STUDY ON SEISMIC RESPONSE OF HORIZONTALLY CURVED BRIDGES IN COMBINATION WITH SKEWED ABUTMENTS

A

THESIS

Submitted in partial fulfilment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

IN

CIVIL ENGINEERING

With specialization in

STRUCTURAL ENGINEERING

Under the supervision

of

Dr. Tanmay Gupta

(Assistant Professor)

by

Dikshit (182651)

to

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY

WAKNAGHAT, SOLAN – 173234

HIMACHAL PRADESH, INDIA

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STUDENT'S DECLARATION

I hereby declare that the work presented in the thesis entitled **"Study on seismic response of horizontally curved bridges in combination with skewed abutments"** submitted for partial fulfilment of the requirements for the degree of Masters of Technology in Civil Engineering with specialization in structural engineering at **Jaypee University of Information Technology, Waknaghat** is an authentic record of my work carried out under the supervision of **Dr. Tanmay Gupta**. This work has not been submitted elsewhere for the reward of any other degree/diploma. I am fully responsible for the contents of thesis.

Dikshit

Signature of Student

Dikshit

182651

Department of Civil Engineering

Jaypee University of Information Technology, Waknaghat, India

29.May.2020

CERTIFICATE

This is to certify that the work which is being presented in the thesis titled **"STUDY ON SEISMIC RESPONSE OF HORIZONTALLY CURVED BRIDGES IN COMBINATION WITH SKEWED ABUTMENTS"** in partial fulfillment of the requirements for the award of the degree of Masters of Technology in Civil Engineering with specialization in structural engineering submitted to the Department of Civil Engineering, **Jaypee University of Information Technology, Waknaghat** is an authentic record of work carried out by **Dikshit (182651)** during a period from August, 2019 to May, 2020 under the supervision of **Dr. Tanmay Gupta** Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

The above statement made is correct to the best of our knowledge.

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I, Dikshit would like to acknowledge my work on **"Study on seismic response of horizontally curved bridges in combination with skewed abutments".** I am also thankful to **Dr. Ashok Kumar Gupta (Professor & Head)**, Department of Civil Engineering and all the faculty members for their immense cooperation and motivation for the research of my project.

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ABSTRACT

The present study investigates the seismic response of skew-curved concrete box-girder bridges under free vibrations and forced vibrations. A bridge having in-plan curvature in combination with the skewed abutments is termed as skew-curved bridge. 3-D models of the bridge with varying configurations are generated in the CSiBridge. The curvature angle for the parametric study has been varied as 0°,30°,60° and 90° in combination with skew angles of 0°,15°,30°,45° and 60°. Modal analysis and response spectrum analysis for all the bridge models has been performed. Modal response of the various bridge configurations has been presented in graphical form in order to have knowledge of the mode shapes, time periods and fundamental frequencies of the bridges. Furthermore, mode participation factor for three orthogonal directions also have been determined for every configuration of the bridge considered. After performing response spectrum analysis, variation of out-of-plane bending moment, in-plane bending moment, and longitudinal torsion along with the span length under horizontal (i.e. longitudinal and transverse) and vertical component of seismic excitations has been also presented using graphical representation. Results indicate that increase in skew angle leads to decrease the time period ratios in first vertical mode of vibration. Time period ratios for first longitudinal mode are found to increases as the degree of skewness and curvature increases, whereas mode participation factor decreases with increase in curvature and increases with increase in skewness for the same mode. Mode participation factor of first transverse (in-plane) vibration mode increases with increase in both skew and curvature angle. Results of response spectrum analysis indicates that all the three principal moments experience higher moment demand under transverse components of seismic excitations. For skew-curved bridges moment demand gets increases with increase in curvature in most of the cases. However, increase in skew angle causes decrease in moment demand in most cases.

Keywords: Skew-curved bridges, Modal Analysis, Seismic Analysis, Skew Angle, Curvature Angle

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LIST OF SYMBOLS

Symbol	Description
θ	Skew Angle
β	Curvature Angle
H_i	Tributary length of the pile
k_i	Equivalent linear stiffness of soil springs
k_h	Soil modulus
D	D is the diameter of pile
n_h	Depth independent subgrade reaction coefficient
k_{gap}	Stiffness of gap elements
k_{bw}	Stiffness of backfill elements
f	Natural frequency
ω	Angular frequency
T	Time Period
k	Stiffness
m	Mass

LIST OF ABBREVIATIONS

Abbreviation	**Description**
NPA	Nonlinear Pushover Analysis
RSM	Response Spectrum Method
SCM	Seismic Coefficient Method
THM	Time History Method
NTHA	Nonlinear Time History Analysis
CM	Centre of Mass
IDA	Incremental Dynamic Analysis
SSI	Soil Structure Interaction
MDCR	Multi-Directional Cable Restrainer
PGA	Pseudo Ground Acceleration
FHWA	Federal Highway Association

CHAPTER 1
INTRODUCTION

1.1 General

Bridge is a structure which facilitate a passage over an obstacle without closing the way under it. The obstacles can be a river, valley, railway, roads etc. and the required passage may be for different purposes such as railway, pedestrians and roads. As evident by many past earthquakes, bridges suffer a serious damage when strong earthquake occurs. Several types of seismic failures such as pier failure, expansion joint failure, deck unseating failure, etc. have been observed due to severe earthquakes, such as San Fernando Earthquake in 1971, Costa Rica Earthquake in 1991, Northridge Earthquake 1994, Kobe Earthquake in 1995, and Chi-Chi Earthquake in 1999. Skewed and horizontally curved bridges suffered more damages because of the superstructure's rotation or due to shift towards outside of the curve line.

a) Hospital Overpass Bridge Collapse

b) Collapse of Miraflores Overpass

Figure 1.1 Failure of bridges under seismic excitations [4]

In 2010 Maule, Chile, earthquake, two-span Hospital Overpass Bridge with skew angle of 45°, located at Highway No. 5 suffered damages [4] as shown in figure 1.1(a). These damages occurred due to rotation of deck which occurred because of skewness. A1 & A2 are two abutments, P1 is the centre pier, D1 & D2 are two simple spans.

In figure 1.1 (b), the damage of Miraflores Overpass is shown. The acute corner of the outer ring has been noticed to shift nearly 1.5m towards skewed transverse direction during the earthquake. Due to this transverse movement, unseating occurred at abutments of Miraflores Overpass which was three skewed overpass bridge in Santiago.

