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Research Article

Investigation of seismic behavior of horizontally curved bridges in comparison with equivalent straight bridges according to the AASHTO LRFD specifications

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ABSTRACT

Horizontally curved bridges have more complex geometries compared to straight bridges. Their design, structural analysis, and construction require specialized knowledge and expertise. The curved geometry of these bridges affects load distribution and structural behavior. Understanding these behaviors is critical for improving the safety and durability of these bridges. For this reason, many studies have been carried out in order to understand the seismic behavior of horizontally curved bridges and to take the necessary measures in order to design resilient structures. In addition, seismic design regulations have set restrictions on the maximum curvature of bridges and permit engineers to use an equivalent straight bridge for their analysis and design. This paper investigates the restrictions and reviews the AASHTO LRFD Specification Design Fundamentals concerning the seismic responses of horizontally curved bridges by using equivalent straight bridges. In this regard, the seismic responses of 27 horizontally curved and 3 straight bridges, for a total of 30 RC bridges with different span numbers and bridge lengths, are investigated. Numerical parametric structural models have been generated for the selected variables such as; bridge length, span number, span length, and subtended angle. By using the structural analysis program, multi-mode response spectral analyses have been performed for the maximum credible earthquake (MCE) excitation level. The modal periods and frequencies, modal mass participating ratios, maximum displacement of the pier, and internal forces of the structural elements are obtained from the structural analyses of the bridges. The analysis results are compared with horizontally curved bridges and equivalent straight bridges to determine the effect of subtended angle on the seismic behavior of the bridges. It was shown in the study that bridge length and span number had a significant effect on the seismic response of horizontally curved bridges compared to straight bridges. Besides, the subtended angle limitations that AASHTO LRFD specifications put forward regarding allowing the curved bridges to use an equivalent straight bridge should be reviewed again. It suggests that a bridge is considered regular if the subtended angle is smaller than 90^0. However, according to the analysis results, the dynamic modal quantities, the displacement and rotations of the pier, and the internal forces of the pier columns and the deck of the bridges could reach their maximum values at lower angles of curvature than 90^0. Therefore, the limitations of the subtended angle should be reviewed and re-evaluated for several variable

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parameters by using linear and non-linear analysis methods. The aspects that make this research valuable and different from other studies are firstly, that the parametric models had a wide range of different subtended angles of curvature, bridge span numbers, and bridge lengths. Besides, the analysis results evaluated for the wide scope of the determined bridge configurations to realize the curvature effect of the bridges are very important to designing resilient bridges under seismic excitation.

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INTRODUCTION

Transportation systems from the past to the present and the bridges that are a part of them have been one of the most important factors determining the level of civilization of a country, as well as providing the transportation network within the country.

Damages to bridges after major earthquakes not only affect transportation but also indirectly impact the socio-economic conditions of countries, depending on the level of damage. Therefore, it is of great importance to determine the seismic behavior of bridges and to design them according to those criteria. By examining the types of damage that occurred in past earthquakes, a number of studies have been carried out to develop bridge designs in this aspect. With the increasing population, the coincidence of urban and suburban roads has led to the need for different intersection solutions. Therefore, the use of horizontally curved bridges has become widespread for their aesthetic and economic advantages, which exhibit geometric compatibility. The geometric irregularities of these types of bridges cause more complex and destructive behavior compared to straight bridges. The seismic behavior of bridges in a curved alignment plane contains additional potential damages due to their complex geometries, although similar damages were observed for both curved and straight bridges, as examined in past earthquakes. Particularly as a result of the heavy damage to bridges after the 1971 San Fernando earthquake, the behavior of these bridges under the influence of large ground movements became more significant. In the following years, the 1989 Loma Prieta earthquake, the 1992 Petrolia earthquake, the 1994 Northridge earthquake, and the 2008 Wenchuan earthquakes brought more attention to the importance of damage to bridges in many horizontal curve alignments. The main types of damage in bridges were unseating of the superstructure, column shear collapse, foundation collapse, bearing collapse, and insufficient column bending capacity.

For this reason, many studies have been carried out in order to understand the seismic behavior of horizontally curved bridges and to take necessary measures in order to design resilient structures. In addition, seismic design regulations have set restrictions on the maximum curvature of bridges and permit engineers to use an equivalent straight bridge for their analysis and design.

Bridges with significant horizontal curvature do not exhibit the behavior of an idealized, typical single-degree-of-freedom (SDOF) system. Therefore, the effects of curvature must also be included in the structural analysis. Conversely, the behavior of bridges with relatively less horizontal curvature can be idealized as a single-degree-of-freedom (SDOF) system.

A curved bridge that can be idealized as an SDOF system can be analyzed as if it were straight. In AASHTO LRFD specifications [1], a force-based seismic analysis design philosophy is adopted, whereas in the AASHTO Seismic Guide Specifications [2], a displacement-based design philosophy is emphasized. In AASHTO LRFD [1], for bridges that have horizontal curvature in plan, the condition that allows bridges to be idealized as straight bridges is specified as having a subtended angle of 900 degrees, whereas this limit has been revised to 300 degrees in the AASHTO Guide Specifications [2]. These conservative limitations arise due to uncertainties in the behavior of curved bridges under seismic excitations. So to point out the importance of the subject, the numerical and experimental studies can be summarized as follows:

Most of the studies include the free vibration response of the horizontally curved bridges and the dynamic behavior under the effect of live loading ([3-7]). In the study, by Williams et al. [4] the multi-directional seismic response of curved bridges was investigated using scaled models with shake table testing. They determined the vulnerability levels of the curved bridges under symmetric mode shapes [8]. Therefore, the torsional effect primarily causes damage to the bearings that provide ductility, and the vulnerability level depends on the shear and bending strength of the hinge bearings and the strength of the shear key. Kawashima et al. [9] presented the analytical and experimental correlation of the seismic responses of bridges. The aim of the study was to emphasize the discontinous behavior of expansion joints during seismic excitation. In addition, they found that the impact of vertical ground motion is relatively smaller under horizontal transverse seismic effects. In the study by Abdel-Salam et al. [10], it was found that response spectrum analysis fails to capture the range of internal forces when considering the high frequencies of vibration modes in curved bridges. They identified the radius of curvature as the most critical geometric parameter affecting the seismic behavior of curved bridges. In the study by Sennah et al. [11], the development of design criteria for straight and curved box girder bridges in existing specifications was examined. The study emphasized the necessity for advanced research to address the maximum load distribution in both straight and curved bridges. In the study by Mwafy et al. [12], the detailed seismic performance of a complex curved bridge design was compared with that of constructed bridges for local and global behavior. The comparative study showed significant differences in the lateral capacity and dynamic characteristics between the designed and constructed bridges. Past studies have examined the effect of curvature on the seismic behavior of steel bridges.

Abdel-Salam and Heins ([10], Galindo et al. [13], and Seo and Linzell [14] have demonstrated that as the radius of curvature increases, curved bridges become more susceptible to damages such as deck unseating and crushing during seismic events. Seo and Linzell [15] defined parameters such as span number, length, and curvature radius as the most significant factors affecting the displacement of bearings in continuous bridges. Recently, researchers have been evaluating the seismic performance of curved reinforced concrete bridges. They have focused on the pushover analysis of short-span reinforced concrete bridges and explored the effects of various load directions in seismic analysis. Based on their studies, Araújo et al. [16] concluded that curved bridges exhibit multidirectional dynamic responses and are more sensitive to seismic load directions compared to straight bridges. Khan Easa [17] evaluated a large parametric study that consists of curved bridges with subtended angles varying from 00 to 1800 degrees and having the total arc length equal to the length of the equivalent straight bridge in order to investigate the limitations of the AASHTO specifications about the curved bridges. In his PhD thesis, Shirazi [18] studied the seismic fragility of horizontally curved bridges. According to the study, in addition to ground movements, the horizontal curvature of bridge geometries significantly impacts the seismic fragility of bridges. The seismic responses of individual columns have shown a notable correlation with system fragility curves. The dynamic characteristics of bridges are sensitive to curvature. The curvature geometry is particularly important at curve span angles exceeding 300 degrees. In curved bridges, the combination of longitudinal and transverse modes reduces the primary mode in the bridge response and leads to a combination with larger modes. In their study, Sextos and Taskari [19] investigated the effects of seismic load directions on long-span curved bridges using the finite element method. They modeled the soil under the piers and abutments to examine their influence on the bridges. As a result, all uncertainties aside, increasing the seismic load direction has gradually resulted in a gradual change in bridge behavior. Pahlavan et al. [20] investigated the fragility analysis of two-span curved bridges. They found that the key parameter highlighting fragility in curved bridges is the radius of curvature. Abbasi's [21] PhD thesis examined the mid-span expansion joint design in decks and the effects of shear keys on bridge behavior for both regular and irregular bridges. As a result, shear keys have a more significant effect on the seismic behavior of curved bridges than straight ones.

Reza Siami Kaleybar Payam Tehrani [22] investigated the effects of geometrical irregulatities on the curved bridges under seismic excitation and examined the AASHTO Specificication limitations for the curved bridges. Therefore, numerical analyses were done for the selected bridges that have different arrangement types of spans, column heights, abutment conditions, and subtended angles to obtain a wide-spectrum solution. The nonlinear analysis results for bridges with varying column heights and subtended angles differ from those obtained through linear analysis.

This study indicates that the AASHTO Specificiton limitations for the curved bridges, regarding the analysis method and the subtended angle for the use of equivalent straight bridges, should be reassessed. However, many of the studies mentioned above have not examined the limitation on the subtended angle of curved bridges, as suggested by AASHTO specifications, for analyzing the equivalent straight bridge instead of the curved bridge. In addition genereally, displacements and the dynamic behavior of the bridges were investigated in the studies rather than the internal forces of the structural members. Besides, the variation range of the subtended angle is insufficient to evaluate and compare the dynamic behavior of the curved bridges and equivalent straight bridges. In this study, parametric models of bridges were generated by varying the number of spans, bridge length, and the subtended angle of a wide range of curvature angles, which is different from the other studies on this topic.

Multi-mode response spectral analyses were performed for both horizontally curved and equivalent straight bridges under the maximum credible earthquake (MCE) excitation level. As a result of the linear elastic analyses, the dynamic behavior mode shapes and related dynamic quantities (period, natural frequency, and modal mass participation ratios vs.) of the parametric bridges were obtained. Additionally, the displacements at the top of the pier columns, as well as the internal forces of the structural elements (pier column and deck internal forces) have been determined to compare the behavior of the horizontally curved bridges and the straight bridges.

Aashto LRFD Bridge Design Specifications (2020) & AASHTO Guide Specifications for LRFD Seismic Bridge Design (2011)

The dye used in this study is Reactive Orange 16.Reactive Orange 16 is an anionic dye and azo belongs to the class. In Table 1 its characteristics are summarized. Its general characteristics are shown. Figure 1.

According to the table, the seismic analysis methods can be as follows: UL is the uniform load elastic method, SM is the single-mode elastic method, MM is the multi-mode elastic mode, and TH is the time history method.

Table 1. Minimum analysis requirement for seismic effects

Seismic zone	Singe span bridges	Multispan bridges					
		Other bridges		Essential bridges		Critical bridges	
		Regular	Irregular	Regular	Irregular	regular	irregular
1	No Seismic Analysis Required	*	*	*	*	*	*
2		SM/UL	SM	SM/UL	MM	MM	MM
3		SM/UL	MM	MM	MM	MM	TH
4		SM/UL	MM	MM	MM	TH	TH

Table 2. Regular bridge requirements

Parameter	Value				
Number of spans	2	3	4	5	6
Maximum subtended angle for a curved bridge	90^0	90^0	90^0	90^0	90^0
Maximum span length ratio from span to span	3	2	2	1.5	1.5
Maximum bent/pier stiffness ratio from span to span	-	4	4	3	2

In addition, both of the specifications define a bridge as regular depending on the number of spans, maximum subtended angles, maximum span length ratios, and pier stiffness ratios in the AASHTO LRFD (Table 2) [1]. The AASHTO specifications also propose that a curved contінous bridge may be analyzed as if it were straight, provided that all of the following conditions are met: a) the bridge is regular, b) the subtended angle in plan is not greater than 30^0 (based on the 2011 AASHTO guide specifications) or is not greater than 90^0 (based on the AASHTO LRFD 2020 design specifications); and c) the span lengths of the equivalent straight bridge are equal to the arc lengths of the curved bridge [1,2].

