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Torsional Strength of Horizontally Curved Continuous Reinforced Concrete Box Girder Bridges

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HIGHLIGHTS

- The effect of horizontal curvature on continuous box girder bridges, including load position impact, was studied.
- Torsional moments on the outer face exceeded the inner face, even for loads near the inner face.
- Increasing curvature raised outer face torsion but lowered inner face torsion, except with very sharp curvatures.

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ABSTRACT

The horizontally curved box girder bridges are considered important nowadays because of their low cost compared to the load capacity and torsion moments that they can carry. This study presents a finite element analysis of a continuous box girder bridge using CSI finite element bridge software. Three spans with 40 m length, 12.5 m width, and 2.3 m height are studied. The analysis included different radii of curvature with different loading locations along the transverse direction of a cross-section. Several conclusions were reached, the most important of which is that the torsional moments in the outer face are superior to the inner face, even when loading near the inner face. That is, the torsional moments are affected more by the radius of curvature amount than by the location of the load. In general, the maximum torsional moments increase with the decrease of the curvature radius in the outer face. Nevertheless, the maximum torsional moments decrease with the decrease of the curvature radius in the inner face, except for the case of the curvature radius of 100 m. That can be attributed to the fact that the radius of curvature in this case is considered sharp, resulting in high torsional moments.

1. Introduction

Nowadays, box girder bridges have become very common due to their relatively low cost, performance efficiency, and beautiful architectural shape. The amount of curvature varies depending on the nature of the region's geography and the bridge's purpose. Some of them are straight, and others contain a little curvature. There are also bridges with a high curvature in turns. Bridges are exposed to different types of loads, and the loads' location changes continuously, resulting in changing behavior [1-5].

Because of their durability and financial benefits, continuous-span layouts are commonly used on modern curved bridges at multilevel urban interchanges. Horizontally curved bridges with continuous girders of constant depth provide good-looking structures. Compared to other structural options for curved road alignments, the overall cost of horizontally curved bridges is frequently competitive. For instance, due to the cost reductions obtained in the substructure, restrictions on the cantilevered overhang, the number of expansion joints, bearing features, kinked girders, and/or a sequence of straight short-span chords might be used [6].

The box girder's study and design may be split into two categories: longitudinal analysis (i.e., analysis along the traffic flow) and transverse analysis (i.e., across traffic direction). The cross-sectional members' characteristics of the box girder affect the stresses and deformations in the transverse analysis. When loaded, curving girders experience a complex state of forces. The forces created include moments, warping (i.e., nonuniform) torsional moments, pure (i.e., St. Venant) torsion, bending moments, and shear forces. Due to cross-section distortion, torsional moments and moments also form. Yet, by supplying sufficient cross frames, distortion-related effects can be readily decreased to inconsequential levels [7-13].

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The applicability of various techniques of assessing horizontally curved concrete box girder bridges was studied by Nutt, Redfield, and Valentine [14]. This research, which concentrated on local and global force effects, was the foundation for updates in 2010. They presented three methods, which are as follows, for analyzing concrete box girder bridges:

1) Since curvature has little impact on response, the first method permits bridges with a central angle within one span of less than 12 degrees to be studied as if they were straight. Often, a plane frame analysis is used to do this.
2) The second approach uses a spine beam analysis, where the superstructure is idealized as a collection of straight beam chorded segments with a small central angle positioned along the bridge's centerline. A space frame analysis is necessary when the substructure and superstructure are one unit. When space frame analysis was employed, it was discovered that whole-width designs produced conservative findings. When considering a global reaction like torsion or transverse bending, minimizing the number of live load lanes applied to the total width model to those that can fit on the bridge is appropriate.
3) A third type of analysis using advanced three-dimensional computer models is necessary for bridges with large curvatures or distinctive plan geometry. Bridges with irregularly oriented skewed supports or varying widths are only two examples of unusual plan geometry.

Curvature is considered one of the important factors that should be studied in more detail to know its effect and thus secure the structure from torsional moments. The curvature causes a change in the torsional moments between the inner and outer faces along the cross-section, even in the case of central loading. Therefore, changing the position of the load along the cross-section leads to important changes that deserve study.

That is why, in the current research work, the amount of curvature was changed for three spans to determine the effect of curvature on torsional moments, considering the location of the applied load.

2. Model Validation

To verify the simulated model, the experimental results of previous research work were compared with the CSI Bridge software's model. In general, there is a lack of experimental research that studies continuous horizontally curved box bridges, which causes a lack of verification data. Consequently, the authors of the current research urge the rest of the researchers to enrich this field. Song et al. [9] and Shen et al. [15] have studied the behavior of horizontally continuous curved box bridges experimentally and theoretically, calculating the deflection, bending, and torsional moments. The specimen (CT10-1) is considered, consisting of three spans: 3 + 3.75 + 3 m and a curvature radius of 10 m. The middle supports were placed with one support in the center, but the end supports were restrained against rotation along the beam axis using two supports, each with a distance of 35 cm symmetrically. Each face span had two deviators installed, while the center span had three. All of the deviators had the same thickness of 8 cm. The pier diaphragms were created to meet the needs of local loading and anchoring. Near the supports, the thickness of the webs and bottom slabs was gradually raised over a length of 25 cm. Eight load cells were employed to assess the supports and restrainers' responses. The bending moments were computed using these reactions. After analyzing the specimen, it was found that there is agreement between the numerical, experimental, and theoretical calculations as in Table 1, especially since designers use this software in analyzing and designing bridges in reality. Figure 1(a) shows the maximum midspan deflection of the CSI Bridge software and Figure 1(b) shows the results of Song et al. [9] as it turns out that there is agreement in deflection in terms of general trends and values. The comparison included the positive bending moments in the middle of the first span, the negative bending moments at the second support (S2), and the third support (S3) in addition to the torsional moments. It is worth noting that this current study did not include a study of the deflection and moments because the difference in their values is very small when changing the amount of curvature. Still, it was reviewed here to show the agreement between the software and the experimental results.