Skew bridges, curved bridges and skew-curved bridges have complex geometry as compared to straight bridges and hence the load distribution pattern will be different for these type of bridge structures. Therefore, it is of utmost importance to examine the seismic behaviour of such kind of bridges. Modal analysis is the first step in seismic analysis of the structure. Modal analysis makes one aware of structure's response under free vibrations. To examine the structure's response of the structure under forced vibrations, there are several methods. In this study, response spectrum analysis method has been used to examine the seismic response of skew-curved bridges. Response spectrum analysis method gives the peak response of the structure and is used when spectrum of ground motion is available.

In this dissertation, the behaviour of skew-curved bridges under free and forced vibration has been investigated in CSi Bridge. Three-dimensional finite element models have been modelled and their modelling has been explained in detail in Chapter 3. Next to modelling, modal analysis and response spectrum analysis has been carried out for skew-curved bridge models. Modal behaviour of skew-curved bridges i.e. behaviour of skew-curved bridges under free vibrations has been deliberated in Chapter 4 in brief. Chapter 5 conveys the results of seismic response of skew curved bridges under different directions of seismic excitaions

1.2 Skew Angle and Curvature Angle

Skew angle is the angle between the alignment of the intermediate or end support & normal drawn to the longitudinal axis of bridge-deck. It is represented by "θ" in figure 1.2(a) and (b). Curvature angle is shown in figure 1.2(b) which is represented by "β".

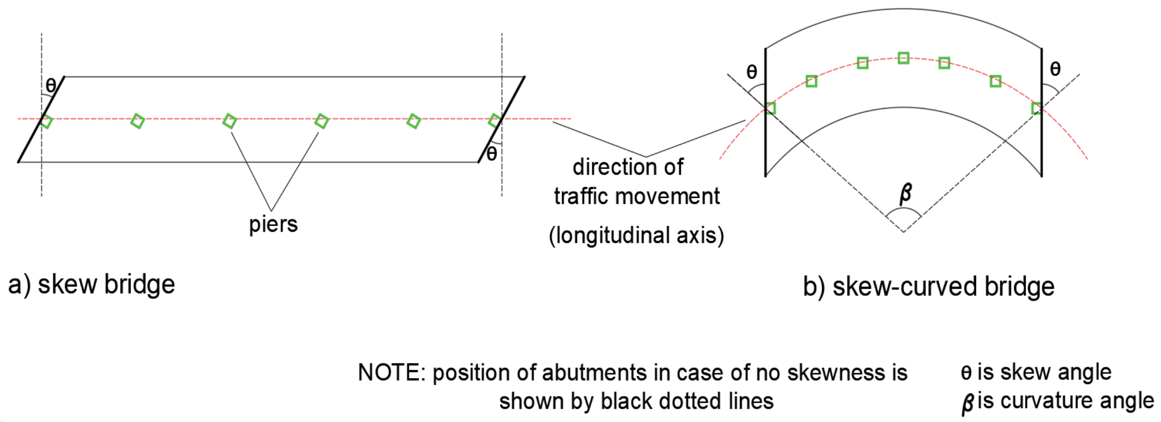


Figure 1.2 Representation of skew angle and curvature angle in different bridge configurations

1.3 Skew and Skew-Curved bridges

There are several kinds of bridge-classifications based on various factors. Based on the alignment, bridges are classified as straight and skew bridges. Bridges in which the bridge deck and substructure (piers and/or abutments) alignment are not perpendicular to each other are termed as *skew bridges*. Figure 1.3 shows the geometry of skew bridge having skew angle ‘θ’.

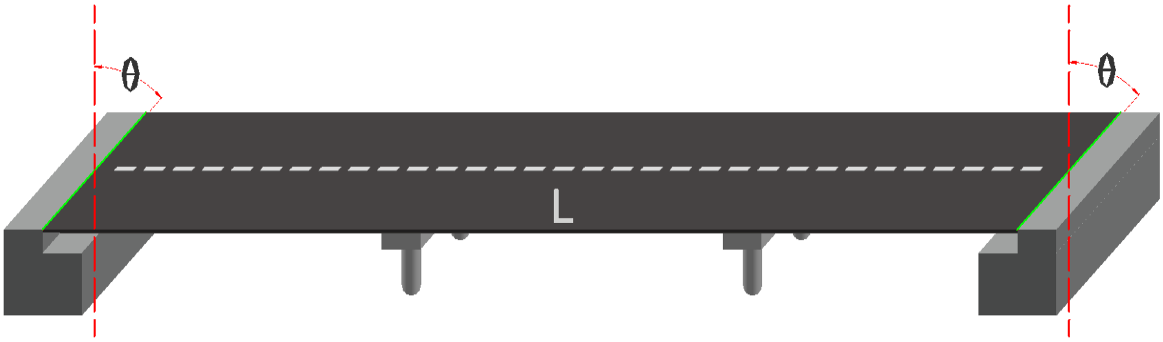


Figure 1.3 Skew Bridge Geometry

In *horizontally curved bridges* i.e. the bridges having in-plan deck curvature; the gravity load itself induces warping normal stresses, torsional shear stresses, and flexural stresses in the structural components of bridges due to its complex geometry. *Skew-curved bridges* are the bridges in which the deck slab have the in-plan curvature in combination with skewed substructure elements.

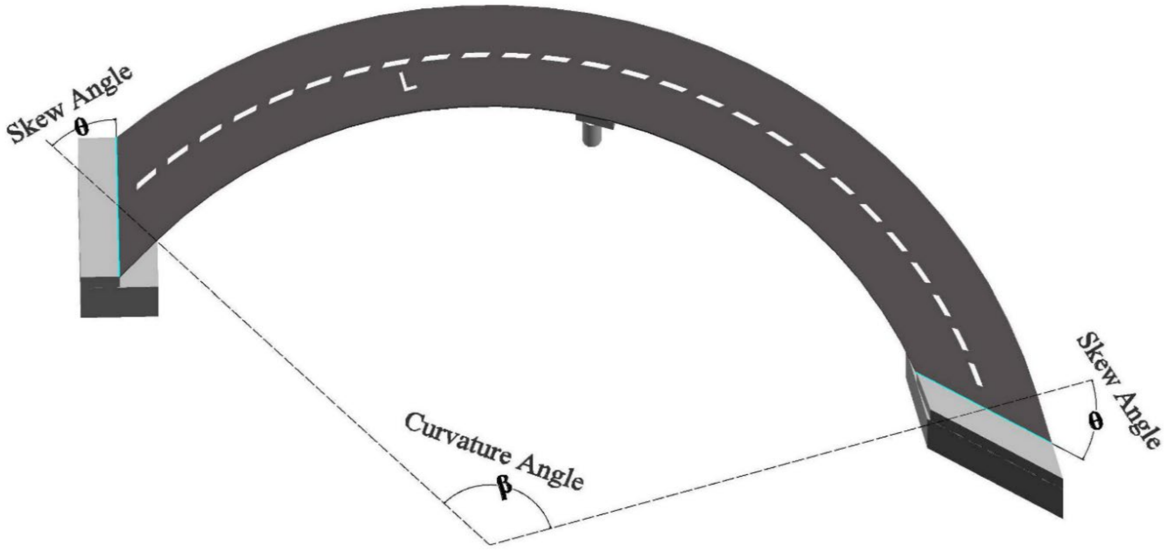


Figure 1.4 Skew-Curved Bridge Geometry

Transportation system of any city heavily rely properly designed skew-curved highway bridges as they provide easy access or exit from complex intersections, which are valuable in dense urban areas & they also have ability to conform to existing layouts. Nowadays, skew-curved bridges are mostly constructed in modern transportation system of many cities.