According to AASHTO LRFD, bridges are also classified for the seismic categories defined due to S_{D1}. Bridge regularity, importance class, and seismic zone are the criteria used to determine the dynamic analysis method. In this study, the bridges' importance class was determined to be critical for those located in the seismic zone 2 region. For examining the regularity conditions subtended angle of the bridges are varied between 0^0 up to 180^0. Therefore, for both of the conditions, regular and irregular, elastic dynamic analysis performed to investigate the dynamic behavior of the bridges and to compare with the limitations defined in AASHTO specifications.

GENERATING STRUCTURAL MODELS OF THE BRIDGES

Configuration of Parametric Bridges

In this study, a total of 30 reinforced concrete bridges, including 3 straight and 27 curved bridges, were studied. Bridges have respectively three, four, and five spans with a total length of 135m, 180m, and 225m.

The geometries of the bridges were determined by adjusting the radius of curvature and the subtended angle so that the arc lengths of the bridges would be equal to the lengths of equivalent straight-axis bridges. For one of the abutments, three restraint conditions were considered as fixed, and the others were designed to be fixed only in the vertical direction (i.e., fixed or free in both longitudinal and transverse directions and simplified abutment). The piers are monolithically connected to the deck. The three configurations considered in this study for the bridges are shown in Figure 1a.

For each configuration, the subtended angle varies from 00 to 1800 degrees with an interval of 15^0-30^0 degrees (Fig. 1b). The pier heights were determined as 15m for all bridges. The irregularity of the bridges was provided with the subtended angles varying from 0^0 to 180^0 whereas for regularity condition equal column heights and equal span lengths were studied in bridges.

STRUCTURAL ANALYSIS AND DESIGN OF BRIDGES

The parametric bridge models were generated, designed, loaded and analyzed in accordance with the AASHTO LRFD Bridge Design Specifications [1] and TBEC [23].

The columns were designed with a rectangular geometry of 2m x 4m (Fig. 2a) and the deck was considered as a post-tensioned concrete box girder with mono-cell (Fig. 2b). The deck had a transverse moment of inertia of $72.041m^4$ and a cross-section area of $7.2792m^2$.

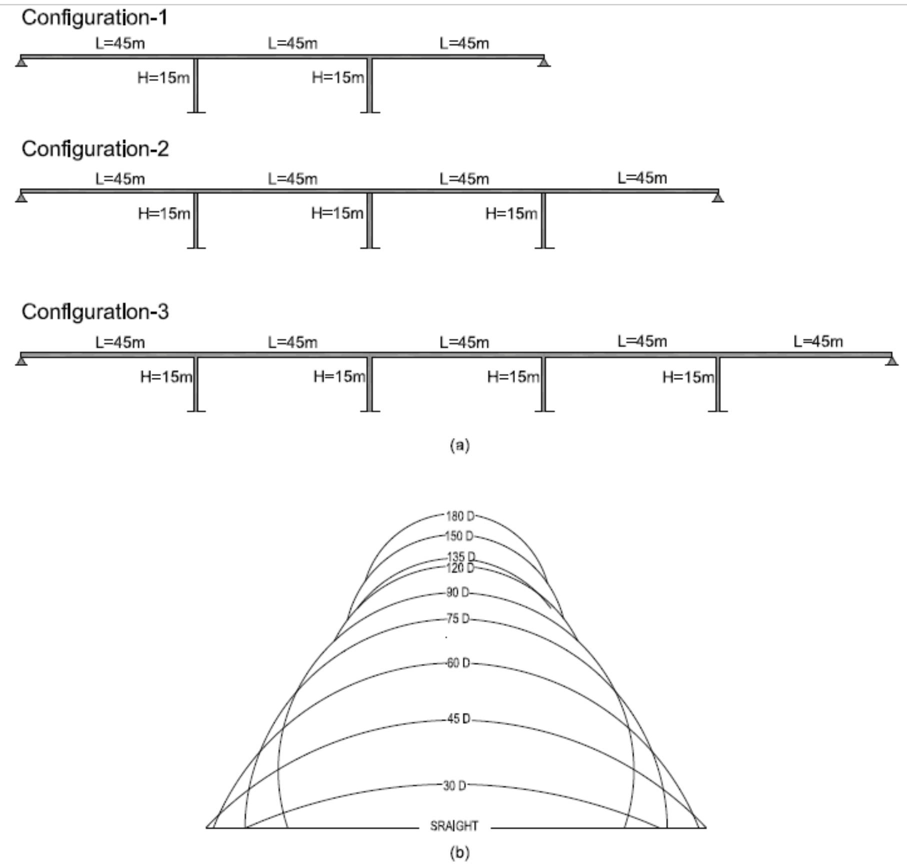

Figure 1. a) Different bridge configurations b) Plane view of straight and curved bridge with different subtended angles.

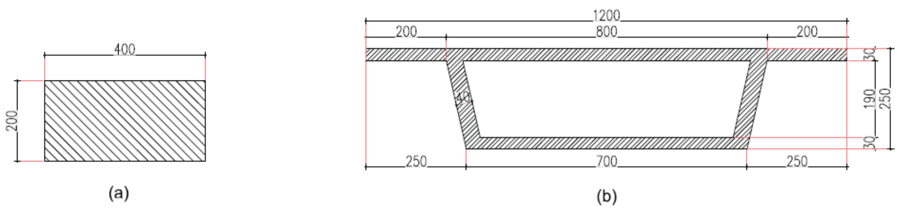

Figure 2. a) Pier column section b) Deck section.

The material of the deck was determined as C45(fck=45Mpa) type concrete and the other structural elements had C30(fck=30Mpa). The selfweight of the structural elements were taken into consideration by the program where concrete unit weight defined as gc =25kN/m3 and gk =23kN/m3 for asphaltic coating and levelling. In addition, according to the AASHTO specifications, parameters such as percentage of longitudinal bars, limitations of ductility, the minimum concrete cover, the percentage of the axial load, spacing of transverse reinforcement, the ratio of transverse bar volume to the core volume, and the shear capacity design of columns were considered.

The seismic loads acting on the bridges have been taken into account by using multi-mode response spectral analysis method in accordance with AASHTO LRFD Table 2 “seismic design”[1]. Seismic loadings were determined for different seismic ground motion levels (DD-1) and soil class (ZB) as defined in Section 2.2 of the TBEC 2018 Regulation [23]. The design response spectrum has been derived from ‘Turkey Earthquake Hazard Maps’ and the associated website https://tdth.afad.gov.tr/. Horizontal elastic design spectrum was created and incorporated into the structural models of the bridges (Fig. 3). The seismic load combinations were defined as follows by adding the earthquake loads obtained from the multi-mode response spectral analysis to the dead load.

$$1.0\ DL + 1.0\ EQ_X + 0.3\ EQ_Y \quad (COMB1)$$

$$1.0\ DL + 0.3\ EQ_X + 1.0\ EQ_Y \quad (COMB2)$$

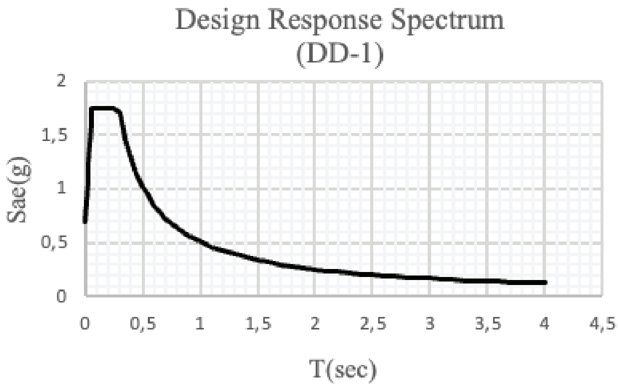

Figure 3. Design response spectrum.

Numerical modeling studies were conducted for the determined variable parameters and bridge configurations. During the structural modelling stage, a general purpose structural analysis program SAP2000 [24] has been used. Bridges with selected configurations; 3-span, 4-span, and 5-span bridge configurations were modelled in 3-D using the SAP2000 structural analysis program (Fig. 4).

In the structural models, the deck and the piers were defined with frame finite elements. The abutments were not modelled exactly instead they were represented with rigid links. Besides, it is important to define the pier-deck connection regions in a manner that accurately reflects the real behavior of the structural elements and geometry. Specifically, for monolithic pier-deck connections, these rigid regions can be represented in the model using fictitious bar elements with infinite rigidity or elastic spring (link) elements with infinite rigidity (Fig. 5).

Elastic spring link elements were selected in the models. The deck were defined with finite shell elements firstly, but analysis results had showed that frame element definitions were preferably used for reliability and the convenience of the analysis results. The additional dead loads of asphaltic cover, guardrails and the pavements were added to the unit weight of the deck definition. "From Element and Additional Masses" option, the program allows the mass distributions from joints and at each node. The program, assigns masses that are compatible with the length of the beam finite elements at that node. Response spectrum data were defined as a function to be used in multi-mode spectral analysis and seismic load cases are defined by these function. The program, correctly analysed the bridge models without any warnings. After the structural analysis the first predominant periods of the bridges were also checked by the excel sheets to verify the result of the program.

For each bridge configuration, numerical models were created and initially analyzed using the linear elastic analysis method. Subsequently, the bridge behaviors in both

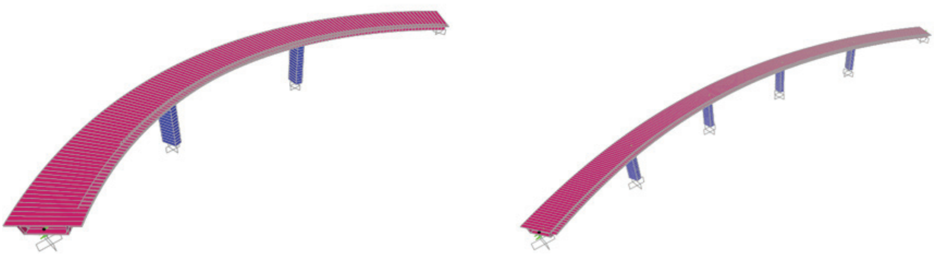

Figure 4. 3-Span, 5-Span Bridges with subtended angles 60^0-120^0 respectively.

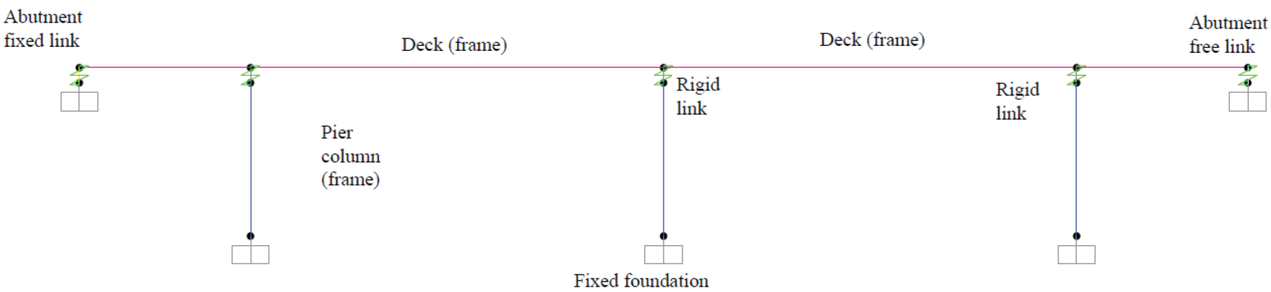

Figure 5. 4-Span Bridge structural model.

straight-axis and curved configurations were examined using the elastic dynamic analysis method defined in AASHTO LRFD [1]. Firstly, a model was prepared for the bridge, and multi-mode response spectral analyses were performed by applying the seismic response spectrum to this model. According to the analysis results, modal quantities of dynamic behavior (mode shapes, periods, frequencies, mass partipation ratios), the displacement at the top of the piers, internal forces occured in the structural elements (columns and deck) were obtained both for equivalent straight bridges and curved formed bridges. The obtained results were graphed to compare the seismic behavior of the bridges and to evaluate the effect of the subtended angle variation due to the radius of curvature. Lastly to get more refined analysis results according to the AASHTO specifications limitations only the subtended angle limit exccedance was taken into consideration in this study.

