ability of the section to resist twisting.
3. A circular shape is more symmetrical around the axis of rotation, which means that twisting is equal around the axis without weak points or concentration of stresses as in a rectangular shape.
4. The circular section uses the material more efficiently in resisting torsional moments, as every part of the material contributes equally to resisting the moment.

Therefore, when designing elements that will be subjected to large torsional moments, it is preferable to use a circular section to achieve the best performance.

- It was found that the bending moments in the circular section are the largest, followed by the rectangular section, then the clipped section, and the least is in the trapezoidal section, as shown in Figure 8(d). The presence of positive and negative moments, as it is a continuous bridge, makes the whole section effective (Salem, 2022). In the negative moment region, the compression is in the lower part, and since part of it is reduced in the trapezoidal section and the clipped section, the bending moments are reduced.

Effect of Section Height

To study the effect of height, the height value of a rectangular section was changed to be 2m, 4m, 6m, 8m, 10m and 12m. By changing the height of the section, the following results were obtained:

- It was found that the deflection reached high values, especially in outer span, in the case of a small height of 2m, reaching 0.049 m, as shown in Figure 9(a). This happened due to the control of bending moments and therefore flexural deformation. By increasing the height by 100%, the deflection decreases by 75% and the cost increases by 18%. By increasing the height by 200%, the deflection decreases by 86% and the cost increases by 36%. As the height increases, the difference in deflection values decreases, meaning that the behavior is non-linear. At high values of 10m and 12m, the bridge begins to behave like a deep beam. Its deflection values became low, because the ruling behavior in it is the shear behavior. Because the loads are transferred directly from the load to the support points in the deep girders (Abdul-Razzaq & Dawood, 2021; Abdul-Razzaq et al., 2021; Abdul-Razzaq et al., 2025; Shakir et al., 2023), it turns out that there is a high deflection in the support zones to concentrate the stresses there.
- When the height increased, the shear increased linearly, as shown in Figure 9(b). This can be explained by several reasons:

1. The moment of inertia of a rectangular section about an axial axis is proportional to the cube of the height of the section. This means that increasing height increases the section's resistance to bending, making the girder stiffer. Greater stiffness results in decreased bending and increased shear stresses in certain zones, especially near support points.
2. Shear stresses in concrete girders are unevenly distributed across the height of the section. Near the neutral axis, shear stresses are greater. As the section height increases, the distance between the neutral axis and the outer fibers becomes larger, leading to increased values of shear stresses.
3. When the girder height increases, the distribution way of loads across the section changes. A higher girder can transmit greater loads through shear, and therefore, the shear forces applied to it are greater. Also, increasing the height of the girder increases the length of the path along which shear stresses must be transmitted through the section.

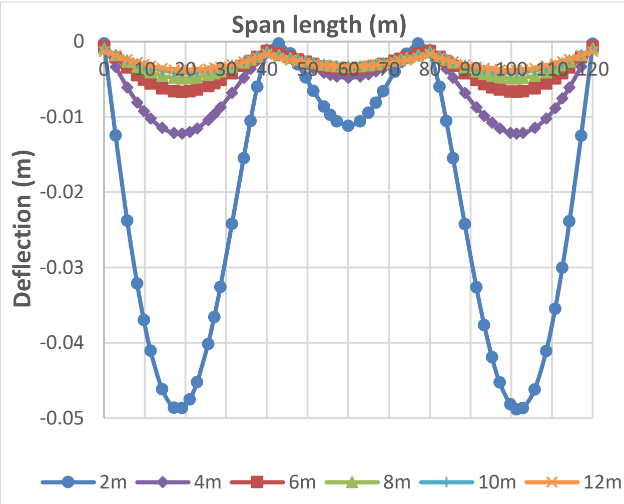
- At high girders, uneven distribution of torsional stresses can lead to increased torsional moment, as shown in Figure 9(c). As the section height increases, the distance between the outer fiber and the axial center increases. Consequently, that torsional stresses are distributed over a larger zone, resulting in an increase in torsional moment. By increasing the height of the girder, the load distribution can become more eccentric with respect to the girder axis. This leads to the generation of larger torsional moments, as loads acting away from the main girder axis generate larger torsional moments due to the increased moment arm.