1.4 Problem Statement

This dissertation aims to investigate the investigate the modal and seismic behaviour of skew-curved bridges. When a structure undergoes seismic excitations, during that interval a large amount of horizontal force is applied on the structure in short period. Bridge's behaviour under the effect of applied seismic force, decides its seismic performance. Under seismic and service loads, behaviour of skew and/or curved bridges become more complex due to the influence of its unconventional geometry. Due to the action of seismic waves, the vibrations occur in the bridge system generates internal deformations and stresses which governs seismic response of bridge. Investigation for seismic response of skew-curved bridges has been performed based on parameters such as seismic input and dynamic characteristics of structural system. Finally, the response parameters which affect the seismic behaviour of skew-curved bridges under seismic excitations has been also studied.

1.5 Organisation

This dissertation addresses the problem by studying the past numerical, analytical and experimental studies based on skew, skew and/or curved bridges as discussed in Chapter 2. Furthermore, 3-D bridge models have been generated in the finite element program CSi Bridge. Modelling details of the bridge modal has been discussed in detail in Chapter 3. Next to bridge modelling, modal analysis has been carried out to get the modal response of the skew-curved bridges. Chapter 4 emphasis on the behaviour of skew-curved bridges under free vibrations. To get the seismic response of the skew-curved bridges, response spectrum analysis has been performed on the generated 3-D bridge models. Chapter 5 gives the details about the response spectra function and response spectrum analysis of the skew-curved bridges. Conclusions drawn on the basis of these results of modal analysis and response spectrum analysis has been discussed in Chapter 6. Figure 1.5 shows the methodology of the proposed work.

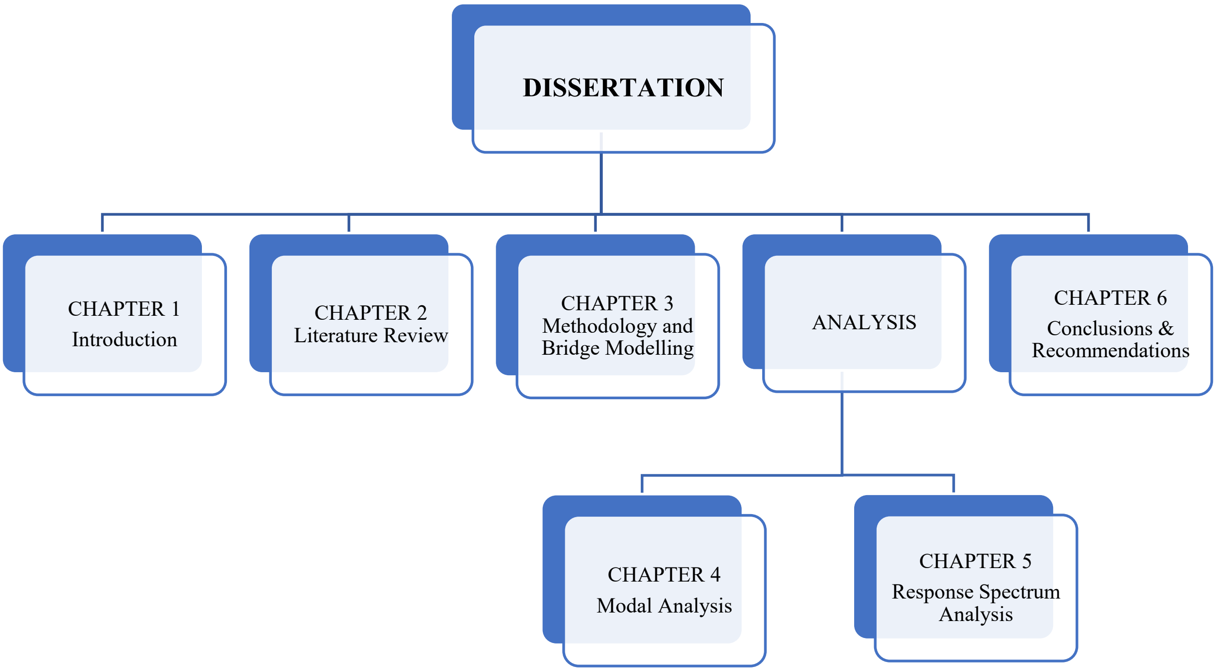


Figure 1.5 Organization of Dissertation

CHAPTER 2
LITERATURE REVIEW

2.1 General

When a structure undergoes seismic excitations, during that interval a large amount of horizontal force is applied on the structure in short period. Bridge's behaviour under the effect of applied seismic force, decides its seismic performance. Under seismic and service loads, behaviour of skew and/or curved bridges become more complex due to the influence of its unconventional geometry. As compared to straight bridges, skew bridges exhibit higher potential to unseat [1]. When skew bridges are subjected to seismic force, unseating of the deck occurs due to the translation motion and rotation of the deck [1-4]. Seismic demands in case of curved bridges are higher as compared to the seismic demands in case of straight bridges [5]. The bridges become more vulnerable as the horizontal deck curvature increases. In case of curved bridges, seismic response in the longitudinal and transverse directions get coupled [6]. Moreover, when such skew alignment of abutments is introduced in curved bridge geometries, their susceptibility for damage under earthquake forces becomes manifolds [7]. Owing to action of the seismic waves, the vibrations occur in the bridge system generates internal deformations and stresses which governs the seismic response of the bridge.

2.2 Effect of Skewness on Seismic Performance of Skew Bridges

Seismic performance is ability of structure to withstand its desired functions, for instance serviceability, safety etc. during and after the earthquake. If a bridge gets partially or fully collapsed during an earthquake it will not only endanger the lives of people crossing the bridge but also who are beneath it thus good seismic performance of any bridge structure is of utmost necessity for its safe design. A vast research has already been carried out by various researchers using many different strategies upon seismic performance of skew bridges, however, improvements in seismic design are still needed.