ANALYSIS RESULTS OF THE STRUCTURAL MODELS OF THE BRIDGES

In this part, the results obtained by using linear modal analyses for different bridge configurations are discussed. For the determined bridge configurations, multi-mode response spectral analyses were performed under the horizontal design response spectrum drived from the 'Turkey Hazard Map' for soil class ZB and the seismic ground motion level DD1 (2475-year return period). AASHTO LRFD specification design criteria were taken into account in the seismic analysis of the bridge (equivalent straight and curved bridges). Earthquake directions due to horizontal curvature were taken into consideration in the structural models. The sign convention for frame internal forces described in the structural program is illustrated in Figure 6 [23]. This sign convention can be described by defining the concept of the positive and negative faces of an object. The intenal forces were obtained from the analysis results according to this sign convention.

Elastic Dynamic Analysis Results of Bridges with 3-Spans of 135m (3x45m) in Length

In this study, to evaluate the limitations and analysis methods suggested by AASHTO Specifications for curved bridges, elastic dynamic analyses were performed, and the results were obtained for both equivalent straight bridges and curved bridges. 3-spans of 135m (3x45m) in length bridges were one of the bridge configurations. As a result of multi-mode response spectral analyses of these bridges, modal quantities of dynamic behavior (i.e., period, natural frequency, modal mass participation) and the pier displacements, and the structural element internal forces were obtained for the equivalent straight-axis bridge of 135m in length and for the curved bridges that had an arc length of 135m with a variable subtended angle of 300-1800 degrees.

The results of the linear modal analyses were obtained, and the variations of the relevant modal quantities with respect to the subtended angle of curvature are presented in Figure 7.

According to the analysis results, the displacements and rotations at the top of the pier columns of the bridges were examined (Fig. 8). The displacement of the pier in the longitudinal direction of the bridges increased as the subtended angle increased, reaching a maximum rate nearly 15 times greater than that of an equivalent straight bridge when compared to a curved bridge with a subtended angle of 180°.

The AASHTO LRFD specification suggests that a bridge is regular if the subtended angle is smaller than 90°; however, according to the analysis results, the displacement of the pier slightly increases for the initial values of the curvature angle.

The displacement of the column in the transverse direction of the bridges did not increase linearly with the

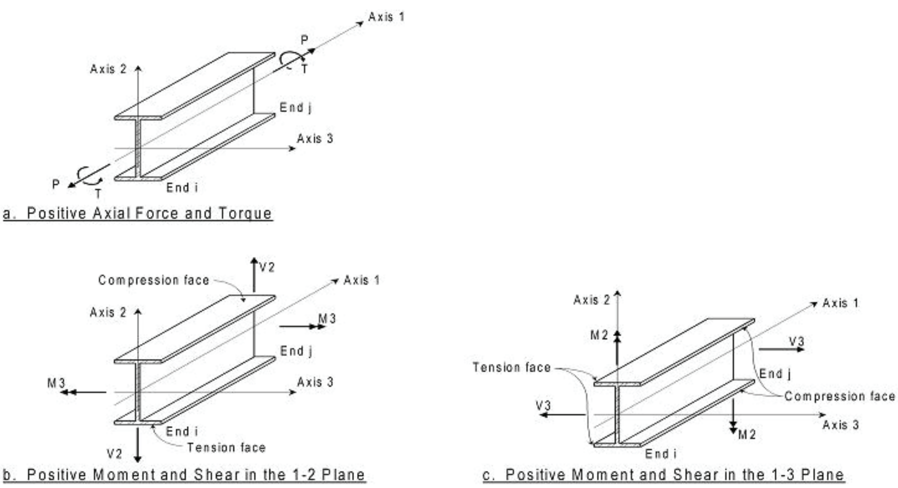

Figure 6. Sign convention for frame internal forces.

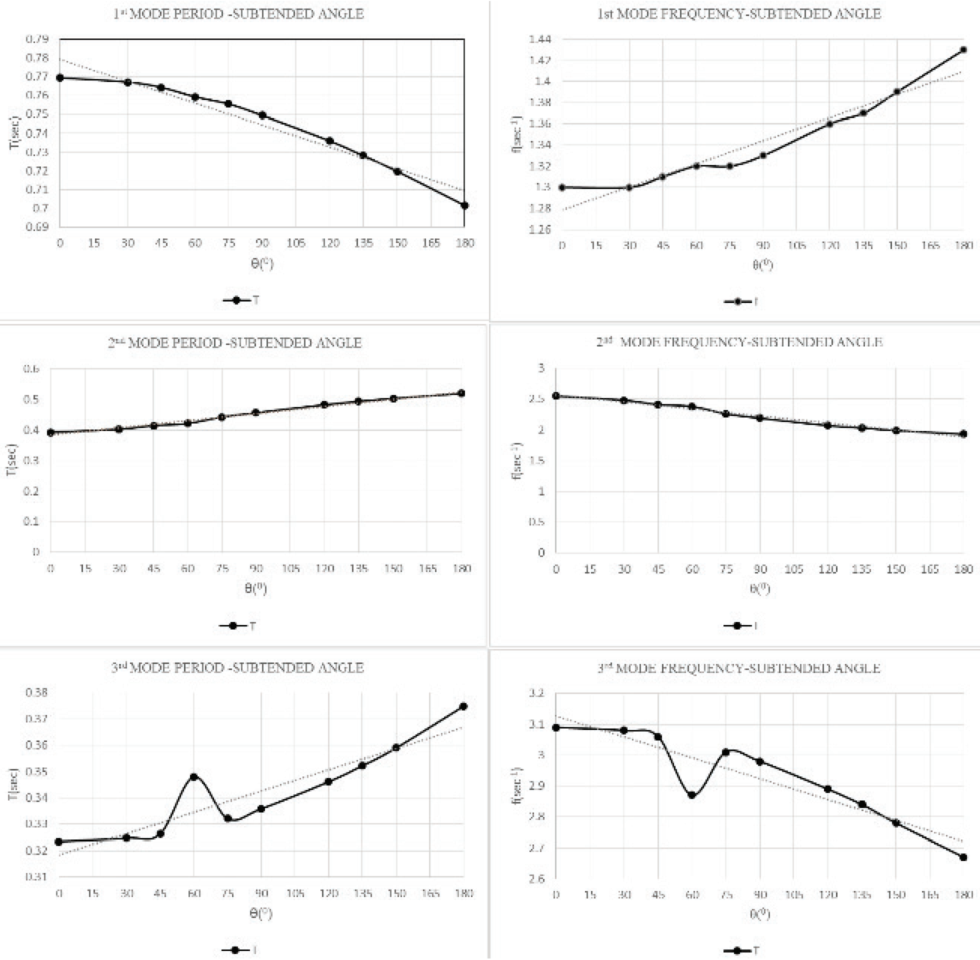

Figure 7. Period and frequency of the first three predominant modes-subtended angle variation.

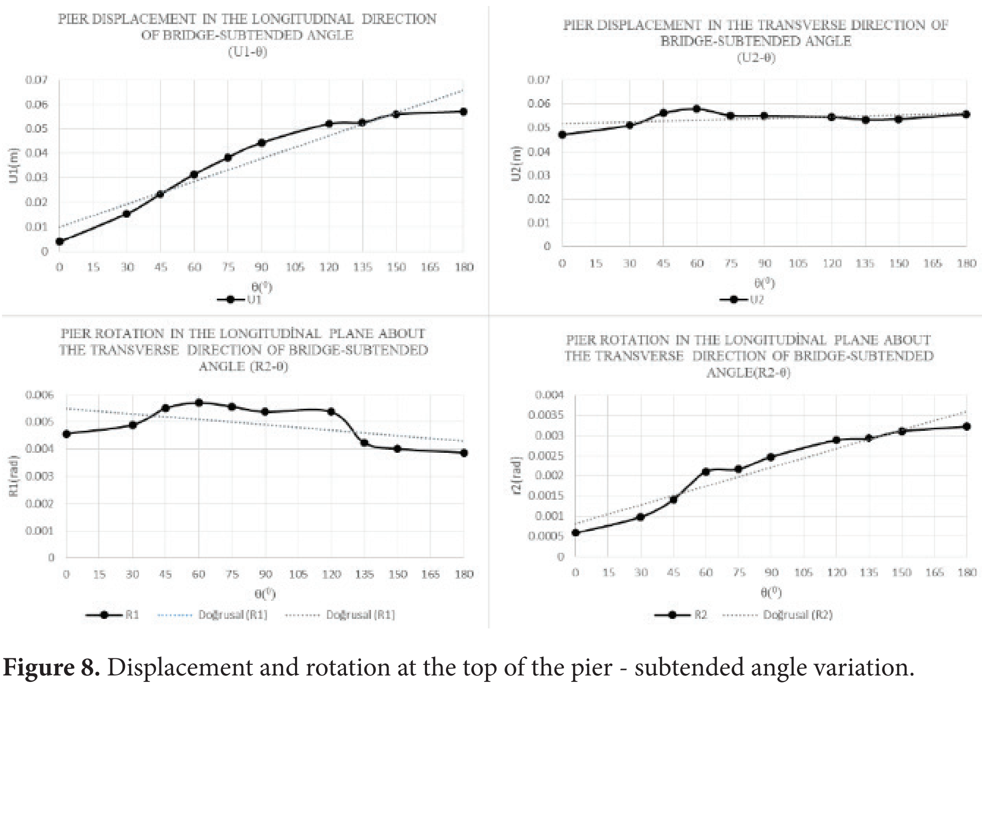

Figure 8. Displacement and rotation at the top of the pier - subtended angle variation.

increase in the subtended angle. The rotation of the pier in the longitudinal direction of the column reached its maximum value for the bridge at a subtended angle of 60°. Lastly, the rotation of the column about the transverse direction of the bridge increased with the variation of the subtended angle. The bridge with a 180° subtended angle had a column rotation nearly six times greater than that of the equivalent straight bridge.

According to the multi-mode response spectral analysis results, the internal forces of the pier columns of the bridges were examined (Fig. 9). The axial force, the shear force in the longitudinal direction of the bridge, the torsional moment, and the bending moment in the longitudinal direction of the bridge increased as the subtended angle increased. Notably, after the subtended angle reached 30°, the shear force and the bending moment in the longitudinal direction increased to nearly five times those of the equivalent straight bridges. The shear force and the bending moment in the transverse direction of the bridge reached their maximum values for the bridge with a subtended angle of 60°, which is 37% larger compared to the internal forces of the piers of the equivalent straight bridge.

The internal forces of the bridges' decks were examined using multi-mode response spectral analysis results (Fig. 10). The shear forces, bending moments, and torsional moments of the decks in both directions increased as the subtended angle of the bridges increased, except for the axial force. Particularly notable was the substantial increase in the torsional moment with variations in subtended angle. For instance, the torsional moment of the deck with a subtended angle of 180^0 was six times greater than that of the equivalent straight bridge. In comparison, the torsional moment of the deck with a subtended angle of 60^0 was three times greater than the equivalent straight bridge. After the subtended angle surpassed 30^0, the shear force and bending moment in the transverse direction increased at a rate nearly three times higher than that of the equivalent straight bridges.