Table 1: Model validation

	Experimental	**Calculated [9,15]**	**CSI bridge**	**Experimental/ CSI bridge**	**Calculated / CSI bridge**
Deflection (mm)	14.54	13.27	13	1.12	1.02
Moment +ve (kN.m)	123	115	125	0.98	0.92
Moment -ve @S2 (kN.m)	140	170	167	0.84	1.02
Moment -ve @S3 (kN.m)	125	115	136	0.92	0.85
Torsion (kN.m)	7.3	10	6.2	1.18	1.61

3. Finite Element Modeling

A single-cell box girder cross-section with two lanes is presented in Figure 2 (a) for a bridge with three spans of 40 m long, 12.5 m wide, and 2.3 m high. The horizontal curvature has different radii: 100 m, 200 m, 300 m, 400 m, 500 m, 600 m, 700 m, 800 m, and straight (∞, i.e., no curvature). CSI Bridge software, version 23.3.1, models the bridge using the finite element method as an area object with a 1.2 sub-mesh size, as illustrated in Figure 3.

The superstructure elements of the bridge were represented, including its main superstructure and its transverse cross-section using 27.6 MPa concrete, Table 2. In addition to the representation of the substructure, which includes the abutment at the beginning and the end of the bridge, besides piers in the middle, the details of the bearing and diaphragms at the supports are also presented in Figure 2 (b).

The applied loads are self-weight and 1000 kN concentrated forces at mid-spans with different locations along the cross-section in the entire section, near the inner and outer face (2 m from the inner and outer face). The bridge was analyzed, and its torsional behavior on the faces and entire section was investigated. The nature of the supports was accurately represented in the software finite element method. Consequently, the first support at the abutment is the roller and median support, and the last one is a pinned.

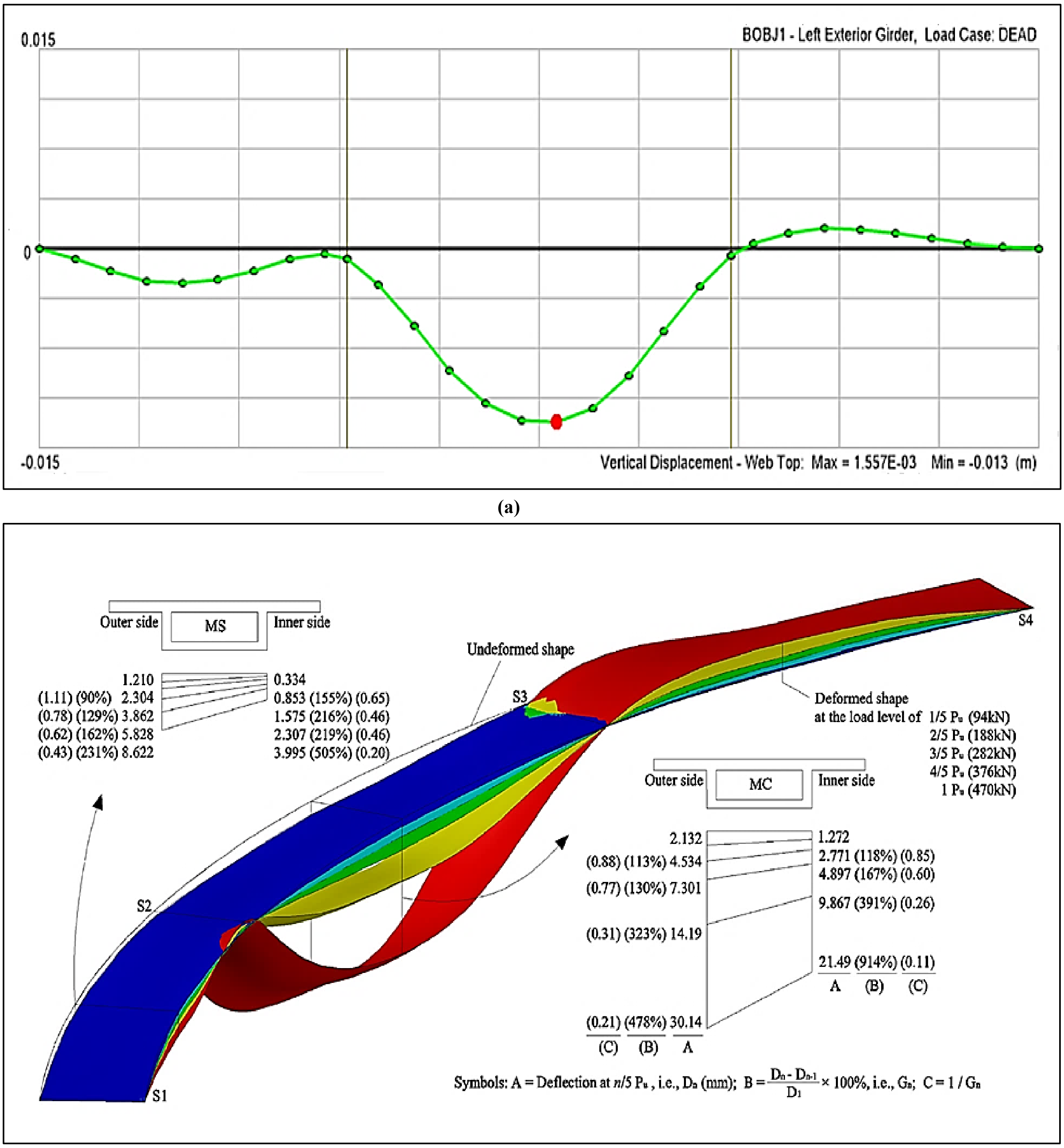
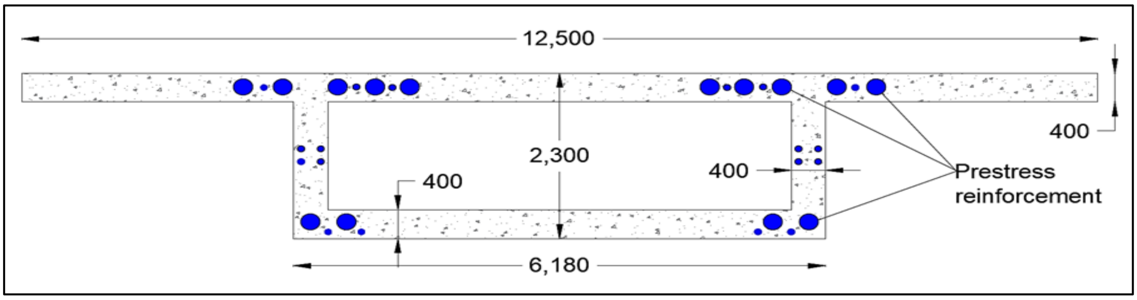
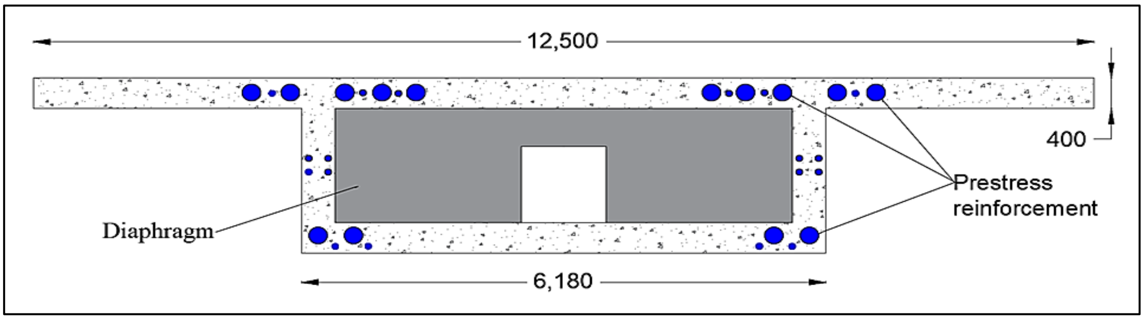