As the distribution of forces in skew bridges is quite different in comparison to straight bridges, their structural response do-not show same behaviour as straight bridges. In straight bridges the load follows a straight path in span direction whereas, this pattern is not followed in case of skew bridges, rather it travels via a short path towards the obtuse corners of skew bridge [8]. At obtuse corners of skew bridge such behaviour leads to the coupled response of longitudinal and transverse displacement which causes the subsequent rotation in direction of skewness. Moreover, seismic response differs much more due to oblique impact in skewed bridges. At acute corners, skew bridges tend to rotate in horizontal plane, and a possibility of uplift at these supports become very real [2].

Bridges having greater degree of skewness are more sensitive to higher modes effects [9]. Seismic response of skew bridges is influenced by various factors such as column ductility, degree of skewness and ground motions characteristics [10]. Parameters such as unseating of deck at acute angle, gap openings, coupled response of the deck (i.e. translational and rotational) have been reviewed for skewed bridges under seismic excitation.

2.2.1 Unseating Mechanism in Skew Bridges under Seismic Loading

The displacement of bridge-deck at abutment's acute corners, due to the coupled motion (translation and rotation) is known as the unseating of skew bridge under seismic excitation. Skew bridges without shear key, under the effect of longitudinal ground motion experience unseating of the bridge deck at acute corner [11]. Figure 2.1 shows in two steps, how unseating happens in typical skew bridge under seismic excitations [12]. In first step the bridge moves towards the left abutment and collision between the abutment back wall and superstructure take place due to closing of the gap. In the second step, counter clockwise rotation (because of the reaction from backwall and transverse ground motion) of the superstructure leads the bridge to rotate around obtuse corner. This rotation causes displacement of bridge deck in a direction away from their abutments due to which unseating of bridge deck is experienced at acute corners of skew bridges [3,4]. However, insignificant transverse displacement was experienced at intermediate bents of the most bridges [3].

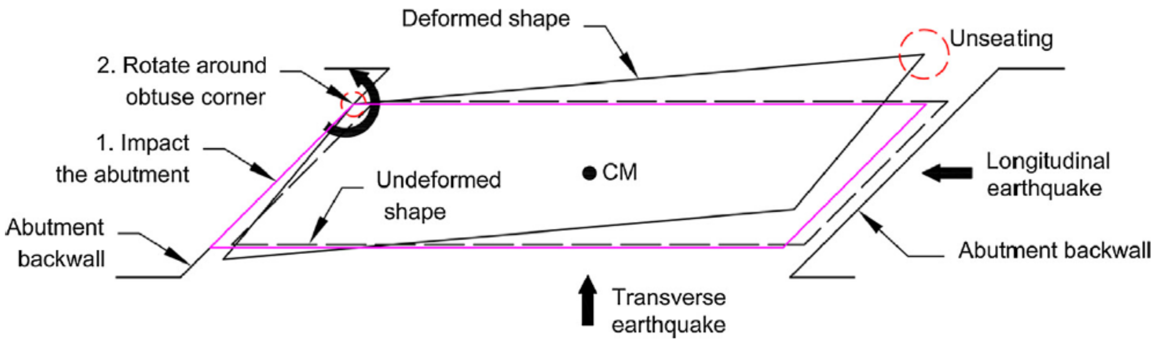


Figure 2.1 Unseating Mechanism in a typical Skew Bridge during Earthquake [12]

At the acute corner gap openings become larger and become smaller toward the obtuse corner, similarly acceleration components of the mass centre get increased and hence, deck get unseated at the acute corner [2, 8]. Under seismic excitations, bridge vulnerability gets increased with the increase in skewness irrespective of design procedure of the bridge (seismically, non-seismically designed) or the use of retrofitting technique [13]. Watanabe and Kawashima (2004) observed that various seismic actions such as pounding and incoherent response of substructures leads to rotation of the skewed bridge [14]. Wu et. al (2019) suggested larger support lengths to provide stability against the unseating of girder in skew bridges which are situated in near-fault regions [15,16].

2.2.2 Fragility Analysis for Skew Bridges

Researches have performed seismic evaluation for bridges to understand their vulnerability under seismic excitations via fragility analysis which also estimates total seismic loss (probability of failure). For highly skewed bridges, various components of bridge such as transverse abutments, transverse bearings & shear keys experience higher fragility due to excessive transverse displacement of the bridge [17]. Also, for a fixed skew angle, probability of damage for several demands has been noticed to get significantly affected by variations in properties of soil [18]. Angle of incidence of ground motion do not significantly affect fragility characteristics of skew bridge, however, as the skew angle increases, such characteristics get deteriorated irrespective of the incident angle of ground motion. [19].

On studying the probabilistic seismic behaviour of skew bridges, Bayat et. al (2015) found that time periods ranging between 0.9 and 1.4 times of fundamental period was the critical range of time periods in acceleration spectrum [20]. Study on combined effects of column height ratio and skewness for bridge system fragility discloses that column height ratio has negative effect on fragility of bridge and this effect get increased with increase in skewness and damage state [21].

Bridge-specific fragility curves generated by Mangalathu et al. (2018) using artificial neural network showed that parameters such as intensity measure of ground motion, ratio of longitudinal reinforcement in column, and length of the span significantly influences the seismic fragilities. Whereas, direction of earthquake, gap between shear key and the deck, coefficient of bearing, acceleration for shear key capacity, and damping ratio had a slight influence on all the seismic fragilities [22].

2.2.3 Analytical Studies for Skew Bridges

Many researchers had tried to investigate various dynamic aspects of skew bridges by performing analytical studies. Maragakis & Jennings (1987) analysed a model for the rigid body motions of a short skew bridge having span length of 91.4m with skew angle of 20° [23]. Authors explained impact between abutments and bridge-deck, and incentive of in-plane rotational vibrations of the bridge deck due to this impact. During strong earthquake motions, planar rigid body rotations of deck were induced which causes damage at the abutments of skew bridges and seismic pounding significantly affect transverse displacements of deck at the ends. However, there were assumptions that torsional resistance of the columns was assumed to be elastic & effects of the abutment mass were neglected. Contact was assumed to concentrated at the middle of bridge deck but in actual, the point of contact between abutment and the deck keeps changing.