Effect of Section Width

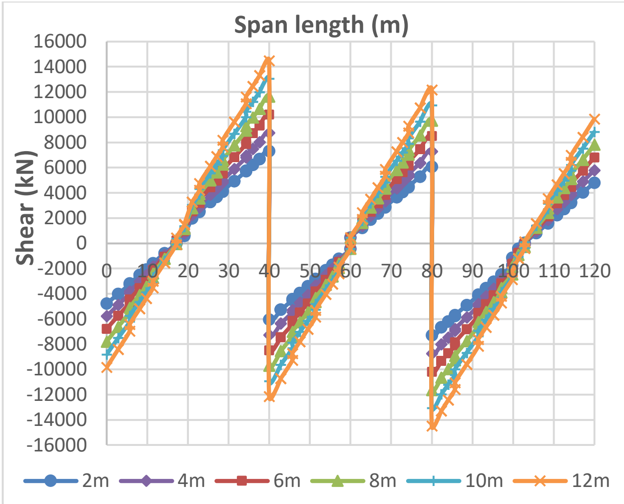
To study the effect of the width of the rectangular section, its values were changed to be 13m, 15m, 17m and 19m. By changing the width of the section, the following results were obtained:

- As the section height increases, the girder resistance to bending moment increases, as shown in Figure 9(d). The moment of inertia of the section increases with increasing height, leading to an increase in the section's resistance to bending. Increasing the height means that the section can resist greater bending moments without failure or significant deformation.
- As the total width of the box girder increases, its self-weight increases. This additional weight acts as an additional load leading to increased deflection, as shown in Figure 10(a). When width is increased without an equivalent increase in height, the height-to-width ratio of the girder may decrease, reducing its overall stiffness and increasing deflection under applied loads. Rigidity is proportional to the aspect ratio. When the width of the girder increases, the applied loads are distributed over a wider zone, which may result in a greater distribution of loads across the full width of the girder. This can lead to an increase in overall deflection.

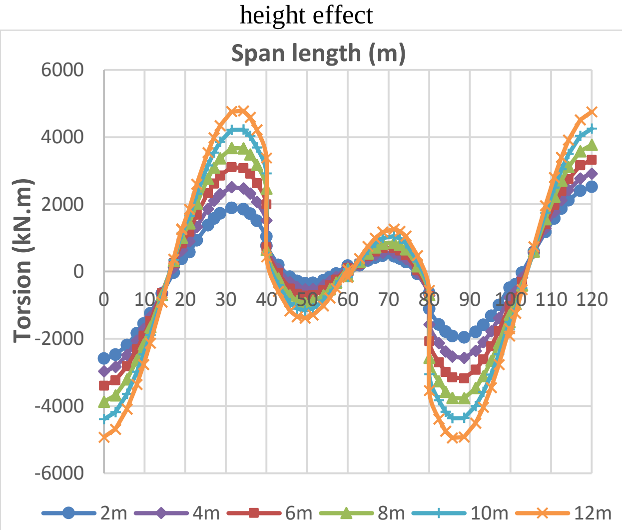
- When the width increased, the shear increased linearly, as shown in Figure 10(b). This is because the moment of inertia of a rectangular section about a neutral axis is directly proportional to the width of the section. This means that increasing the width increases the resistance of the section to bending, making the girder stiffer. Increasing the overall width of the girder means that there is more zone for shear stresses to distribute. This may reduce the concentration of stresses, improving the girder's overall shear resistance ability. On the other hand, increasing the width affects the section in the transverse direction to a greater extent, especially in the load and support zones.
- In wide girders, uneven distribution of torsional stresses can lead to increased torsional moment as shown in Figure 10(c). As the cross-sectional width increases, the distance between the outer fiber and the axial center increases, which means that torsional stresses are distributed over a larger zone, resulting in an increase in torsional moment. By increasing the girder width, the load distribution can become more eccentric with respect to the girder axis. This leads to the generation of larger torsional moments, as loads acting away from the main girder axis generate larger torsional moments due to the increased moment arm.