Figure 1: Deformation shapes of specimen CT10-1 (a) Using CSI bridge (b) Experimentally by Song et al. [9] (aspect ratio: 1:30)



(a)



(b)

Figure 2: Cross-section dimensions of the box girders in mm (a) at midspan (b) at support

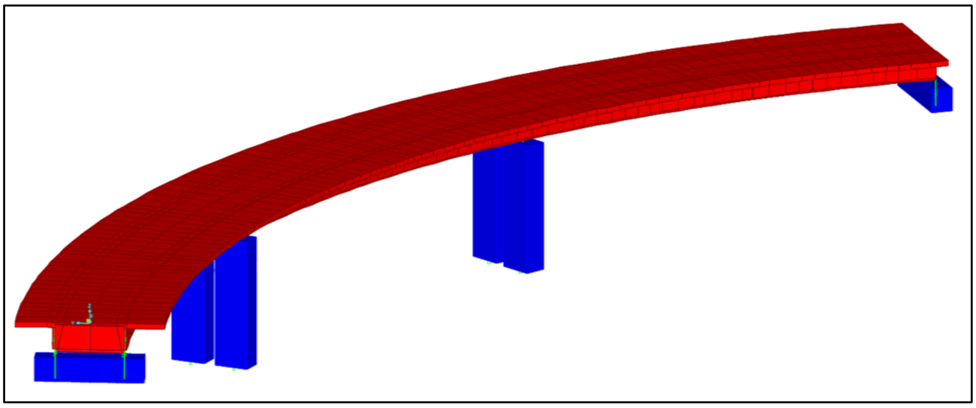


Figure 3: Finite element modeling using CSI bridge software

Table 2: Properties of Material

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

4. Numerical Results

The location of the loads affects the box girder bridge, so the presence of the load in a location results in a different behavior than if it was in another location, depending on the geometry of the box girder bridge. Here, the location of the loads in the transverse direction was changed according to the difference in the radius of the curvature, presenting the results of the torsional moments along the span: the entire section, the outer face, and the inner face.

4.1 Load at Cross-Section Center

In the case of a non-curved bridge, when the load is applied in the middle of the cross-section, as shown in Figure 4, the torsional moments are low in the entire section. In more detail, the torsional moments reached their maximum value at the end supports reached a significant increase near the middle supports towards the end span, Figure 5. The outer face was generally superior to the inner face in terms of maximum torsional moments, but the behavior differed. Thoroughly, the torsional moments increased with the curvature radius decrease in the outer face. In contrast, the torsional moments decreased with the curvature radius decrease until the curvature radius reached 200 m, then increased when the curvature radius reached 100 m. This increase is because the slight curvature increases the torsional moments in the outer face and reduces them in the inner face. As for the sharp curvature, the increase is large in the outer face, so it does not match the decrease in the rest of the large curvature radii. It is worth noting that this increase occurred at the middle supports, while in the rest of the regions, there was a significant decrease in the torsional moments at the curvature radius of 100 m. Unlike in the entire section, there was no significant difference between the end and middle spans in the outer and inner faces, as in Figures 6 and 7. By increasing the curvature (decrease in the radius of the curvature), the maximum torsional moments was increased slightly between 800-500 m. In decreasing the radius of the curvature, the effect increased significantly non-linearly, as shown in Figure 8.