The shear force and bending moment in the transverse direction reached their maximum for the bridge with a subtended angle of 180^0. Up to a subtended angle of 90^0,

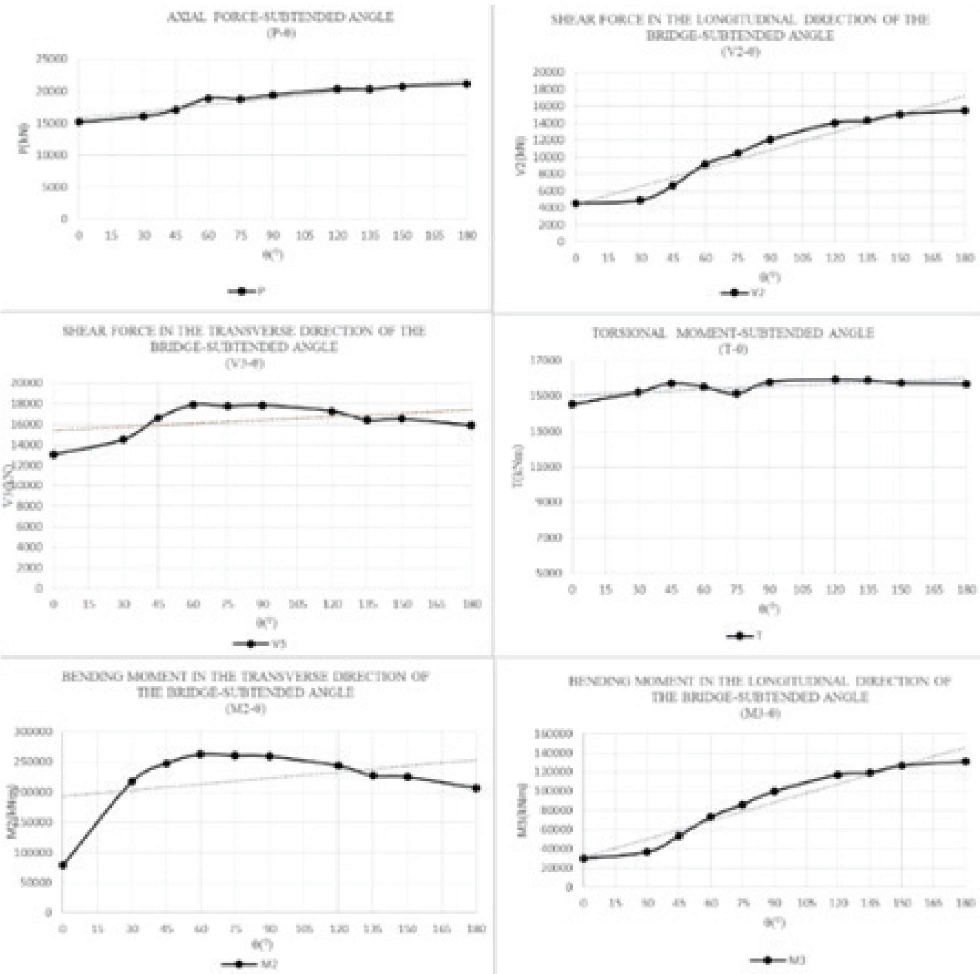

Figure 9. Internal forces of the columns of the bridges - subtended angle variation.

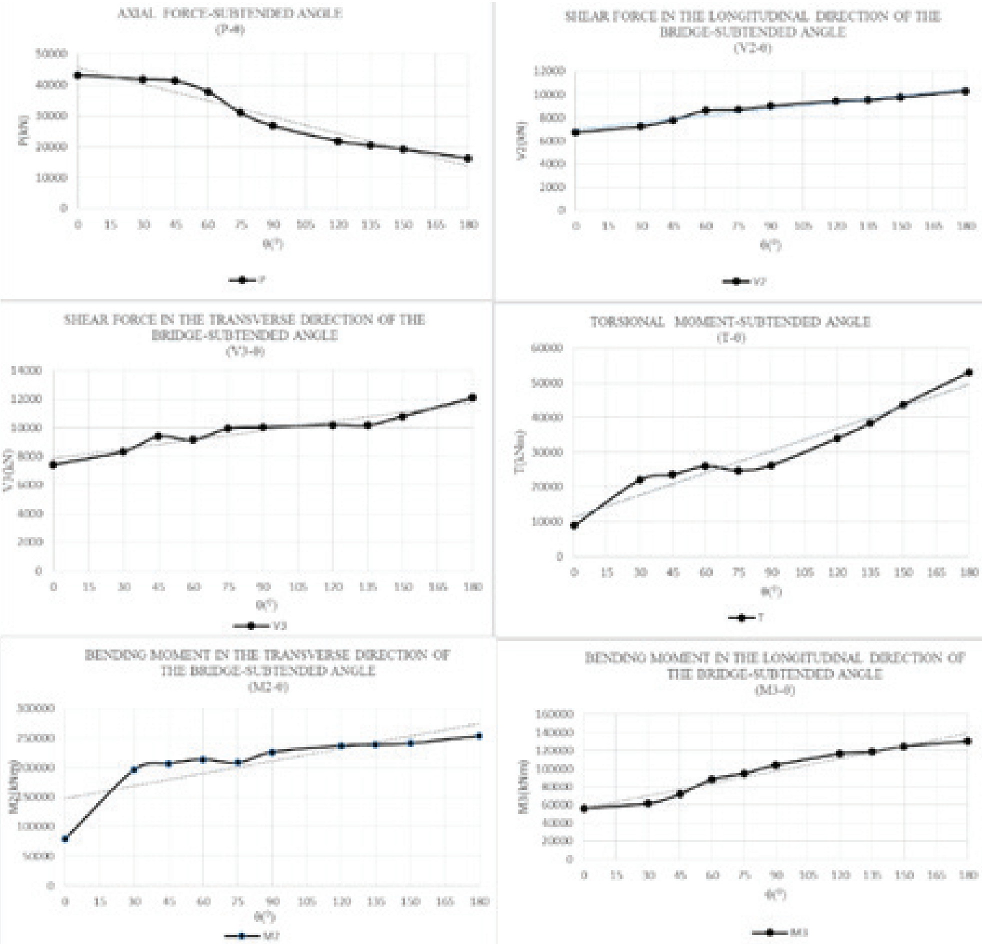

Figure 10. Internal forces of the deck of the bridges - subtended angle variation.

the internal forces increased at a rate 2.7 times higher than those of the equivalent straight bridges.

Elastic Dynamic Analysis Results of Bridges With 4-Spans of 180m (4x45m) in Length

In this study, to evaluate the limitations and analysis methods suggested by AASHTO specifications for curved bridges, elastic dynamic analyses were performed, and the results were obtained for both equivalent straight bridges and curved bridges. One of the bridge configurations analyzed was a 4-span bridge with a total length of 180 m (4x45 m). As a result of the multi-mode response spectral analyses of these bridges, the modal quantities of dynamic behavior (i.e., period, natural frequency, modal mass participation), pier displacements, and structural element internal forces were obtained for an equivalent straight-axis bridge of 180 m in length and for curved bridges with an arc length of 180 m and a variable subtended angle ranging from 30^0 to 180^0 degrees.

The results of the linear modal analyses were obtained, and the variations of the relevant modal quantities with respect to the subtended angle of curvature are presented in Figure 11.

According to the analysis results, the displacements and the rotations at the top of the column of the pier of the bridges were examined (Fig. 12). The displacement of the pier in the longitudinal direction of the bridges increased as the subtended angle increased at a rate of nearly three times more than the equivalent straight bridge compared to a curved bridge that had a subtended angle of 180^0. The AASHTO LRFD specification suggests that the bridge is regular in cases where the subtended angle is smaller than 90^0 but according to the analysis results, the displacement of the pier slightly increased for the initial values of the curvature angle.

The displacement of the column in the transverse direction of the bridges increased with an increase in the subtended angle at a ratio of 1.25. The rotation of the pier in the transverse plane about the longitudinal direction of the column had the maximum value for the bridge with a subtended angle of 60^0 and decreased at a rate of nearly 44% up to the subtended angle of 180^0. Lastly, the rotation of the column in the longitudinal plane about the transverse

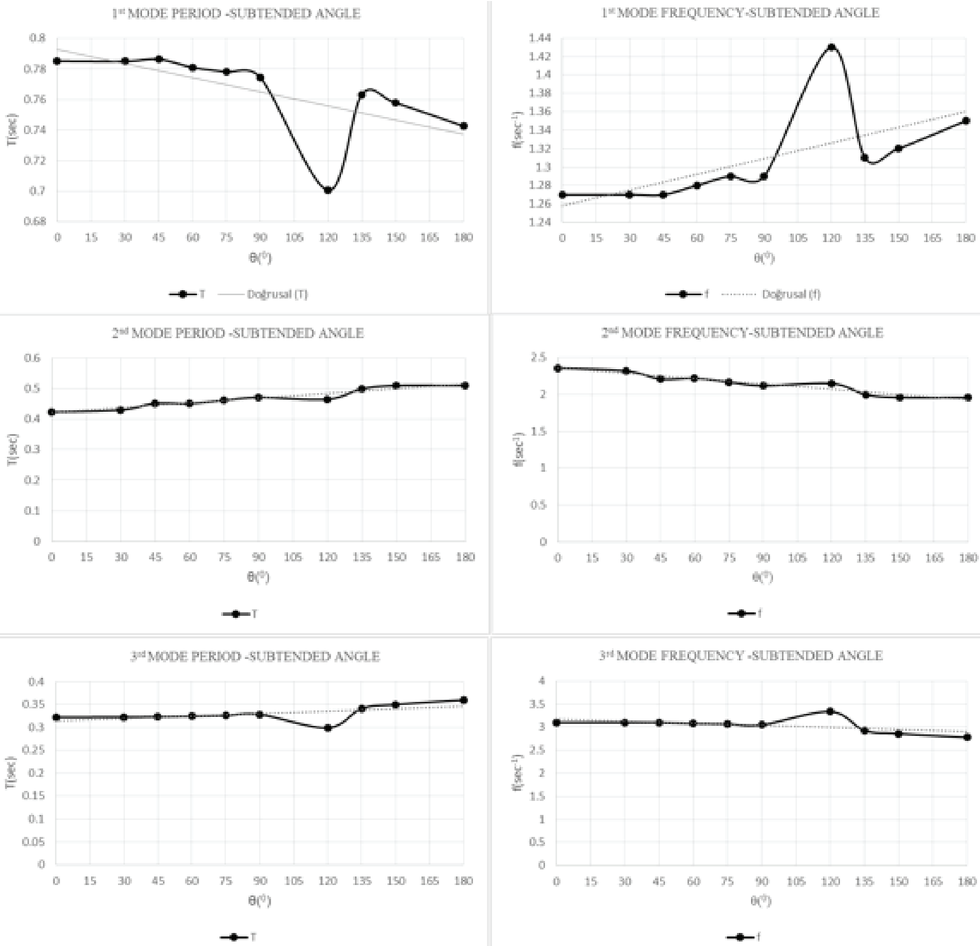

Figure 11. Period and frequency of the first three predominant modes-subtended angle variation.

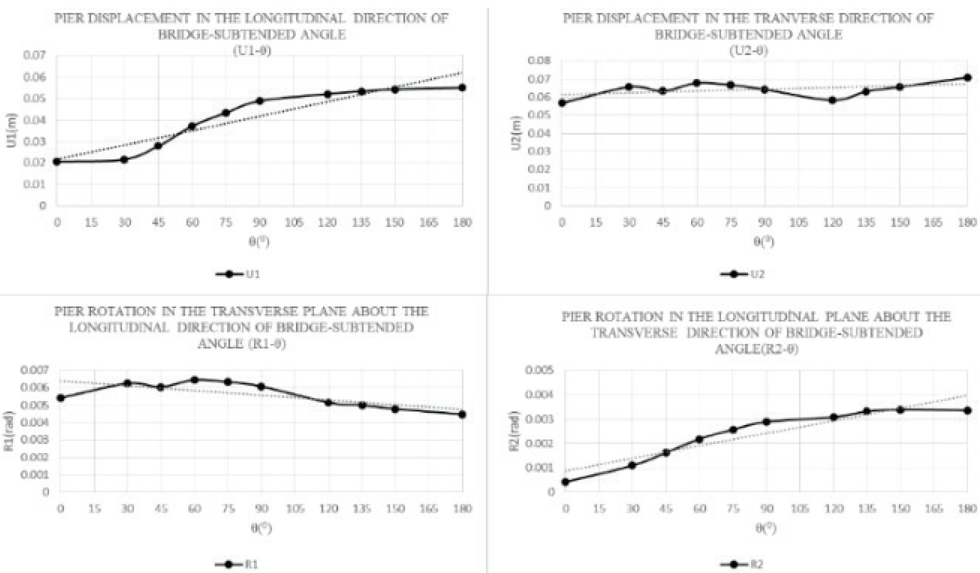

Figure 12. Displacement and rotation at the top of the pier - subtended angle variation.