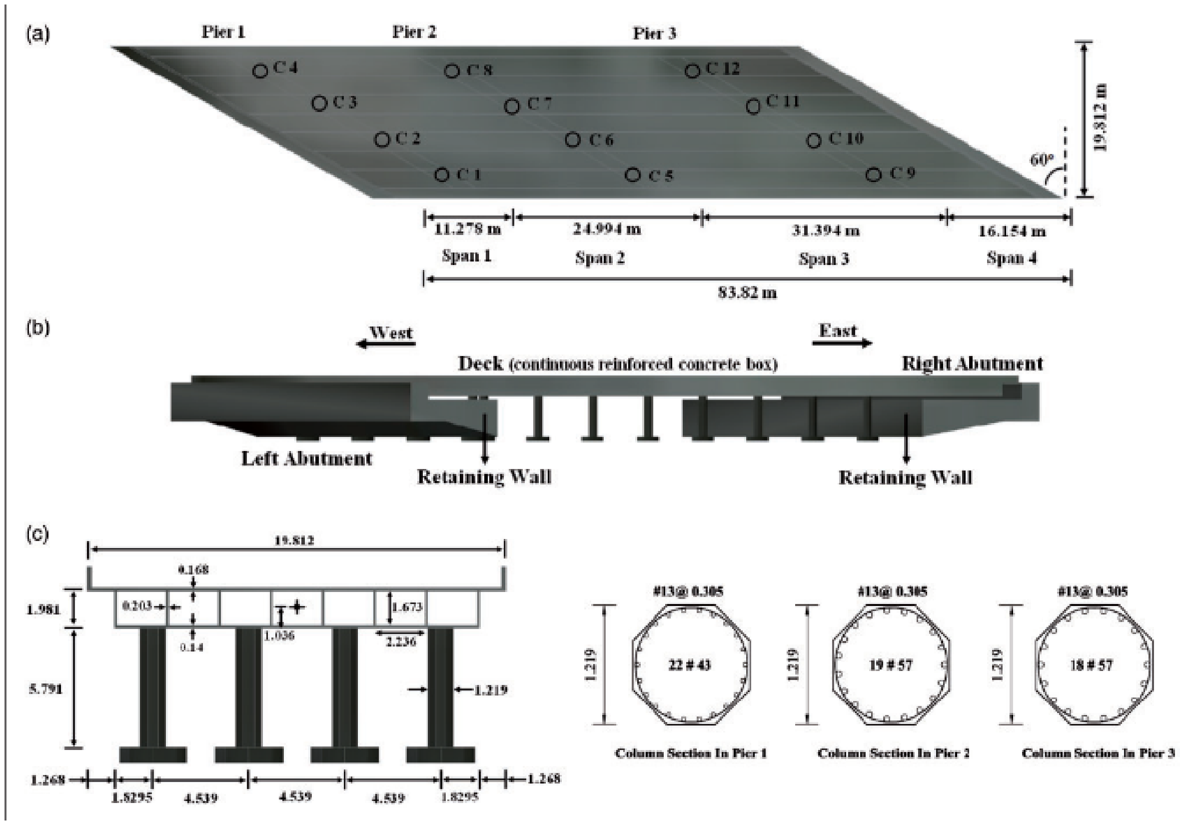
Meng et. al (2001) concluded that dynamic response of skew bridge is significantly influenced by rotational to translational frequency ratio (R/T). As R/T ratio of the bridge increases, the maximum normalised displacement of the bridge gets decreased irrespective of the damping considered [24]. Translational modes under free vibrations were found to be naturally coupled for symmetric skew bridges having one span [25]. An approximate seismic analysis was presented by Kalantari and Amjadian in which reaction forces of the elastomeric bearings were considered at abutments to prove that translational modes deviate from bridge principal axes in case of symmetric skew bridges [26-28]. In their later study, they incorporated the effect of seismic pounding on skew bridge torsional response [29]. Dimitrakopoulos also investigated effects of deck-abutment pounding for skew bridges and observed that tendency of skew bridges to express transverse displacement and rotation of the deck after pounding is dependent on skewness, friction and in-plan geometry [30,31].

Foothill Boulevard Undercrossing suffered serious damages under the great 1971 San Fernando earthquake and many researchers had tried to find out the reasons behind the failure of this bridge [1,11] by analytical approach. Figure 5 shows the structural details of the bridge.

2.2.3.1 Foothill Boulevard Undercrossing

Ghobarah and Tso (1973) examined the dynamic response of Foothill Boulevard Undercrossing, San Fernando Valley, California which was subjected to devastating San Fernando earthquake in 1971 [32]. Structural details of aforementioned bridge have been conveyed in figure 2.2. They generated a beam analytical model to analyse seismic response and concluded that for the failure of the bridge, the coupled flexural and torsional deformations of the deck were primarily responsible. Therefore, authors recommended that combined effect of torsional and flexural vibrations must be considered, while designing the skew bridges. However, use of the fixed boundary conditions at end of the spine model was a doubtful deliberation, as the bridge suffered in plane horizontal translation and rotation at the ends.

Furthermore, Özşahin & Pekcan (2019) studied effect of torsional ground motion (TGM) on linear elastic seismic response of the same bridge [33]. Approximately 50% higher shear stresses were observed when TGM was considered. Increasing stiffness eccentricity lowered the effect of the TGM due to its relative contribution on deck rotation, however for the different gap sizes, the torsional ground motion had constant values.



(a) Plan view of all four spans (b) Elevation (c) Column Elevation & Column cross-section

Figure 2.2 Structural Details of Foothill Boulevard Undercrossing [2]

2.2.4 Numerical Studies

Majority of the research upon skew bridges has been performed using various numerical methods implemented via high speed computers to distinguish their seismic behaviour. Finite element programs such as OpenSees [34], SAP2000[35], ANSYS have been most frequently employed in numerical studies by various researchers.

Maleki (2002) performed parametric study to investigate the effect of modelling assumptions on seismic analysis and revealed that assumption of rigid deck can be used safely for certain range of span length and skewness in skewed slab-girder bridges having pinned or elastomeric type of bearings, [36].

To investigate effects of spatially variable ground motions upon seismic response of multi-span RC skewed highway bridge Lou and Zerva (2005) performed linear elastic and nonlinear inelastic simulations in ANSYS and DRAIN-3DX respectively [37]. They recommended use of nonlinear analysis in order to perform a more realistic investigation under strong earthquake forces for the above-mentioned conditions as linear analysis greatly overestimated the seismic demand of the bridge. However, these results were only applicable in case of longitudinal excitations.

Pottatheere and Renault (2008) assessed seismic vulnerability of skew bridges having a skew angle of 0°, 12.33° and 45° using fragility curves [38]. Authors noticed that probability of damage get increased with increase in degree of skewness whereas, bearings and columns were found as most vulnerable bridge components. Higher stiffness of the soil enhances the capacity to resist rotation of pier [39].

Force distribution in shear keys of skew bridges was studied by Wu (2019) using thirteen skew angles and 4 gap sizes in OpenSees [11]. Ground motions were taken from PEER Ground Motion Database [40] to conduct nonlinear response history analysis which showed that shear keys near acute corner become more vulnerable to damage as compared to the obtuse corner shear keys. To evaluate the forces among shear keys, longitudinal loading must be taken into account when the longitudinal gap was closed.