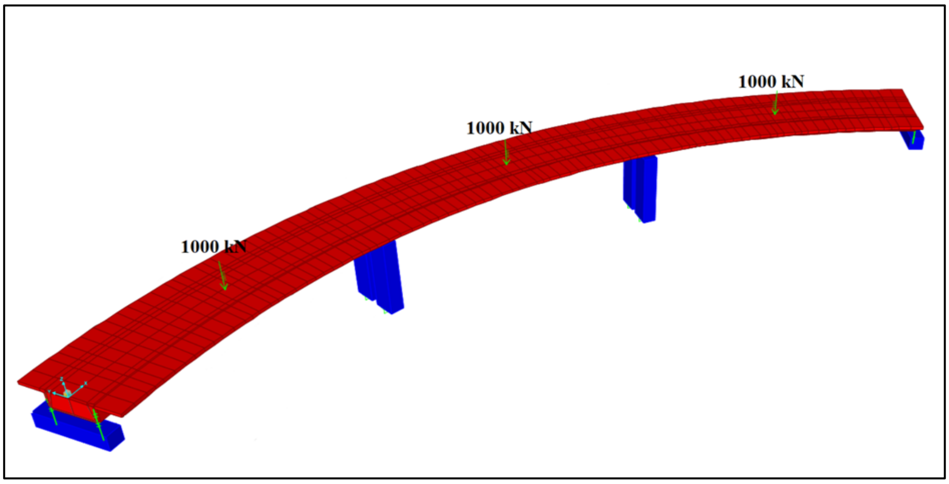


Figure 4: Load on the cross section's center of the box girder bridge

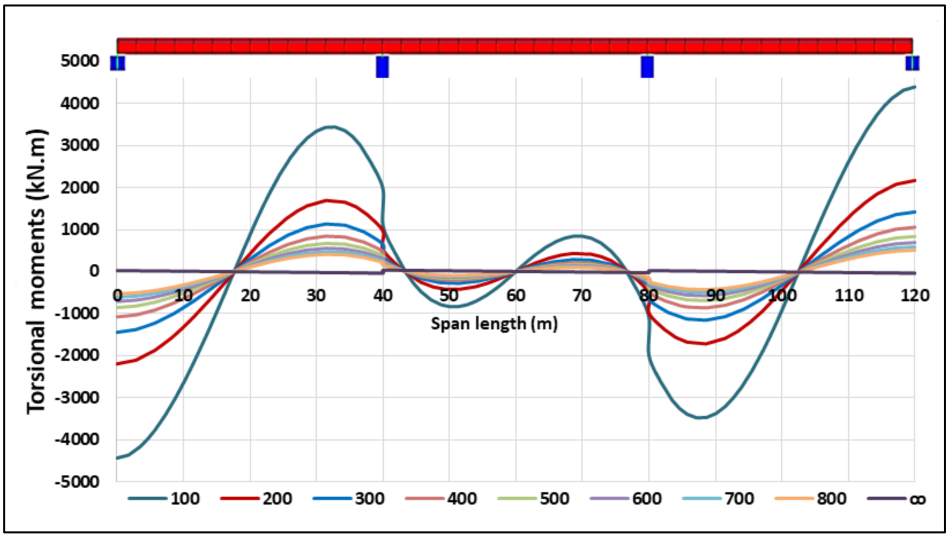


Figure 5: Entire section of torsional moments along the span under central loading