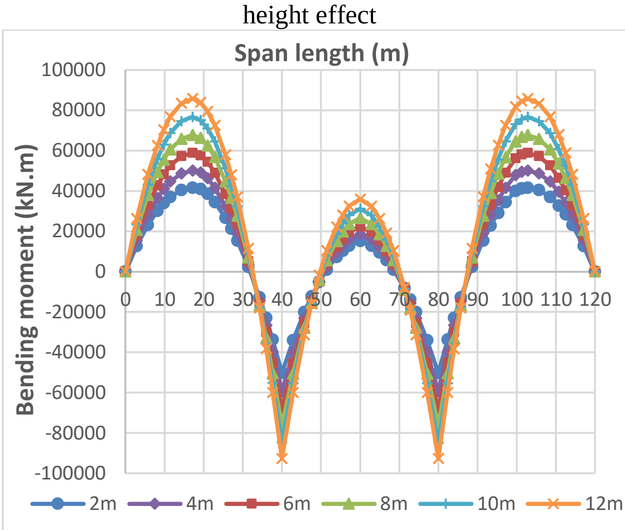
(a) Deflection along the span under section height effect



(b) Vertical shear along the span under section height effect



(c) Torsional moment along the span under section height effect

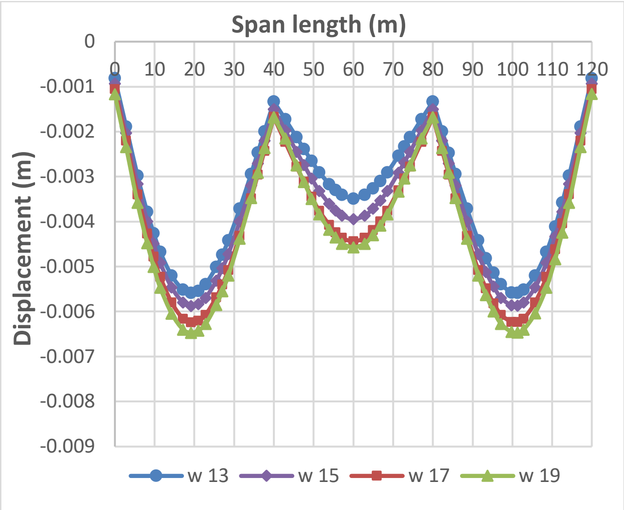


(d) Bending moment along the span under section height effect

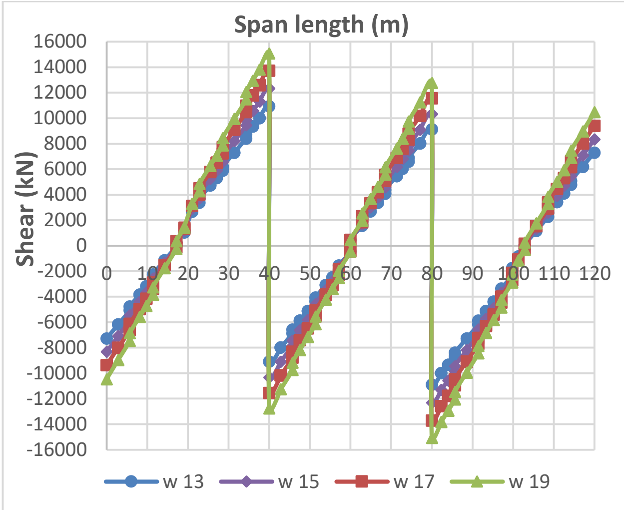
Figure 9. Section height effect

- As the section width increases, the girder resistance to bending moment increases, as shown in Figure