2.2.4.1 Specific Case Studies on Foothill Boulevard Undercrossing

Foothill Boulevard Undercrossing was also investigated numerically by many researchers for instance, Imbsen et al. (1984) analysed the bridge for 1971 San Fernando earthquake using finite element program SEISAB with beam model, however such modelling resulted only in preliminary approximation of the damage [41]. Further, the same study was continued by Wakefield et. al (1991) describing the dynamic behaviour via free vibration analysis, linear & nonlinear time-history analysis of above-mentioned skewed RC box girder bridge using DYNAFLOW with built-up plate models [42]. They concluded that planar rigid body rotations of the deck significantly influence dynamic response of bridge as compared to the torsional and coupled flexural deformations, when connection between abutments and deck was not rigid. Which confirmed theory given by Maragakis et. al (1987) [23] that torsional and flexural deformations of the bridge deck can be neglected.

Furthermore, Meng and Lui (2000) continued study on seismic response of same bridge by performing response spectrum method of analysis in SAP2000 [43]. Three models i.e. elastic-deck model, stick model and rigid-deck model were developed in order to determine natural periods of the bridge. Out of these modelling techniques only elastic deck model could realistically compute axial forces and displacement occurred in structure, thus improving upon finite element practices used by previous researchers. The effect of superstructure flexibility, skewness, and supporting columns boundary conditions, all of these plays vital role in dynamic behaviour of bridge and hence, should not be ignored in dynamic analysis. The failure of bridge was predicted due to lack of torsional reinforcement and proper cross-section size of the middle bent column of the bridge.

2.2.4.2 Nonlinear Time History Analysis Approach

Nonlinear Time History Analysis (NTHA) have been carried out on skewed bridges by many researchers and their demonstrated results are presented below.

Abdel-Mohti and Pekcan (2008) examined the seismic response of skewed reinforced concrete box-girder bridges [44] by developing simplified beam-stick and finite element models varying the skew angles from 0° to 60° [45]. Nonlinear static pushover, linear and NTHA have been carried out on both type of models. Beam stick model was found successful in predicting the modal coupling because of skewness whereas, finite element models must be considered to predict higher mode effects for bridges having skew angle greater than 30°.

Seismic behaviour of two and three spans RC skew bridges having seat-type abutments using a performance-based methodology in OpenSees (response history analysis) showed that shear key strength is an important parameter which must be considered. When angle of skew at the abutments was increased, chances of bridge collapses and shear key failures were increased. [46,47,49]. Skew bridges with elastomeric bearings were studied to investigated the impact of skewness with various aspect ratios and types of ground motion on maximum displacement demands of the superstructure using OpenSees [48]. Effects of skewness had not increased the maximum displacement demand significantly in abutment's parallel direction whereas, it significantly changed responses in the abutment's normal direction. However, applicability of this research was constraint to single span and two-span bridges only.

In order to investigate impact of initial gap size on displacement of skewed concrete box-girder bridges subjected to bidirectional near-fault ground motions, Han et. al (2017) used SAP2000 3D finite element models [49]. As the gap size was increased in longitudinal direction, seismic response of skewed bridges got decreased whereas, longitudinal displacement shows an opposite trend in case of the straight bridges. However, this study was based on parametric analysis of pure numerical simulations.

2.2.4.3 Ground Motion Directionality

Some researchers had tried to investigate the behaviour of skewed bridges by applying the ground motion from different directions. Seismic excitation's direction significantly affects seismic vulnerability of the skew bridges [50]. Maleki and Bisadi (2006) observed 0°, 60° and 120° as the critical input motion direction in time history analysis of skewed bridges [51]. Via considering earthquake in four directions i.e. -45°, 0°, 22.5°, 45° Bayat et. al (2017) assessed seismic response of skewed bridges in terms of ground motion directionality [52]. Based on 20 ground motion records, an Incremental Dynamic Analysis (IDA) was performed in SAP2000 considering the bridge model proposed by Nielson (2005) [53] which showed that ground motion in longitudinal direction (0°) more significantly affected bridge's response while, 45° direction had the least impact. Noori et. al (2019) further enhanced the state-of-art research by considering soil-structure interaction (SSI) in addition to incorporating ground motions at 12 different angles of incidence ranging from 0° to 180° in OpenSees [54]. It was observed by considering SSI in analysis directionality effects got more pronounced. Abutment, elastomeric bearings, and shear keys becomes more vulnerable to damage (upto 77% more) when ground excitations were considered in the directions other than bridge longitudinal and transverse directions.

2.2.5 Experimental Studies

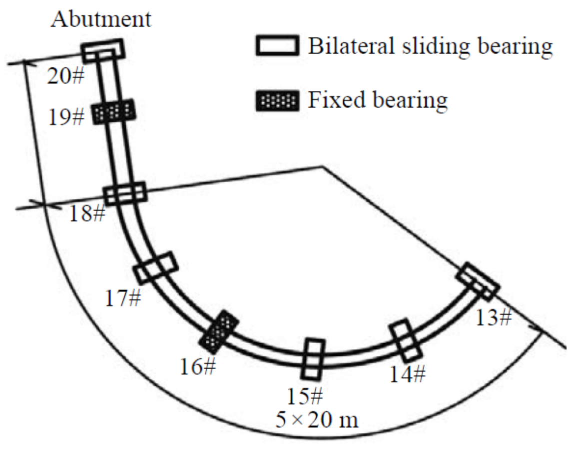
Investigations upon seismic performance of skew bridges by performing experiments such as shake table test were conducted by following researchers.

2.2.5.1 Shake Table Tests

Kun et. al (2017) performed shake table experiments for straight bridge & bridges having 30° and 45° skewed abutments to study the influence of pounding and skewness [55]. Results of experimental analysis showed that with consideration of pounding, bending moment get reduced for straight bridges and for 30° skew bridges whereas gets increased for bridges with 45° skewness. Transverse displacements and in-plane rotations were found to get increased by pounding. Whereas, when impact of both pounding and supporting soil was taken into account individually, it did not give adequate results and suggested that these two factors should be considered together [56]. Wu et al. (2019) also performed shake table tests for single-span skew bridges having seat-type abutments by considering three different earthquakes [15,16]. Influence of intensity (far field and near field) and category of ground motion, input direction, and expansion gap size on seismic response were investigated to show that in-plane rotation was triggered by the bridge-abutment interaction, however, these results were limited for symmetric and simply supported one span skew bridges.