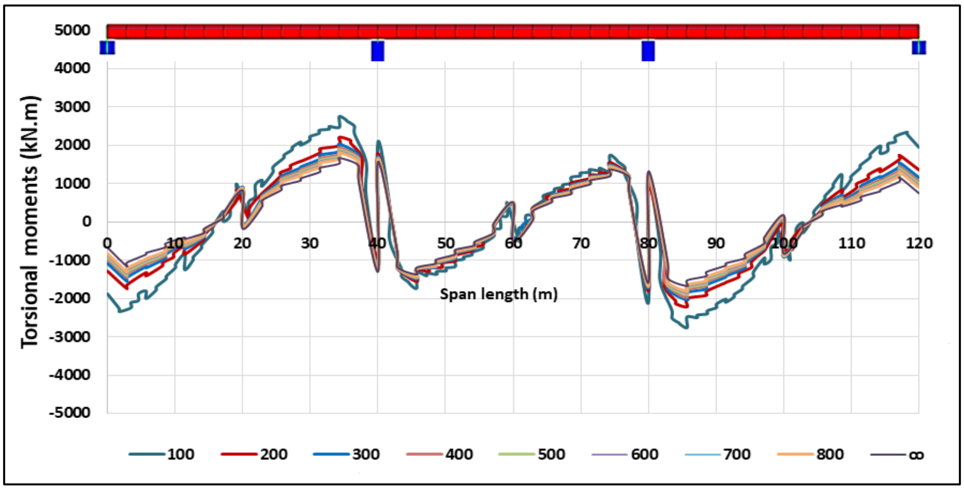


Figure 6: Outer face torsional moments along the span under central loading

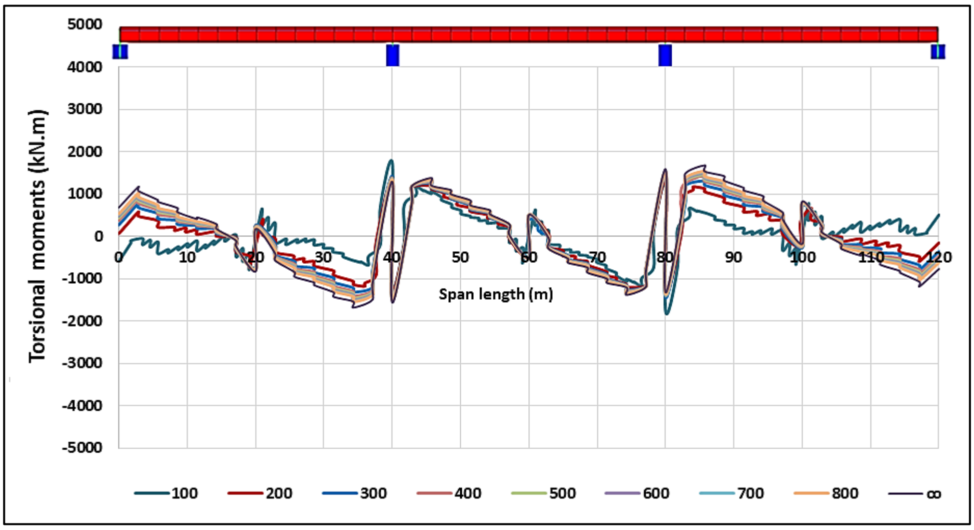


Figure 7: Inner face torsional moments along the span under central loading

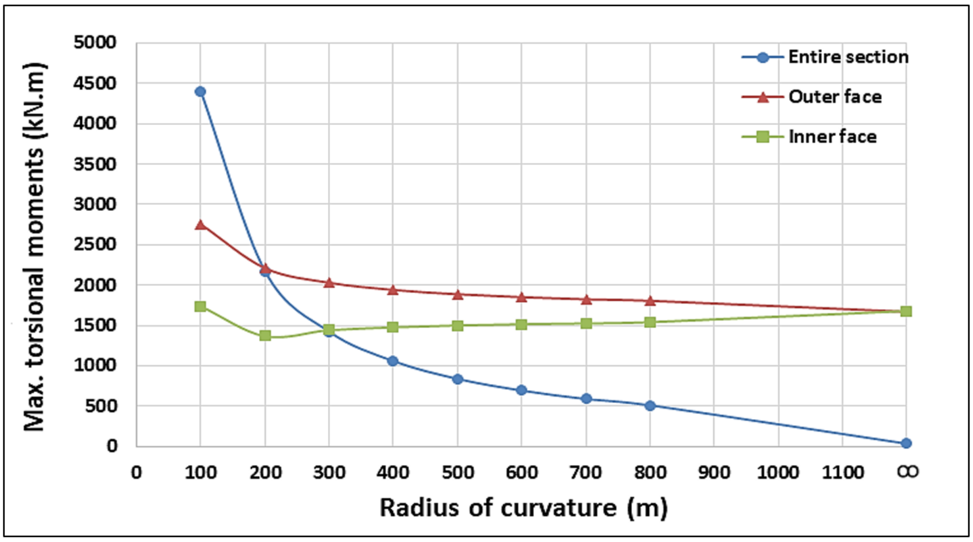


Figure 8: Maximum torsional moment with different curvature for central loading

4.2 Load on The Outer Face

When applying the load near the outer face of the cross-section, as shown in Figure 9, high torsional moments are formed at the entire section, even in the absence of curvature. That occurs because the load moving away from the bridge's center causes torsional moments, as shown in Figure 10. In the outer face, the torsional moments increased in this case compared to the central load because the load moving away from the center of the bridge axis results in torsional moments, and the horizontal curvature results in torsional moments in the same direction. In more detail, the torsional moments reached their maximum value at the end supports and reached a significant rise near the middle supports towards the end span. The outer face is generally superior to the inner face in terms of maximum torsional moments, but they are less than those of the entire section. Torsional moments increased with decreasing the radius of the curvature in the outer face. In contrast, the torsional moments decreased with the decrease in the radius of the curvature in the inner face until the radius of the curvature reached 200 m.

In comparison, it increased when the radius of the curvature reached 100 m. This increase is because the small radius of curvature increases the torsional moments in the outer face and reduces them in the inner face. As for the sharp curvature, the increase is large in the outer face, so it does not match the decrease in the rest of the large curvature radii.

It is worth noting that this increase occurred at the middle supports, while in the rest of the regions, there was a significant decrease in the torsional moments at the curvature radius of 100 m. Contrary to what happened when loading the middle, there was no significant difference between the end and middle spans in the outer and inner faces as shown in Figure 11 and 12. By increasing the curvature (decreasing the radius of the curvature), the maximum torsional moments increased slightly between 800-500 m, while decreasing the curvature's radius increased the effect non-linearly, as shown in Figure 13.

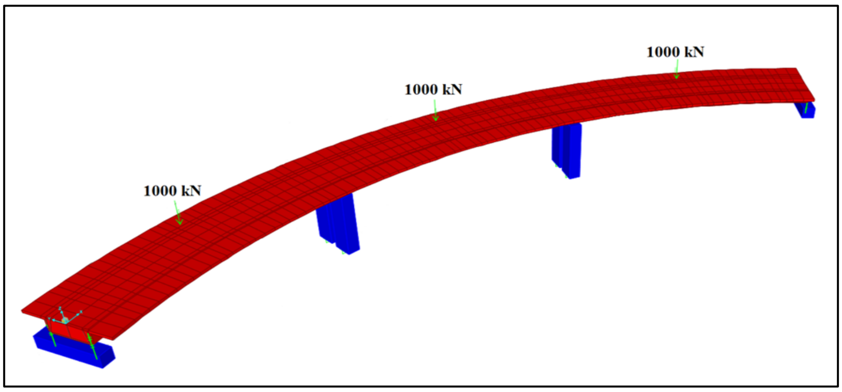


Figure 9: Load on the outer face of the box girder bridge

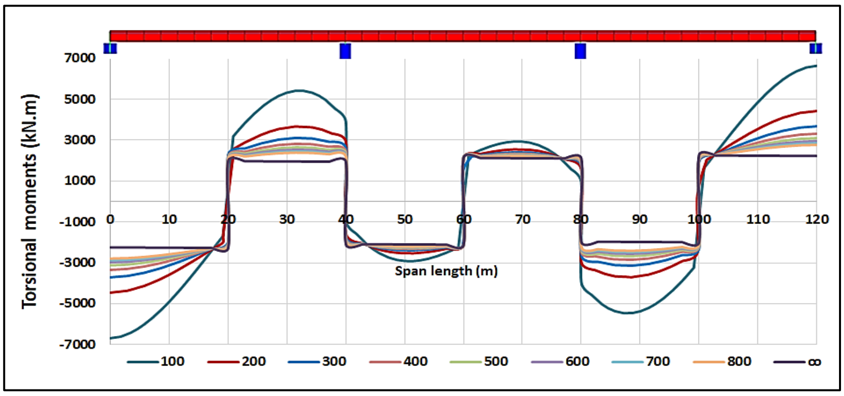


Figure 10: Entire section of torsional moments along the span under outer face loading