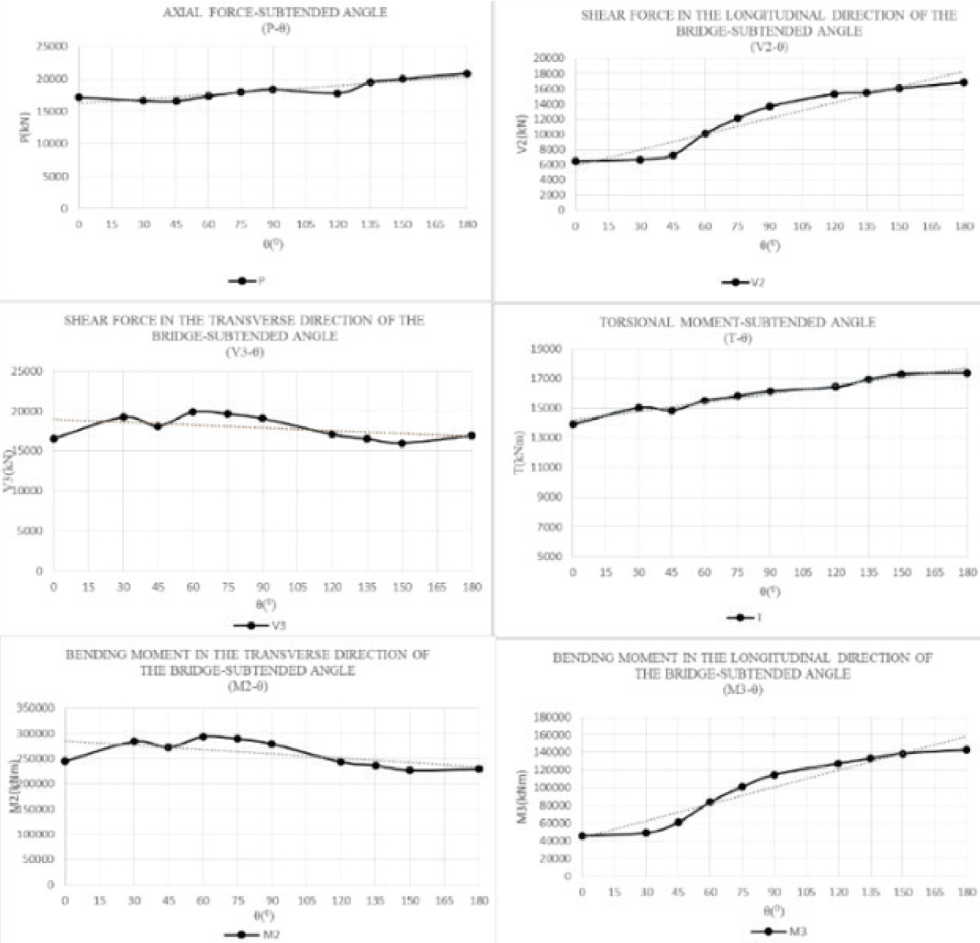

Figure 13. Internal forces of the columns of the bridges - subtended angle variation.

direction of the bridge increased with the variation in the subtended angle.

The bridge with a 180^0 degree of subtended angle had a column rotation nearly eight times greater than the rotation of the equivalent straight bridge.

According to the multi-mode spectral analysis results, the internal forces of the pier columns of the bridges were examined (Fig. 13). The axial force, shear force in the longitudinal direction of the bridge, torsional moment, and bending moment in the longitudinal direction of the bridge increased as the subtended angle increased.

Particularly after a subtended angle value of 30^0, the shear force and bending moment in the longitudinal direction increased to nearly three times more than those of equivalent straight bridges.

The shear force and bending moment in the transverse direction of the bridge reached their maximum values for a bridge with a subtended angle of 60^0, which is 20% larger compared to the internal forces of the piers of the equivalent straight bridge.

According to the multi-mode spectral analysis results, the internal forces of the bridge deck were examined (Fig. 14). The shear forces, bending moments, and torsional moments in both directions of the bridge increased as the subtended angle of the bridge increased, except for the axial force. The increment ratio for the torsional moment was particularly high given the variation in the subtended angle. The torsional moment of the deck of the bridge with a subtended angle of 180^0 was twice that of the equivalent straight bridge. The torsional moment of the deck remained stable between subtended angle values of 30^0 and 120^0 and increased up to a subtended angle of 1800. Additionally, the shear force and bending moment in the transverse direction increased by nearly 50%, reaching their maximum values for a bridge with a subtended angle of 180^0. The bending moment of the bridge increased by 66% up to a subtended angle of 180^0 compared to the results of the equivalent straight bridge.

Elastic Dynamic Analysis Results of Bridges With 5-Spans of 225m (5x45m) in Length

5-spans of 225m (5x45m) in length bridges were one of the bridge configurations used to evaluate the curved bridges and straight bridges. As a result of multi-mode

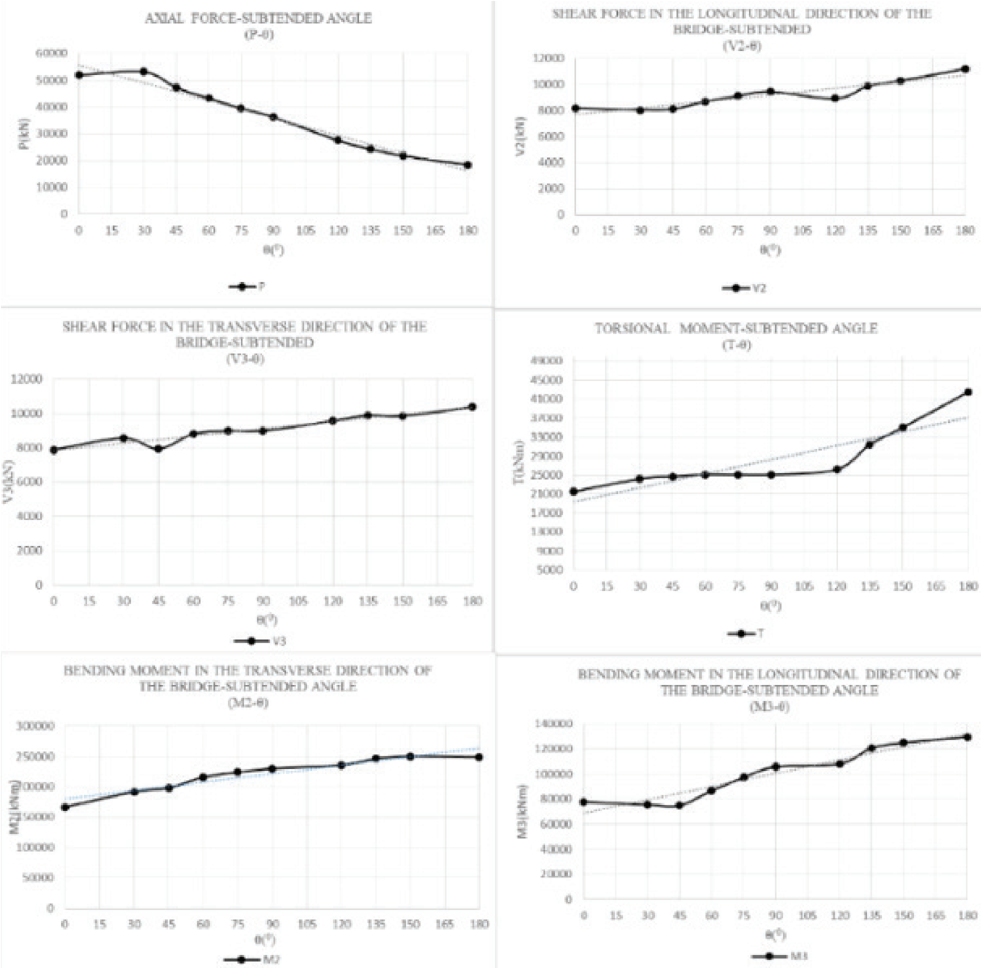

Figure 14. Internal forces of the deck of the bridges - subtended angle variation.

response spectral analyses of these bridges; modal quantities of dynamic behavior (i.e., period, natural frequency, modal mass participation), the pier displacements and the structural element internal forces were obtained for the equivalent straight-axis bridge of 225m in length and for the curved bridges that had an arc length of 225m with a variable subtended angle of 30^0-180^0 degrees.

The results of the linear modal analyses were obtained, and the variations of the relevant modal quantities with respect to the subtended angle of curvature are presented in Figure 15.

According to the analysis results, the displacements and the rotations at the top of the column of the pier of the bridges were examined (Fig. 16). The displacement of the pier in the longitudinal direction of the bridges increased as the subtended angle increased at a rate of nearly two times more than that of an equivalent straight bridge compared to a curved bridge that had a subtended angle of 180^0. The displacement of the column in the transverse direction of the bridges increased with the increase of the subtended angle at a ratio of 1.30 times. The rotation of the pier in the longitudinal direction of the column had the maximum value for the bridge with a subtended angle of 45^0 and decreased at a rate of nearly 23% up to the subtended angle of 180^0 for 5-span bridge. Lastly, the rotation of the column about the transverse direction of the bridge increased with the variation in the subtended angle. The bridge with an 180^0 degree subtended angle had a column rotation nearly four times greater than the rotation of the equivalent straight bridge.

According to the multi-mode spectral analysis results, the internal forces of the pier columns of the bridges were examined (Fig. 17). The axial force, the shear force in the longitudinal direction of the bridge, the torsional moment, and the bending moment in the longitudinal direction of the bridge was increased as the subtended angle increased. Especially after the subtended angle value of 30^0, the shear force and the bending moment in the longitudinal direction increased at a ratio of nearly 2.5 times more than the equivalent straight bridges. The shear force and the bending moment in the transverse direction of the bridge reached their maximum value for the bridge, which had a subtended

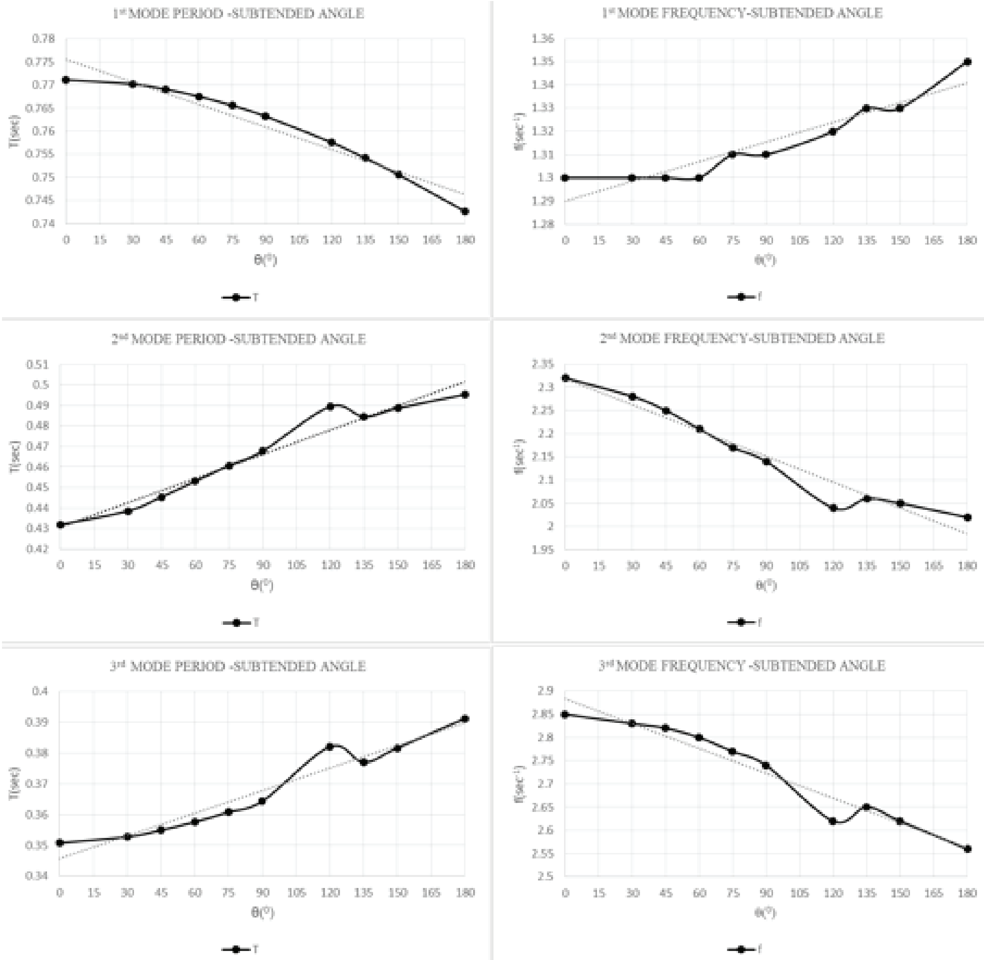

Figure 15. Period and frequency of the first three predominant modes-subtended angle variation.