2.3 Seismic Performance of Curved Bridges with Skew or Non-Skew Abutments

A lot of research has been carried out to examine the seismic performance horizontally curved bridges supported on skewed or non-skewed abutments which indicates such bridges are more susceptible to damage than straight or skew bridges. Similar to the behaviour of skew bridges, horizontally curved bridges also fail due to deck unseating. Unseating happens more often in such bridges owing to irregular geometry and deck-abutment pounding. As compared to simply curved bridges, seismic vulnerabilities of skew-curved bridges get manifolds. Many curved bridges suffered damages during various earthquake, out of which the collapse of extremely curved portion (which include 5 spans) of Baihua bridge during the Wenchuan earthquake is shown in figure 2.3 [57, 58]. The types of failures seen for this bridge include failure of shear key, expansion joints, rubber bearings, pier columns in shear-flexural etc. Han et. al (2009) summarised that collapse occurred due to: 1) complex behaviour of curved bridges 2) Improper design of connection joint between column and transversal beam 3) inadequate support length of transversal beam [59].



a) Baihua Bridge's Plan View

b) Baihua Bridge Collapse

Figure 2.3 Failure of Baihua Bridge during Wenchuan Earthquake [59]

2.3.1 Fragility Analysis

Guo et. al (2019) studied the influence of Multidirectional Cable Restrainer (MDCR) on curved bridge's seismic fragility and perceived that for cases when MDCR was not used, piers had the maximum fragility in each limit state for the system, while they were noticed to be the least vulnerable component when MDCR was used. This is due to the reason that MDCR allows the structure's inertial force to pass through each pier [60].

2.3.2 Impact of Horizontal Curvature on Seismic Performance of Skew or Non-Skew Bridges

In case of curved bridges, the geometry of the bridge is more unsymmetrical and hence the force flow is more complex as compared to the bridges with straight deck configurations. Influence of curvature on seismic response of horizontally curved bridges has been investigated thoroughly in the past. Horizontal curvature is the critical geometric parameter which influence seismic response of the components of bridge. Seismic demands are higher in components of the curved bridges because of dynamic mode coupling, transverse and longitudinal response coupling [61]. During the Wenchuan earthquake, several curved bridges had suffered serious damage and got collapsed [57-59, 62,63].

Curvature of bridge-deck has a significant influence on unseating potential of the superstructure [64] and transverse column drift [65]. Whereas, the influence of material, geometric and structural uncertainties was not addressed by the authors. Skewed supports and alignment of the bearing significantly influence the dynamic characteristics of curved girder bridges [66].

Multiframe curved reinforced concrete box-girder bridges are more vulnerable as compared to straight bridges [67]. Among the parameters (horizontal curvature of deck, deck discontinuity, and altitudinal irregularity), bridge fragility gets most negatively influenced by altitudinal irregularity [68]. Higher displacements of the deck were noticed for continuous bridges in comparison with bridges having in-span hinges, as the presence of in-span hinge causes strain release [5]. Modelling of reinforced concrete bridges shall include effects of expansion joint pounding in horizontally curved bridges and superstructure unseating because of planar rotation in bridges containing skewness [7]. Site effect and wave-passage effect should not be ignored in seismic design because these factors influence the seismic responses of curved continuous girder bridges significantly [69]. Maximum response of the piers varies with variations in angle of earthquake input [70]. Skewed or curved bridges with tall piers should be avoided to construct in high seismic zones. If not, special analysis should be required to authenticate the design [62]. However, the failure probability of the curved bridge under seismic excitations can be decreased using multi-dimension-cable-restainers [60]. Rogers and Seo (2017) assessed seismic vulnerability of curved precast-concrete I-Girder bridges with several different layouts and observed that length of the span significantly influences the bridge response rather than curvature of the bridge deck [71].

2.3.2.1 Effect of Curvature on Time Period and Frequency

For a constant arc length of the curved girder bridge structure, the natural period of first mode increases with decrease in radius of curvature [66]. Influence of warping, mass moment of inertia, and flexibility of piers on the natural frequency decreases as the radius of curvature increases, provided that span length is constant [72]. Warping effect was negligible when radius of curvature exceeded 1.7 times of the span length. Decreasing the radius of curvature will cause the decrease in period of fundamental vibrations [73]. Akbari et. al (2019) performed dynamic assessment upon curved RC box-girder bridges and observed that the natural frequencies decreased in every vibration mode with increase in the values of concrete's compressive strength and the corresponding values of elastic modulus of the material [74]. With increase in curvature angle, natural frequencies of bridge decreased and this decrement became more pronounced in higher modes.

2.3.2.2 Impact of Column Height on Seismic Response of Curved Bridges

Curved bridges with tall pier columns generally show complex dynamic behaviours under the effect of horizontal and vertical ground motions at the same time [59]. In general, it is observed that column fragilities get more effected by height of the columns as compared to curvature of bridge-deck [75]. Mangalathu et. al (2018) assessed probabilistic seismic vulnerability for tall horizontally curved concrete bridges of California by selecting normal, moderately tall, and very tall column heights [6]. Very tall bridges were observed as most vulnerable configuration than that of normally tall and moderately tall bridges.

2.3.3 Analytical Studies

Banerjee et. al (2016) analytically estimated potential of the curved bridge to rotate with consideration of deck-abutment collision, using a classical mechanics-based approach [76]. A box-girder bridge having total length of 165m and a curvature angle of 120° was selected. To perform the seismic analysis, small earthquake dataset was selected via scaling it to PGA level of 0.36g as per IS:1893. Results showed that time period of the translational modes were much higher than time period of rotational mode in seismically isolated configuration while for seismically non-isolated configuration this was not the case.

2.3.4 Numerical Studies

Tondini & Stojadinovic (2012) considered material and geometrical non linearities for time history analysis in OpenSees [65]. Modal analysis upon three bridge prototypes based on varying column height and radii of curvature showed that the longitudinal stiffness was not affected by the curvature of bridge, whereas transverse stiffness increases with the decrease in curvature.

Abbasi and Moustafa (2017) studied the effect of shear keys on seismic response of irregular bridge configurations (skewed, curved- single or multi frame) by performing nonlinear time history analysis using OpenSees [77]. Furthermore, shear key capacity was considered as 0%, 25%, and 75% of the pile capacity of lateral abutment. Authors observed that different bridge configurations' response under moderate & weak ground excitations was significantly affected by shear key capacity. Shear keys whose capacity was 0.75 times the lateral pile capacity were suitable to use for both kind of bridges (i.e. regular and irregular).