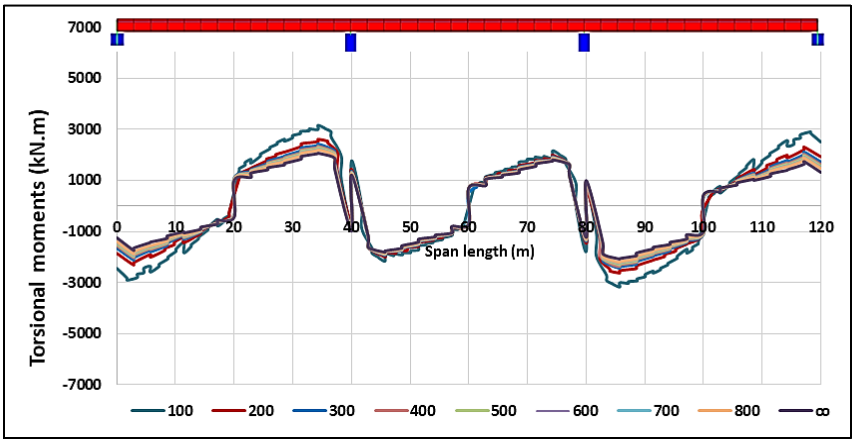


Figure 11: Outer face torsional moments along the span under outer face loading

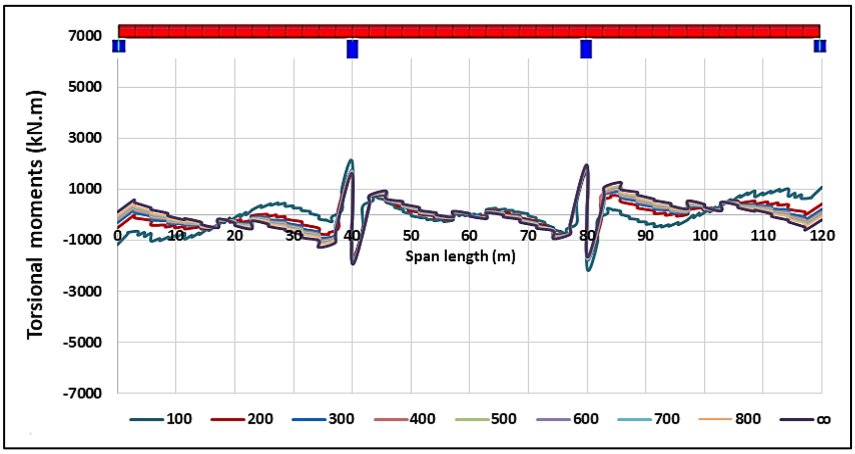


Figure 12: Inner face torsional moments along the span under outer face loading

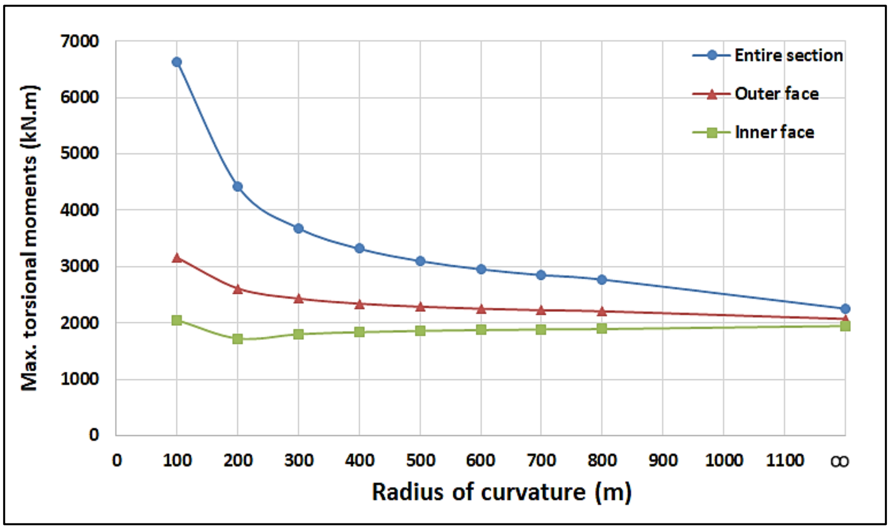


Figure 13: Maximum torsional moment with different curvature for outer face loading

4.3 Load on The Inner Face

When applying the load near the inner face of the cross-section, as shown in Figure 14, torsional moments are formed at the entire section, even in the absence of curvature (∞). That happens because the load moving away from the bridge's center causes torsional moments, as in Figure 15. In the outer face, the torsional moments decreased compared to the central load and the load near the outer face. That is because load moving away from the center of the bridge axis results in torsional moments; besides, the horizontal curvature results in torsional moments that oppose them in the direction. There were no significant differences between the end and middle spans when applying load on the outer and inner faces, as in Figures 16 and 17, contrary to what happened when applying load on the middle. In more detail, the torsional moments reached their maximum values at the end supports, reaching a significant increase near the middle supports towards the end span in the entire section. The outer face is generally superior to the inner face in terms of maximum torsional moments, but they are slightly less than that of the entire section. Torsional moments decreased with a decrease in the radius of the curvature in the inner face. In contrast, the torsional moments increased with a decrease in the radius of the curvature in the outer face until the radius of the curvature reached 200 m, with a clear increase when the radius of the curvature reached 100 m, as shown in Figure 18.