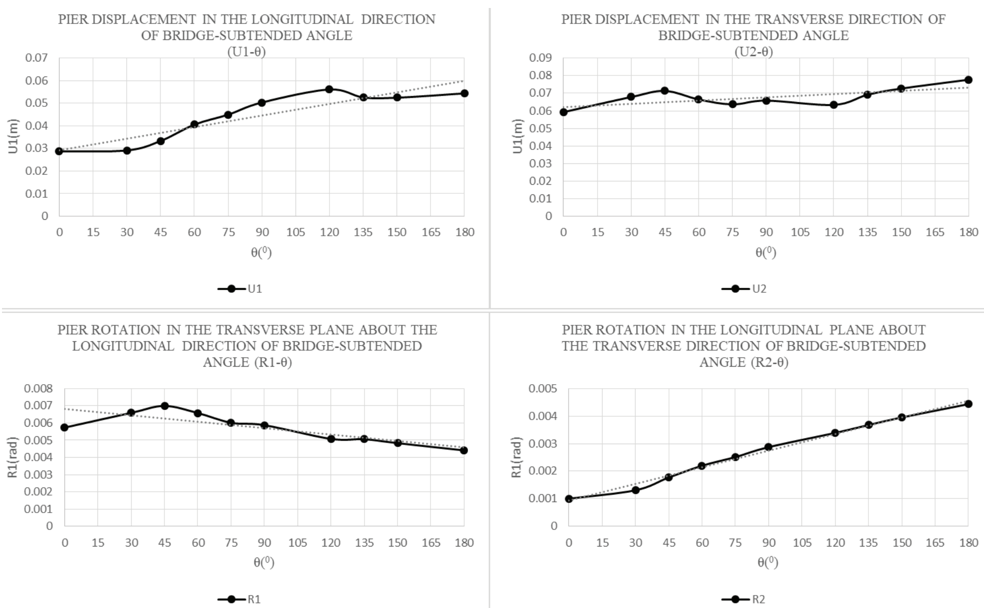

Figure 16. Displacement and rotation at the top of the pier - subtended angle variation.

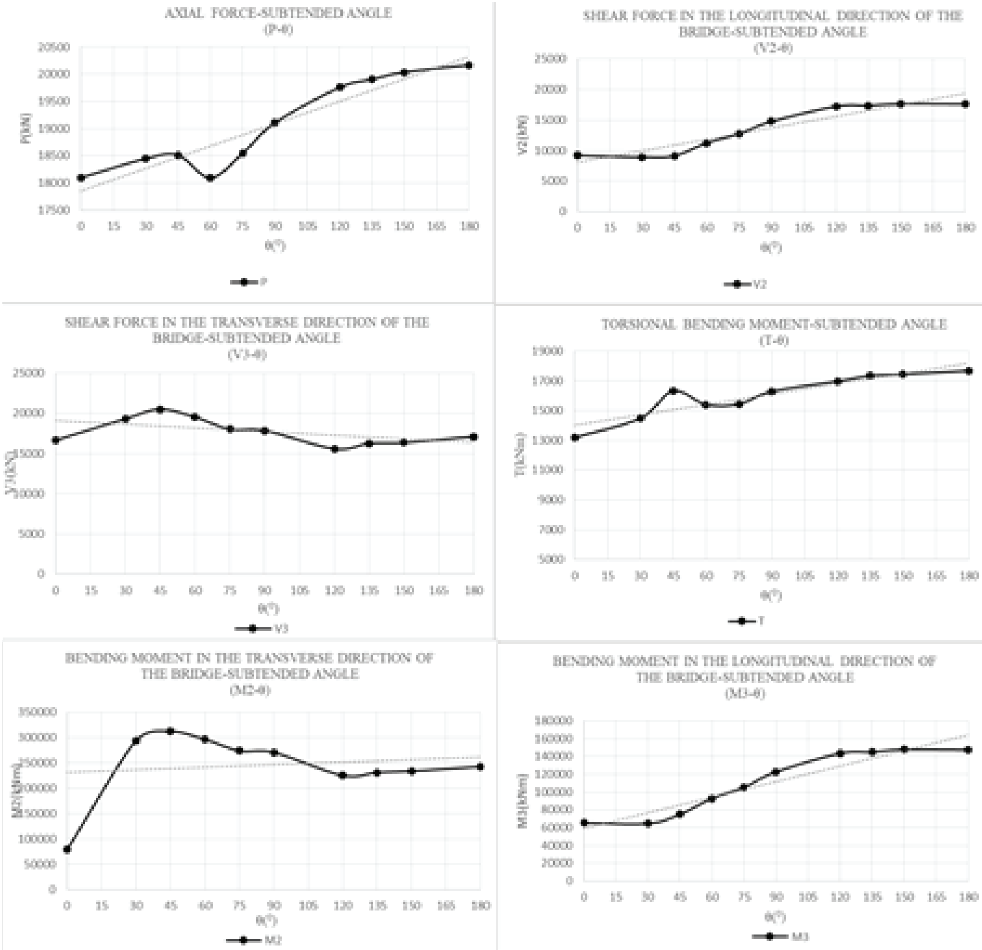

Figure 17. Internal forces of the columns of the bridges - subtended angle variation.

angle of 45^0 that was four times larger than compared with the internal forces of an equivalent straight bridge.

According to the multi-mode spectral analysis results, the internal forces of the deck of the bridges were examined (Fig. 18). The shear forces, bending moments and the torsional moment of the deck in both directions of the bridge were increased as the subtended angle of the bridge were increased except the axial force. The torsional moment of the deck of the bridge with a subtended angle of 180^0 was four times greater than that of the torsional moment of the equivalent straight bridge. The torsional moment of the deck of the bridge with a subtended angle of 45^0 was three times greater than the torsional moment of the equivalent straight bridge. In addition, the shear force and the bending moment in the transverse direction increased at a ratio of nearly three times more than the equivalent straight bridge. In the transverse direction of the bridge reached the maximum value for the bridge that had a subtended angle of 180^0. Bending moment of the bridge increased at the rate of %55 up to the subtended angle 180^0 compared to the results of the equivalent straight bridge.

THE COMPARISON OF ELASTIC DYNAMIC ANALYSIS RESULTS OF BRIDGES WITH 3-4-5-SPANS

In this study, for evaluating the limitations and the analysis methods suggested by AASHTO specifications for curved bridges, elastic dynamic analyses were performed, and the results were obtained for both equivalent straight bridges and curved bridges for the determined configurations of 3-spans, 4-spans, and 5-spans of bridges. As a result of multi-mode response spectral analyses of these bridges; modal quantities of dynamic behaviour (i.e., period, natural frequency, modal mass participation), the pier displacements and the structural element internal forces were obtained for equivalent straight axis bridges and for the curved bridges that had arc lengths of 135m, 180m and 225m with a variable subtended angle 30^0-180^0 degrees. The analysis results were then compared according to variation of the span number and the bridge length.

The results of the linear modal analyses were obtained, and the variations of the relevant modal quantities with respect to the subtended angle of curvature were presented in Figure 19.

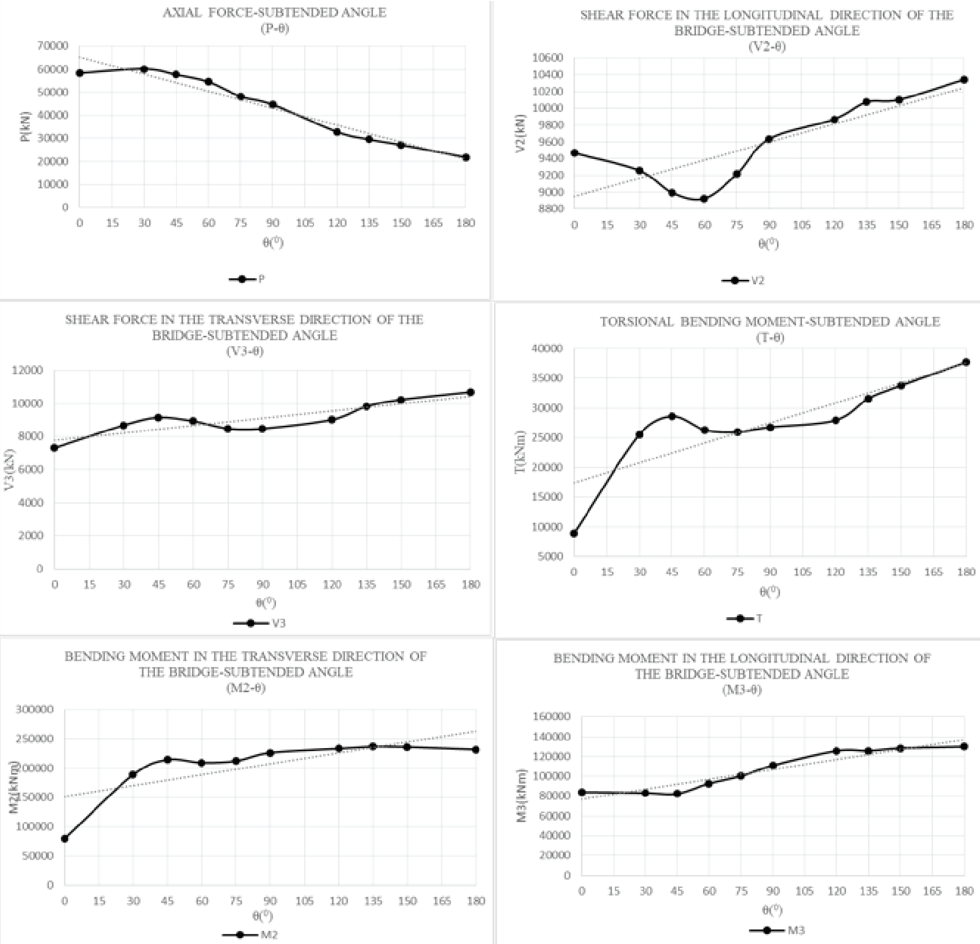

Figure 18. Internal forces of the deck of the bridges - subtended angle variation.

		3-Span Bridge					4-Span Bridge					5-Span Bridge				
Mode Shape	Subtended Angle (^{0})	T (1) (sec)	f (sec^{-1})	SumUX(1)	SumUY(1)	SumRZ(1)	T (1) (sec)	f (sec^{-1})	SumUX(1)	SumUY(1)	SumRZ(1)	T (1) (sec)	f (sec^{-1})	SumUX(1)	SumUY(1)	SumRZ(1)
1st Mode shape	0	0.770	1.3	0	0.31368	0.49082	0.785	1.27	0.000	0.201	0.519	0.771	1.3	0.000	0.161	0.432
	30	0.767	1.3	0.003	0.309	0.667	0.785	1.27	0.008	0.193	0.496	0.770	1.3	0.006	0.156	0.412
	45	0.764	1.31	0.007	0.303	0.645	0.786	1.27	0.015	0.215	0.524	0.769	1.3	0.013	0.151	0.389
	60	0.759	1.32	0.013	0.294	0.611	0.781	1.28	0.023	0.186	0.444	0.768	1.3	0.022	0.145	0.359
	75	0.756	1.32	0.021	0.286	0.577	0.778	1.29	0.035	0.178	0.406	0.766	1.31	0.033	0.136	0.325
	90	0.749	1.33	0.031	0.275	0.533	0.774	1.29	0.048	0.167	0.361	0.763	1.31	0.045	0.126	0.284
	120	0.736	1.36	0.056	0.249	0.430	0.701	1.43	0.076	0.159	0.291	0.758	1.32	0.072	0.101	0.199
	135	0.728	1.37	0.070	0.235	0.375	0.763	1.31	0.096	0.137	0.237	0.754	1.33	0.085	0.088	0.158
	150	0.720	1.39	0.086	0.221	0.320	0.758	1.32	0.120	0.130	0.195	0.751	1.33	0.098	0.074	0.119
	180	0.702	1.43	0.115	0.193	0.219	0.743	1.35	0.135	0.085	0.096	0.743	1.35	0.120	0.046	0.056
2nd Mode shape	0	0.392	2.55	0.000	0.839	0.586	0.423	2.36	0.000	0.836	0.886	0.432	2.32	0.000	0.841	0.852
	30	0.403	2.48	0.086	0.794	0.919	0.430	2.32	0.072	0.799	0.881	0.439	2.28	0.083	0.787	0.846
	45	0.414	2.41	0.169	0.751	0.916	0.452	2.21	0.173	0.819	0.958	0.445	2.25	0.160	0.739	0.844
	60	0.421	2.38	0.260	0.706	0.908	0.451	2.22	0.244	0.694	0.877	0.453	2.21	0.237	0.687	0.845
	75	0.442	2.26	0.336	0.661	0.908	0.462	2.17	0.317	0.647	0.875	0.461	2.17	0.304	0.641	0.852
	90	0.456	2.19	0.405	0.620	0.904	0.471	2.12	0.376	0.602	0.872	0.468	2.14	0.354	0.596	0.855
	120	0.482	2.07	0.506	0.547	0.892	0.465	2.15	0.471	0.536	0.881	0.490	2.04	0.466	0.508	0.849
	135	0.493	2.03	0.539	0.515	0.884	0.499	2	0.486	0.513	0.917	0.485	2.06	0.418	0.499	0.877
	150	0.503	1.99	0.561	0.484	0.874	0.510	1.96	0.531	0.518	0.947	0.489	2.05	0.413	0.474	0.880
	180	0.519	1.93	0.580	0.427	0.844	0.510	1.96	0.475	0.420	0.857	0.495	2.02	0.377	0.437	0.871
3rd Mode shape	0	0.323	3.09	0.000	0.839	0.586	0.322	3.1	0.003	0.836	0.886	0.351	2.85	0.000	0.844	0.911
	30	0.325	3.08	0.086	0.796	0.920	0.323	3.1	0.073	0.803	0.885	0.353	2.83	0.125	0.788	0.906
	45	0.326	3.06	0.169	0.754	0.917	0.323	3.1	0.176	0.826	0.968	0.355	2.82	0.239	0.739	0.904
	60	0.348	2.87	0.261	0.707	0.909	0.324	3.08	0.244	0.704	0.889	0.358	2.8	0.356	0.691	0.902
	75	0.332	3.01	0.338	0.665	0.911	0.326	3.07	0.318	0.660	0.892	0.361	2.77	0.464	0.649	0.902
	90	0.336	2.98	0.409	0.624	0.908	0.328	3.05	0.378	0.617	0.892	0.364	2.74	0.555	0.610	0.896
	120	0.346	2.89	0.515	0.551	0.899	0.299	3.34	0.592	0.566	0.900	0.382	2.62	0.708	0.560	0.894
	135	0.352	2.84	0.550	0.519	0.893	0.341	2.93	0.562	0.548	0.935	0.377	2.65	0.750	0.540	0.888
	150	0.359	2.78	0.576	0.488	0.885	0.350	2.86	0.704	0.575	0.959	0.382	2.62	0.789	0.526	0.884
	180	0.375	2.67	0.605	0.430	0.864	0.360	2.78	0.651	0.490	0.859	0.391	2.56	0.836	0.510	0.874