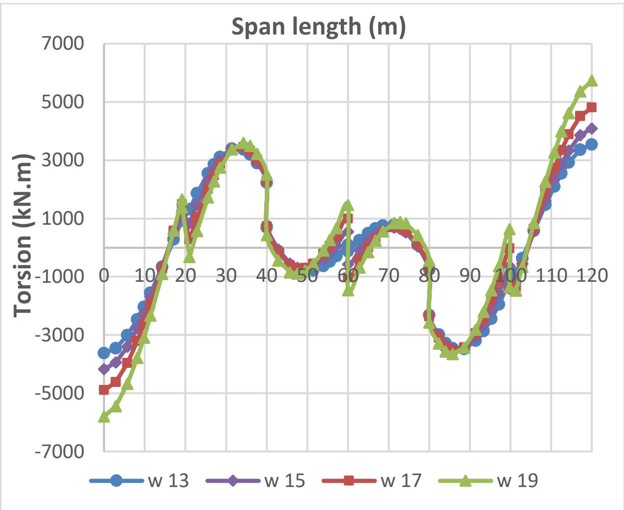
10(d). The moment of inertia of the section increases with its width. This leads to an increase in the section's resistance to bending. Increasing the width by 15%-32% increases the section's resistance to bending by 15%-46% and the cost increases by 13%-38%. Increased width means that the section can resist greater bending moments without failure or significant deformation.



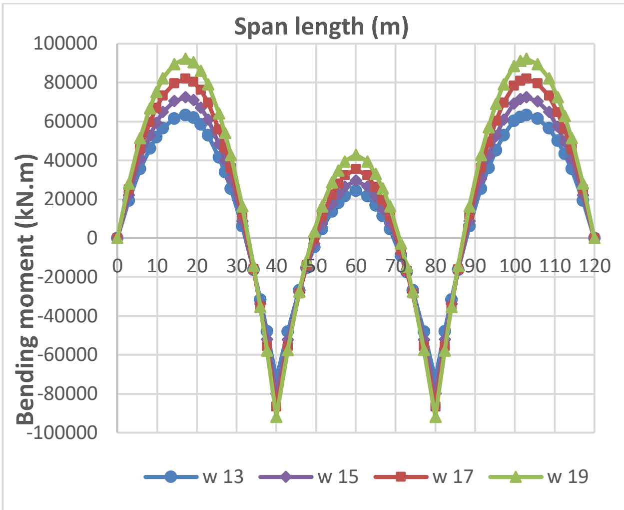
(a) Deflection along the span under section width effect



(b) Horizontal shear along the span under section width effect



(c) Torsional moments along the span under section width effect



(d) Bending moment along the span under section width effect

Figure 10. Section width effect

CONCLUSIONS

A horizontally curved specimen was cast and tested experimentally. This specimen was also modeled using the finite element CSibridge software. Its experimental results were compared with the numerical modeling results. After matching the numerical results with the laboratory results, and verifying their compatibility, the effect of the shape and dimensions of the box girder section on a bridge with realistic dimensions was studied. The results included the deflection, shear, torsional moments, and bending moments. Through these results, several conclusions were drawn, including:

1. The FEM results were verified using a specimen cast and laboratory tested for this purpose. The agreement of the finite element and the experimental results was verified by comparing the deflection, shear, torsion, and bending moments for both. Good results were obtained, which proves that finite elements represent an efficient method for modeling box girder bridges with less time and cost.

2. In the experimental specimen, shear cracks appeared first in the outer web, then in the inner web, followed by flexural cracks. The load-deflection behavior was linear in most of the loading stages due to the dominance of shear forces.
3. By studying the shape of the box section, it becomes clear that the circular shape is the most efficient shape, because it provides an equal distribution of stresses around the center. That makes it more efficient in resisting shear and torsion. The rectangular section has the largest deformation, whether in the outer or inner span, followed by the clipped section, while the circular one in the outer span and the trapezoid one in the inner span have the least deformation. Shear forces and bending moments are the largest in a circular section, followed by a rectangle section, then a clipped section, followed by a trapezoidal one.
4. Deflection reached high values, especially in the outer span. In the case of a small height of 2 m, deflection reached 0.049m. By increasing the height by 100%, the deflection decreased by 75%, while increasing the height by 200% led deflection to decrease by 86%. At high girders, uneven distribution of stresses can lead to increased shear and torsional moments. As the section height increases, the distance between the outer fiber and the axial center increases, which means that the torsional stresses are distributed over a larger zone due to the increased moment arm.
5. As the total width of the box girder increases, its self-weight increases. Increasing the width by 15%-32% increases the section's resistance to bending by 15%-46%, making the girder more rigid. Increasing the overall width of the girder means that there is more zone for shear stresses to distribute. This may reduce the concentration of stresses, improving the girder's overall shear resistance ability.

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