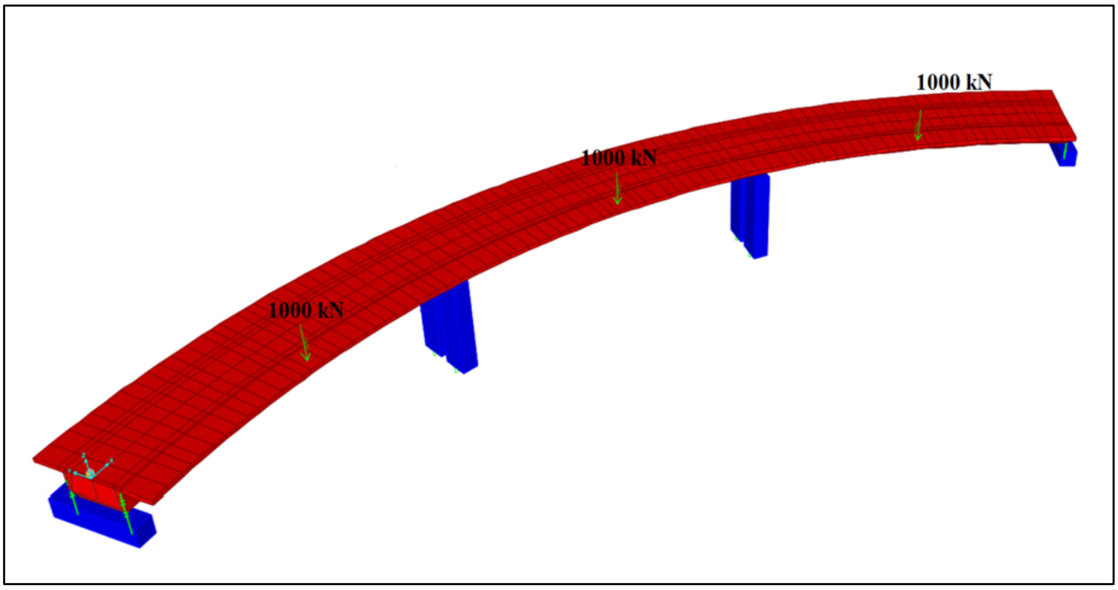


Figure 14: Load on the inner face of the box girder bridge

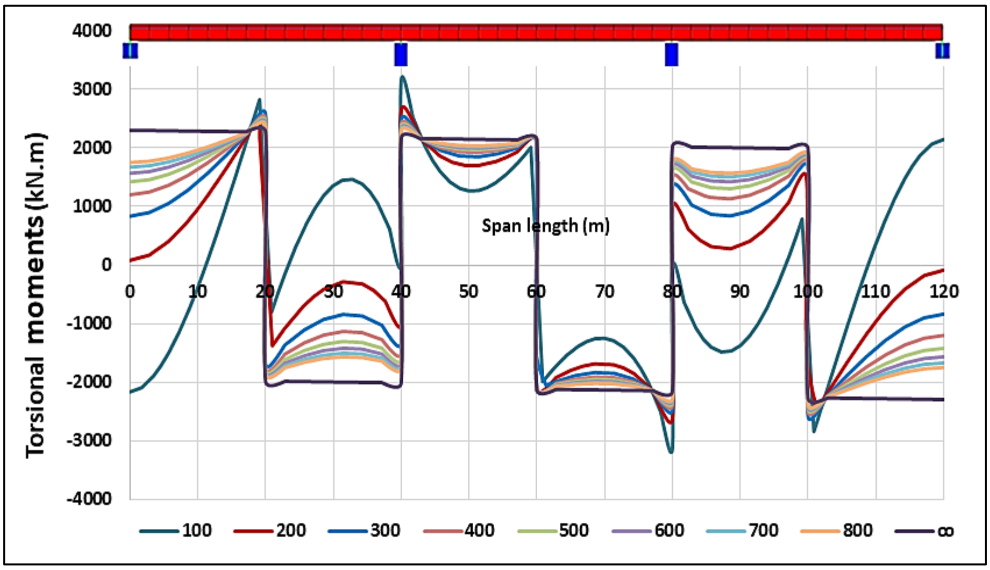


Figure 15: Entire torsional moments along the span under inner face loading

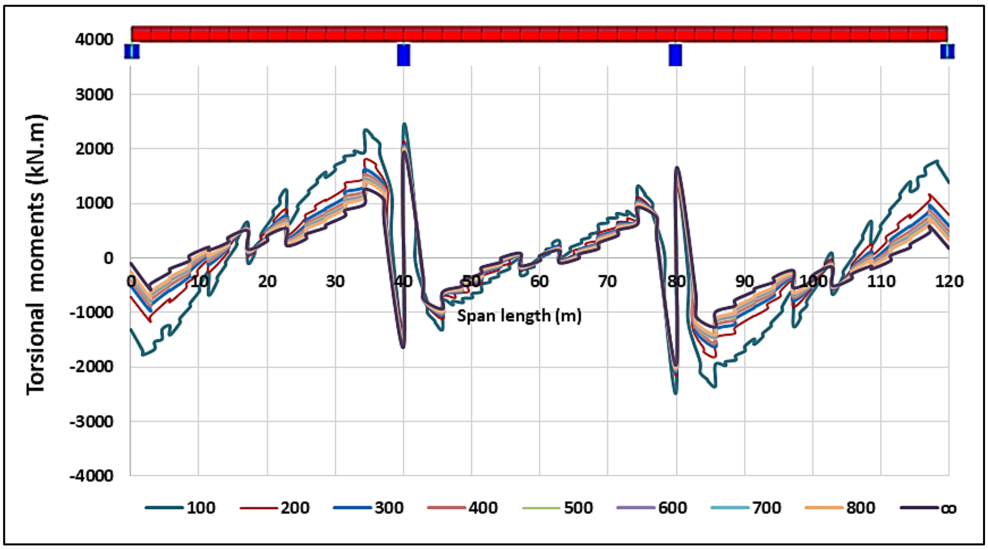


Figure 16: Outer face torsional moments along the span under inner face loading

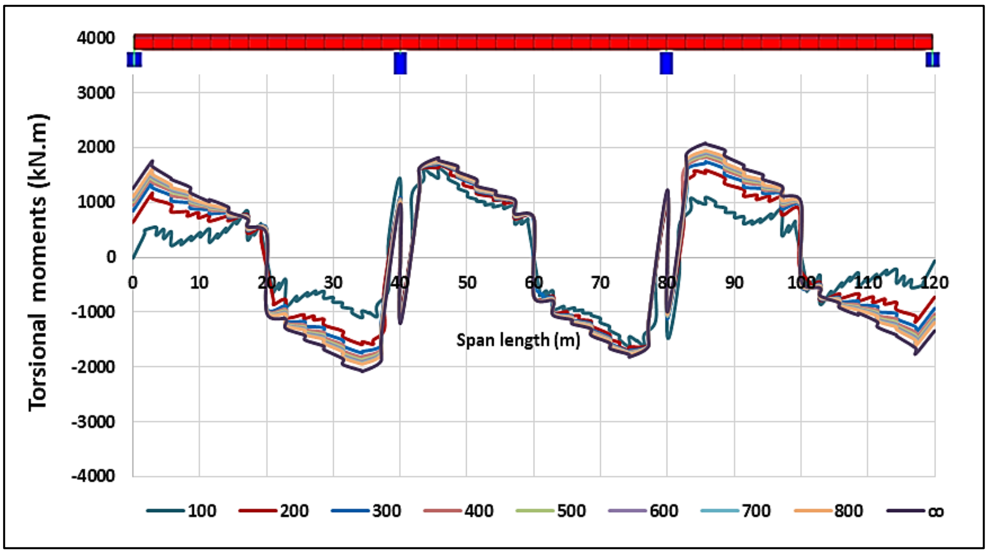


Figure 17: Inner face torsional moments along the span under inner face loading

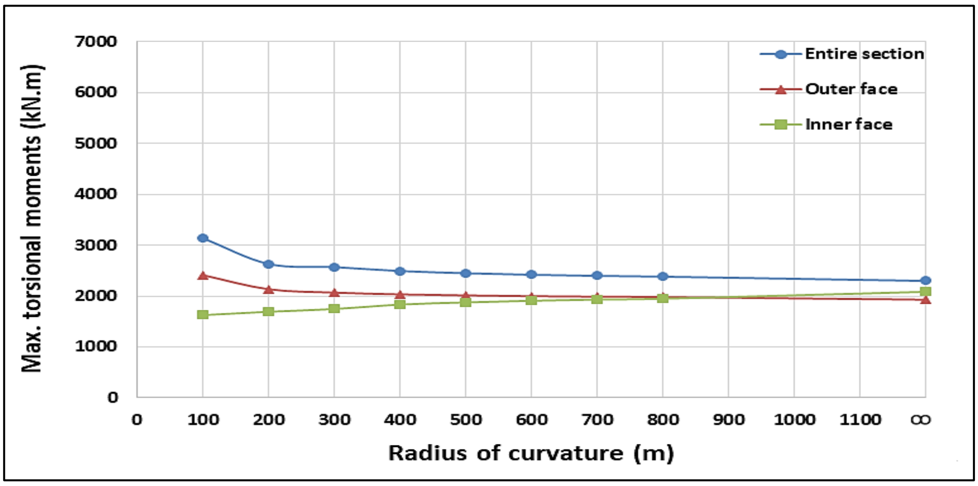


Figure 18: Maximum torsional moments with different curvature for inner face loading

5. Discussion

Torsional moments are affected by the amount of curvature in the bridges, as the presence of the curvature causes the loads to be decentralized on both faces of the longitudinal axis of the bridge. Load decentralization results in an arm of torsion whose amount varies according to the radius of curvature. The smaller the radius of the curvature, the longer this arm, and thus, the increase of the torsional moments. Several levels of curvature have been studied, showing a difference in behavior between them. Despite this disparity, some levels can share behavior, as they can be divided into:

1) In the absence of horizontal curvature and load in the middle of the section, the maximum torsional moments are slight in the entire section, but they increase (equal on both faces of the section) as a result of the effect of self-weight. The torsional moments are generated on both faces of the section, even in the absence of curvature and the presence of the load in the center. Therefore, torsional moments must be taken into account during the design. In the case of the presence of the concentrated load near the outer face, the maximum torsional moments produced on the outer face are higher than the inner face by 6%, while those torsional moments are at their maximum values in the entire section. The presence of the concentrated load near the inner face results in maximum torsional moments on the inner face that are higher than the outer face by 7%, while those torsional moments are at their maximum values in the entire section.
2) In the case of a small curvature (the radius of curvature is greater than or equal to 500 m), and the load is in the middle of the section, the maximum torsional moments increase almost linearly, but they remain less in the entire section than that both in the outer and inner faces. In the case of loading on the inner and outer faces, the torsional moments of the entire section are superior, while the moments of the outer face are higher than those of the inner face, even in the case of loading near the inner face.
3) In the case of high curvature (curvature radius is 200-400 m), the increase in torsional moments generally occurs non-linearly. When the load is in the middle of the section, the torsional moments in the entire section are greatly increased superior to the inner face so that their values become close to the torsional moments of the outer face. In the case of loading near the outer and inner faces, the torsional moments of the entire section remain greater than those of the outer and inner faces.
4) In the case of severe curvature (curvature radius is 100-200 m), the increase in maximum torsional moments is very large, with a noticeable difference in behavior. Therefore, care must be taken in the design of high-curvature bridges. When the load is in the middle of the section, the torsional moments in the entire section greatly increase, surpassing that of the inner and the outer faces.