Figure 19. Modal quantities obtained from the linear modal analyses for all bridge Configurations.

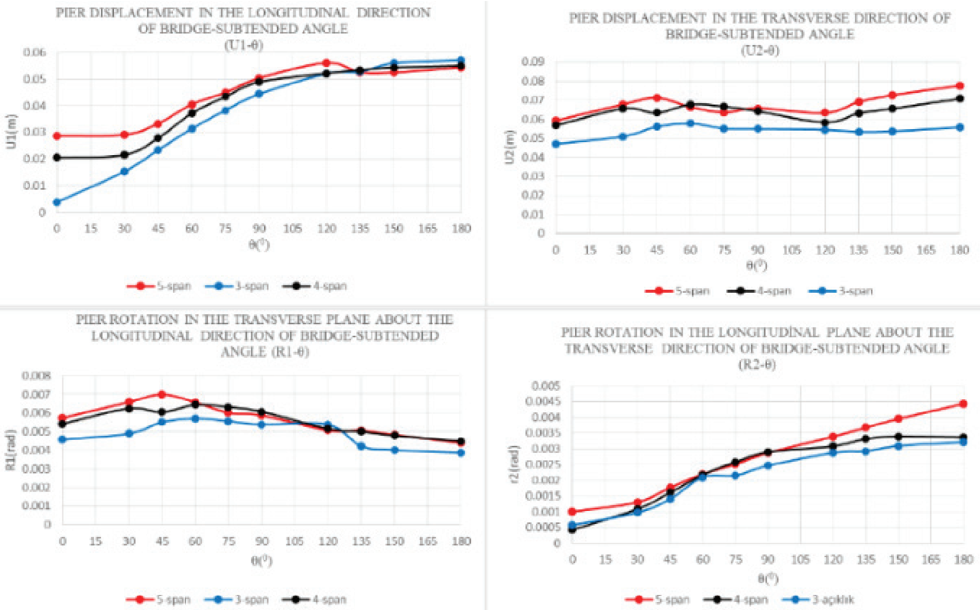

Figure 20. Displacement and rotation at the top of the pier - subtended angle variation.

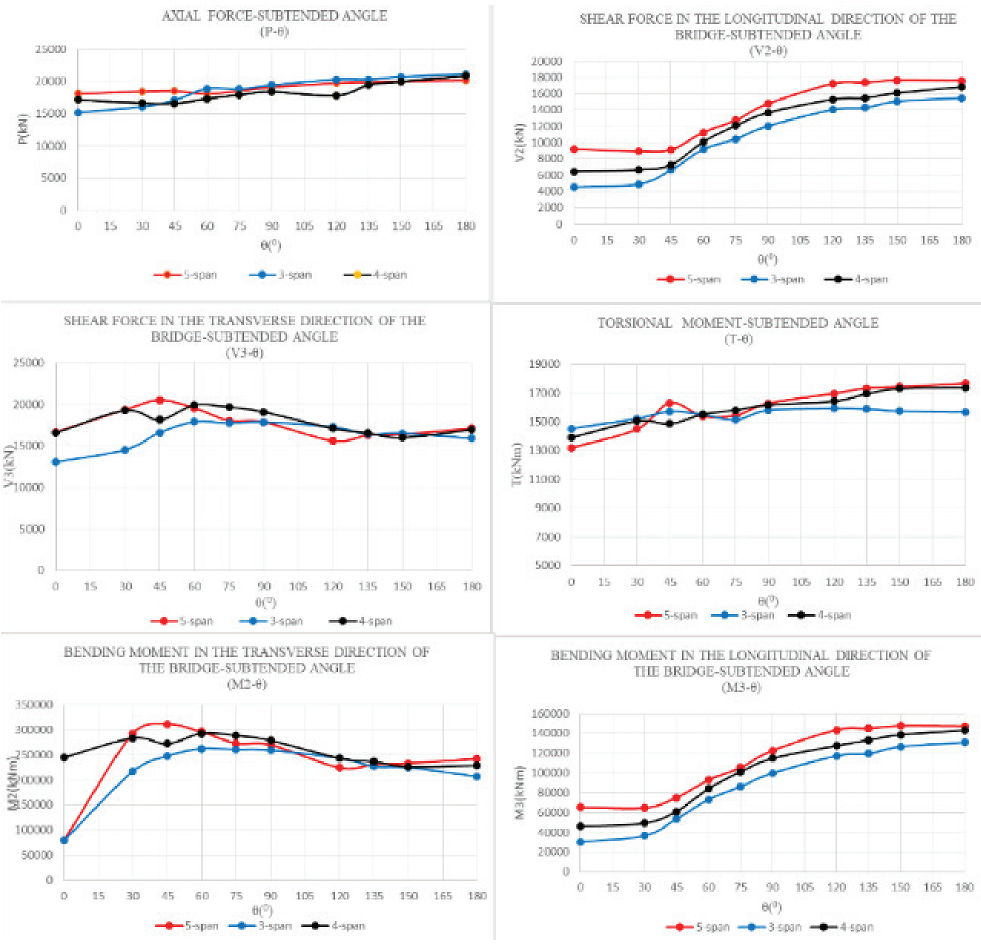

Figure 21. Internal forces of the columns of the bridges - subtended angle variation.

According to the analysis results, the displacements and the rotations at the top of the column of the pier of the bridges were examined (Fig. 20). The displacement of the pier in the longitudinal direction of the bridges increased as the subtended angle increased at a rate of nearly fifteen times more than the equivalent straight bridge compared to a curved bridge that had a subtended angle of 1800 for the 3-span bridge configuration. The displacement of the column in the transverse direction of the bridges increased with the increase of the subtended angle at a ratio of 1.375 times more than for the 5-span bridges. The rotation of the pier in the transverse plane about the longitudinal direction of the column had the maximum value for the bridge with a subtended angle of 450 and decreased at the rate of nearly %23 up to the subtended angle of 180^0 for the 5-span bridge. Lastly, the rotation of the column about the transverse direction of the bridge increased with the variation the subtended angle for all bridge configurations. However, the highest increase rate was for the 5-span bridge with four times greater than the equivalent straight bridge. The bridge with a 180^0 of subtended angle had the column rotation of nearly four times more than the rotation of the equivalent straight bridge.

According to the multi-mode spectral analysis results, the internal forces of the pier columns of the bridges were examined (Fig. 21). The axial force, shear force in the longitudinal direction of the bridge, torsional moment, and bending moment in the longitudinal direction of the bridge increased as the subtended angle increased. Particularly after a subtended angle value of 30^0, the shear force and bending moment in the longitudinal direction increased to nearly three times more than those of equivalent straight bridges for 3-span bridges whereas the maximum values of the intenal forces were obtained for 5-span bridge configurations. The shear force and bending moment in the transverse direction of the bridge reached their maximum values for a bridge with a subtended angle of 45^0 for a 5-span bridge, which is four times greater compared to the internal forces of the piers of the equivalent straight bridge, whereas for 3-span and 4-span bridges the maximum values of those forces were obtained with a subtended angle of 60^0.

According to the multi-mode response spectral analysis results, the internal forces of the bridge deck were examined (Fig. 22). The shear forces, bending moments, and torsional moments in both directions of the bridge increased as the subtended angle of the bridge increased, except for

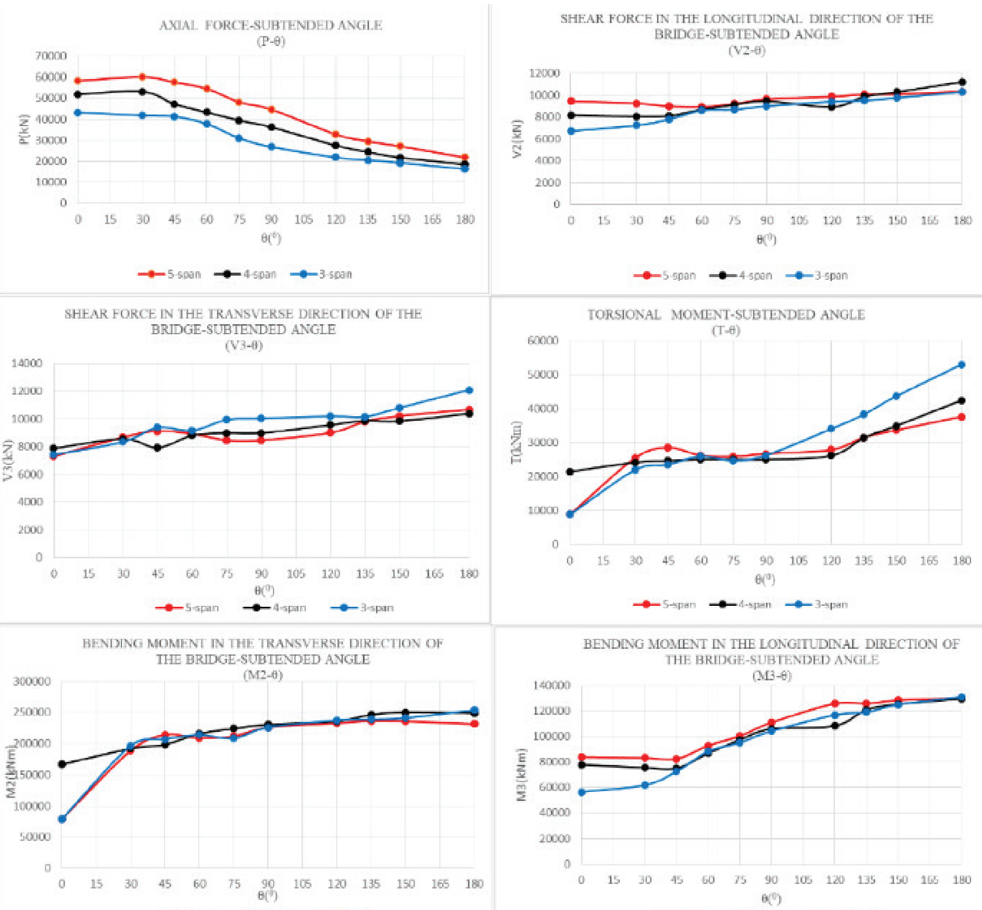

Figure 22. Internal forces of the deck of the bridges - subtended angle variation.

the axial force for all bridge configurations. The increment ratio for the torsional moment was particularly high with the variation in the subtended angle. The torsional moment of the deck of the bridge with a subtended angle of 180^0 was six times more than that of the equivalent straight bridge for the 3-span bridge configuration, which was the greater value of all bridge configurations.

Furthermore, the transverse shear force and bending moment increased by almost 63% and reached their maximum values for a bridge with a subtended angle of 180^0. In comparison to the results of the similar straight bridge for the 3-span structure, the bending moment of the bridge rose by 221% up to a subtended angle of 180^0.

CONCLUSION

In this study, the parametric bridge models were generated, designed, loaded, and analyzed in accordance with the AASHTO LRFD Bridge Design Specifications [1] and the TBEC [22] by varying the number of spans, bridge length, and the subtended angle of the curvature. In AASHTO LRFD [1], for bridges that have horizontal curvature in plan, the condition that allows bridges to be idealized as straight bridges is specified as having a subtended angle up to 90^0 degrees, whereas this limit has been revised to 30^0 degrees in the AASHTO Guide Specifications [2]. These conservative limitations arise due to uncertainties in the behavior of curved bridges under seismic excitations, so in order to investigate these limitations, numerical analyses were carried out. Multi-mode spectral analyses were performed for both horizontally curved and equivalent straight bridges for investigating the effect of the curvature during seismic excitation.

The dynamic behavior mode shapes and related dynamic quantities (period, natural frequency, and the modal mass participation ratios vs.) of the parametric bridges were obtained by using the linear analysis method. Additionally, the displacements at the top of the pier columns, as well as the internal forces of the structural elements (pier column and deck internal forces), have been determined.

The multi-mode spectral analysis results for defined bridge configurations can be summarised as follows by using the fuzzy technique that introduce fuzzy variables and membership functions to describe the relationship between the subtended angle and the results.

Symbols and notations:

q: Subtended angle

T_1, T_2,T_3: The periods of the first, second, and third mode shapes, respectively.

MM_L, MM_T, $MM_{Torsion}$: The modal mass participation ratios in the longitudinal, transverse, and torsional directions

D_L, D_T: The longitudinal and transverse displacements at the top of the pier

R_L, R_T: The rotations of the pier about the longitudinal and transverse directions

N: Axial force of the structural elements

V_L, V_T: The longitudinal and transverse shear force of the structural elements respectively

M_L, M_T: The longitudinal and transverse bending moment of the structural elements respectively

T: Torsion of the structural elements

F(q): Fuzzy sets that describes the relationship between the analysis results and the subtended angle q.

μ(q): Fuzzy membership function that captures the sensitivity of the analysis results with respect to the variation of the subtended angle q.

1. The analysis results indicated that the period of the first mode, denoted; as T_1 decreased as the subtended angle θ increased across all bridge configurations. The membership function $\mu(T_1)$ represents the influence of θ on the period T_1. For the 4-span bridge configuration, the period of the first predominant mode was higher than that of the other configurations. Specifically, at a subtended angle of 120^0 degrees, the period T_1, decreased by approximately 12%. However, as θ approached 180^0 degrees, the period T_1 showed an increase, as captured by the fuzzy set $F_T(\theta)$. For the 3-span bridge configuration, the period decrease ratio with respect to the subtended angle θ was the highest, with a rate of nearly 10%, indicating a significant sensitivity of T_1 to θ . This sensitivity is described by the fuzzy membership function μ(θ). For the second and third mode shapes, denoted as T_2 and T_3, the periods increased as the subtended angle increased. The fuzzy sets $F_{T2}(\theta)$ and $F_{T3}(\theta)$ illustrate this relationship, showing that the behavior of the bridges remained consistent across different configurations during the seismic analysis, as indicated by similar membership functions $\mu(T_2)$ and $\mu(T_3)$.
   This fuzzy-based formulation of the mode period analysis highlights the nuanced relationship between the subtended angle and the dynamic behavior of the bridges. The results underscore the importance of incorporating fuzzy logic into the analysis to account for the uncertainties and variations in the seismic response of curved bridges.
   As a conclusion, although the modal behavior of bridges is independent of the bridge span number and length, the 3-span bridge configuration showed the most rigid behavior depending on the curvature variation.
2. The analysis showed that the modal mass participation ratio in the longitudinal direction (MM_L) of the bridges increased as the subtended angle θ increased. The fuzzy set F_{MML} (θ) describes this relationship, indicating that MM_L reached up to 20 times the modal mass participation ratio of the equivalent straight bridge ($\theta=0^0$) for the 4-span bridge configuration. The membership function $\mu(MM_L)$ captures the sensitivity of the longitudinal mass participation to changes in θ. In contrast, the mass participation ratios in the transverse direction

(MM_T) decreased as the subtended angle θ increased across all bridge configurations. The fuzzy set F_{MMT} (θ) represents this trend, with the membership function μ(MM_T) reflecting the decreasing influence of θ on the transverse mass participation. For the torsional mode, the mass participation ratio ($MM_{Torsion}$) decreased with increasing subtended angle θ for the first predominant mode shape. Among the configurations, the 3-span bridge exhibited the highest torsional mass participation ratio, $MM_{Torsion}$, reaching up to 75%, as characterized by the fuzzy set $F_{MMTorsion}$(θ) and its associated membership function μ($MM_{Torsion}$). As a conclusion, the variation of modal mass participation ratios of the bridges with the variation of subtended angle were directly effected by the span number and bridge length. 4-span bridge and 3-span bridge had the highest modal mass participation ratio variation effects.

3. The analysis results revealed that the displacement of the pier in the longitudinal direction (D_L) of the bridges increased as the subtended angle θ increased. The fuzzy set F_{DL}(θ) describes this relationship, indicating that D_L for the 3-span bridge reached a maximum value nearly fifteen times greater than that of the equivalent straight bridge (θ=0^0) at a subtended angle of 180^0 degrees. Similarly, the longitudinal displacement of the pier increased by approximately 12 times for a curved bridge with a subtended angle of 90^0 degrees. For the 4-span and 5-span bridges, the increase in D_L was nearly 2.5 and 2 times, respectively, as captured by the fuzzy membership functions μ(D_L) for each configuration. In the transverse direction (D_T), the pier displacement increased with the variation of the subtended angle θ, reaching a ratio of 1.375 for the 5-span bridges, as represented by the fuzzy set F_{DT}(θ). The rotation of the pier in the transverse plane about the longitudinal direction (R_L) of the column exhibited a maximum value for a bridge with a subtended angle of 45^0 degrees. As the subtended angle increased to 180^0 degrees, R_L decreased at a rate of approximately 23%, described by the fuzzy membership function μ(R_L). Lastly, the rotation of the pier about the transverse direction (R_T) increased with the variation in subtended angle θ across all bridge configurations. The fuzzy set F(R_T) captures this trend, emphasizing the impact of θ on the rotational behavior of the piers.
   As a conclusion, the pier diplacement in the longitudinal direction variation with the subtended angle decreased by the increase of bridge span number and the bridge length. For the rotation of the pier along the tranverse direction of the bridge variation with the subtended angle increased by the increase of bridge span number and bridge length. Lastly, the pier displacements and rotations of the piers arose critical values for the subtended angle less than 90^0.
4. The analysis revealed that the internal forces in the bridge namely, axial force (N), shear force (V), torsional moment (T), and bending moment (M) in the longitudinal direction (L) of the bridge increased as the subtended angle (θ) increased. Specifically, when θ exceeded 30^0 degrees, the shear force (V_L) and bending moment (M_L) in the longitudinal direction for 3-span bridges were found to be approximately three times higher than those of equivalent straight bridges (θ=0^0). For 5-span bridge configurations, the maximum values of the internal forces, represented by the fuzzy set FL(θ), were obtained. In the transverse direction (T), the shear force (V_T) and bending moment (M_T) reached their peak values for a 5-span bridge at a subtended angle of 45^0 degrees. The fuzzy set F_T(θ) corresponding to this configuration indicated that the internal forces were approximately four times greater than those in the piers of the equivalent straight bridge. For 3-span and 4-span bridges, the maximum values of V_T and M_T occurred at a subtended angle of 60^0 degrees, as determined by the membership functions μ(V_T) and μ(M_T), where μ represents the degree of influence of θ on the respective internal forces. The results, formulated through fuzzy logic, suggest that the subtended angle θ significantly affects the internal forces, particularly in the transverse and longitudinal directions.
   As a conclusion, the pier column internal forces (The axial force, shear force, torsional moment, and bending moment in the longitudinal direction of the bridge) variation with the subtended angle increased as the bridge length and the span number increased. It should be emphasized that, the AASHTO LRFD specification suggests that a bridge is considered regular if the subtended angle is smaller than 90^0. However, according to the analysis results, the internal forces of the pier columns of the bridges could reach their maximum values at lower angles of curvature than 90^0.
5. The analysis results demonstrated that the shear forces (V), bending moments (M), and torsional moments (T) in both longitudinal (L) and transverse (T) directions of the bridges increased as the subtended angle θ increased, except for the axial force, which remained relatively unaffected across all bridge configurations. The fuzzy set F_{TL}(θ) describes the relationship between the subtended angle and the torsional moment in the longitudinal direction, highlighting a particularly high increase ratio with variations in θ. For the 3-span bridge configuration, the torsional moment of the deck reached its maximum value at θ=180^0, which was six times greater than that of the equivalent straight bridge (θ=0^0), as represented by the fuzzy membership function μ(T_L). This was the highest value observed among all bridge configurations. For the 5-span bridge configuration, the torsional moment reached its peak at θ=45^0 degrees, captured by the fuzzy set F_{TL}(θ), before decreasing up to θ=90^0 degrees. Additionally, the shear force (V_T) and bending moment (M_T) in the transverse direction increased by nearly 63%, reaching

their maximum values for a bridge with a subtended angle of 180^0 degrees. The fuzzy membership function $\mu(V_T)$ and $\mu(M_T)$ characterize this trend. The bending moment (M_L) of the 3-span bridge increased by 221% up to a subtended angle of 180^0 degrees compared to the results of the equivalent straight bridge, as captured by the fuzzy set $F_{ML}(\theta)$. This fuzzy logic-based formulation elucidates the complex relationship between the subtended angle θ and the internal forces in curved bridges.

As a conclusion, the deck torsional moment variation with the subtended angle decreased as the bridge length and the span number increased where the torsional behavior of the horizontally curved bridges seriously effected the vulnerability and fragility.

It should be emphasized that, the AASHTO LRFD specification suggests that a bridge is considered regular if the subtended angle is smaller than 90^0. However, according to the analysis results, the internal forces of the deck of the bridges could reach their maximum values at lower angles of curvature than 90^0.

It was shown in the study that; bridge length and span number had a significant effect on the seismic response of the horizontally curved bridges compared to straight bridges. Besides, the subtended angle limitations that AASHTO LRFD specifications put forward regarding allowing the curved bridges to use an equivalent straight bridge should be reviewed again. It suggests that a bridge is considered regular if the subtended angle is smaller than 90^0. However, according to the analysis results, the dynamic modal quantities, the displacement and rotations of the pier, the internal forces of the pier columns and the deck of the bridges could reach their maximum values at lower angles of curvature than 90^0. Therefore, the limitations of the subtended angle should be reviewed and re-evaluated for several variable parameters by using linear and non-linear analysis methods.

The aspects that make this research valuable and different from other studies are, firstly, the parametric models had a wide range of different subtended angles of curvature, bridge span numbers, and bridge lengths. Besides, the analysis results evaluated for the wide scope of the determined bridge configurations to realize the curvature effect of the bridges is very important to design resilient bridges under seismic excitation. It is of great importance that critical bridges that provide transportation, communication, and logistics should remain standing without damage in major earthquakes. Therefore, the up-to-date studies that discuss the restrictions of the regulations to get better solutions are very important to advance in the analysis and design fields of civil engineering.

For future studies, to realize the effect of curvature angle, in addition to linear analysis, nonlinear time history and pushover analysis should be done under near-fault seismic excitations. Besides, for long multi-span horizontally curved bridges, different bearing solutions (elastomeric bearings, lead rubber bearings, and spherical bearings) should be investigated to ligthen the mass of the deck in order to reduce the seismic effects. Lastly, according to the results of these researches the limitations of the specifications about the horizontally curved bridges should be reevaluated to design resilient bridges.

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