The difference in the results of the outer face and the inner face is because two forces affect these results, which are the shear force resulting from shear and the other is the shear force resulting from torsion. The shear forces take the same direction on both bridge faces, while the torsional shear forces are contradictory on both faces of the bridge. Therefore, these forces are combined in the outer face, so their influence increases, and they are subtracted in the inner face, so their influence decreases.

Finally, it must be noted that the high torque formed due to the eccentricity of the load can be overcome by changing the shape of the bridge section with the addition of anti-torque reinforcement.

6. Conclusion

The effect of curvature in continuous reinforced concrete box girder bridges was studied using CSI Bridge finite element software. The curvature radius was created with values of 100, 200, 300, 400, 500, 600, 700, 800 m and straight. Also, the location of the concentrated load was moved from the outer face to the inner face, passing through the middle of the span, to investigate the behavior in these zones. Many conclusions have been reached, the most important of which can be summarized as follows:

1) Torsional moments vary with the radius of curvature and the location of the load variation, which makes the behavior different along the bridge. The behavior is linear at high curvature radii, and increments in torque are small. However, by decreasing the radius of the curvature, non-linear behavior results, and in severe curvature, the increase is very large.
2) The torsional moments in the outer face exceed the inner face by about 54%, even when applying load near the inner face. That is, the torsional moments are affected by the amount of curvature more than they are affected by the location of the load.
3) In general, the maximum torsional moments increase with the increase of the curvature in the outer face. In contrast, the maximum torsional moments decrease with the increase in the curvature in the inner face, except for the case of the curvature radius of 100 m. That occurs because the curvature, in this case, is considered sharp, resulting in very high torsional moments.
4) The outer face differs from the inner face because two forces affect them, which are the shear force resulting from shearing and the other is the shear force resulting from torsion. The shear force takes the same direction on both faces, while the torque force is opposite on the inner face. Therefore, forces gather in the external aspect, and their influence increases and they are subtracted in the internal aspect, and their influence decreases.
5) The torsional moments were increased when the load was centered in the outer face because the resulting torque results from the sum of the eccentric torsional moments of the load and the eccentric torsional moments of the bridge axis because they are in the same direction. Nonetheless, the torsional moments decreased when the load was centered in the inner face because the formed torque resulted from subtracting the eccentric torsional moments of the load and the eccentric torsional moments of the bridge axis because they are in the opposite direction.

Author contributions

Conceptualization, A. Dawood, K. Abdul-Razaaq and W. Abdlulsahib; writing—review and editing, A. Dawood, K. Abdul-Razaaq and W. Abdlulsahib, All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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