2.3.4.1 Skew-Curved Bridges

Wilson et. al (2014) performed nonlinear time-history analysis for various combinations of skewness and curvature varying from 0° to 45° skewness and up to 1370m radius of curvature using SAP2000 [7]. Presence of combined skewness and curvature led to high superstructure deformations and increased demand to capacity ratio in columns which can cause substructure damage. It was suggested that for high levels of skewness i.e. greater than 30^0, certain ranges of curvature i.e. less than 1370m should be adopted & for rest more complex combinations of the two geometries, a more exact modelling technique should be implemented.

Bent connection type was noticed to have significant affect on seismic performance of the skew-curved bridges having integral abutments. In cases when high drift ratios are present in bridges rather than the cases when base shear or base moment governs the design of piers, fixed bent connection should be preferred [78].

Serdar and Folić (2018) performed nonlinear dynamic analyses of three-span continuous concrete box girder skew-curved bridges using Seismostruct [79]. Bridges with two varying bent types, three varying skew angles and two values of curvature i.e. twelve types of bridges were analysed. For skew-curved bridges experiencing less seismic excitations, displacement of column top and deck rotation generated due to skewness decreases due to arching effect. When more seismic excitations occur effect of skewness becomes predominant. Larger actions occur in substructure of skew-curved bridges and hence should be evaluated more carefully [80]. Not including the vertical component of ground motion in analyses can increase the risk factor [81].

2.3.5 Experimental Studies

Shake table experiments were also performed by many researchers [82-85] to examine the seismic performance of bridges with such configuration. To perform the shake table tests, bridges were constructed by reducing them to a suitable scale.

2.3.5.1 Shake Table Tests

During the San Fernando earthquake in 1971, the east-half of the 5/14 South Connector Overcrossing suffered severe structural damage. Many researchers made attempt to catch on the reasons of these damages [83,84]

Williams & Godden (1979) performed series of shake table tests with consideration column ductility, impact at expansion joints [83]. Critical locations for damage were observed at the base of the long columns and the expansion joints. Kawashima and Penzien (1979) studied dynamic behaviour of the same bridge theoretically and experimentally [84] and noticed that effect of vertical excitation on horizontal transverse response was relatively small. It was pointed out that with increase in superelevation of the bridge deck coupling of horizontal and vertical modes gets increased. Li et. al (2015) performed experiments for a 1/10-scale typical four-span curved bridge under spatial ground motions, including local site effect, wave passage effect, & ground motion multidimensionality [69]. Authors observed that effect of wave passage leads to the higher pseudostatic displacements and asymmetric modes. Excitations in multidimensions increased the structural responses due to the coupling effect of two excitations in different directions. Li et. al (2019) analysed the influence law of the adjacent pounding parameters including the gap size and direction of excitation via shake table testing and observed that pounding force was greater near the shorter pier as compared to the pounding force near taller pier due to the influence of longitudinal slope [85].

2.4 Influence of Pounding on Seismic Performance of Skewed and Curved Bridges

Under the influence of seismic excitations, bridges tend to rotate about its centre of mass and at the same time translate in both longitudinal and transverse directions due to which collision between abutment and deck occurs when the widths of expansion joints, are not sufficient to handle such motions. This phenomenon of deck-abutment collision is known as seismic pounding (Figure 2.4). A number of studies have been performed till now on seismic pounding for various bridge geometries.

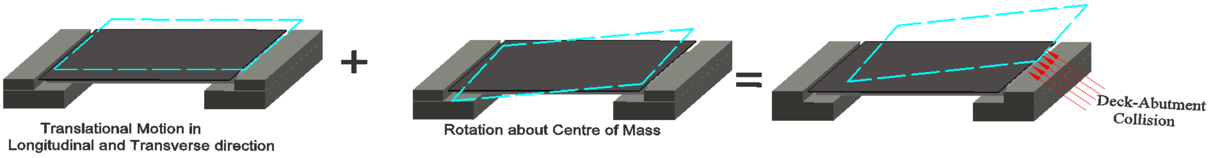


Figure 2.4 Seismic Pounding due to Deck-Abutment Collision

In-plane rotation of skew bridge deck occurs because of pounding between abutments and the deck which causes seismic torsion in the piers [86]. Change in the skewness of abutment directly affects the response of backfill during pounding between deck and abutment. This happens due to non-uniform passive pressure which get produced behind the abutment backwall and causes the deck's rotation about vertical axis [87,88]. In case of curved bridges, amplitude and frequency characteristics of response get affected due to the multiple collisions between girders which leads to generation of large contact forces at the expansion joints [84]. Torsional response of the curved decks gets increased during seismic pounding [89]. Transverse deck displacements, longitudinal deck displacements and rotations increases with increase in the skew angle because of torsional coupling [90]. A parametric study was conducted by Maleki (2005) investigating the pounding effect on bearing retainers [91]. He suggested that not considering gap during analysis may cause the non-conservative results for retainer forces, irrespective of stiffness and category of retainers.

In case of skewed bridges, effect of pounding on bridge response increases with increase in skew angle as it increases deck rotation which leads to greater seismic demands on piers. Pounding is essentially unavoidable in skewed bridges therefore, bridge with monolithic abutments is considered more appropriate in such cases [92]. Acceleration components, transverse displacements, and deck-rotation gets significantly increased for highly skewed bridges having small gap sizes and greater stiffness eccentricities [2]. While for curved bridges, radial, azimuthal corner displacements, and deck-rotation get increased as the gap between deck and the abutments decreases [64].

2.5 Research Gaps

Many past researchers have studied the behaviour of skew bridges and curved bridges individually, under free and forced vibrations. Results of these researches demonstrates that skew bridges and curved bridges have more chances of collapse under seismic excitations due to change in their geometries, and this change in geometric configurations causes change in load distribution pattern.

Modal behaviour and seismic behaviour of the skew-curved bridges has not been studied in past researches. If the behaviour of bridge structures which are having combined skewness and curvature will be studied under free and forced vibrations, it will provide improvisation in the seismic design practises of the skew-curved bridges which will lead to the hazard reduction during the earthquake event.

2.6 Need of the Study

Bridges with such configurations have been reported to suffer various seismic damage owing to superstructure's rotation or shift towards outside of the curve line, which is due to vibrations occurring under strong ground motions. Hence, it is a paramount to examine seismic behavior of skewed-curved bridges.

1. Modal analysis of the skew-curved bridges will help to understand the natural frequencies of the designed bridge structures and hence, the structure can be modified to avoid the resonance with surrounding components and externally applied ground motions.
2. Studying the seismic behaviour of skew-curved bridges will enhance the state-of-the-art for the seismic design of skew-curved bridges.
3. Seismic response characteristics which affect seismic behaviour of skew-curved bridges can be identified.
4. On the basis of the seismic response of skew-curved bridges, modification can be done to improve the design and construction processes of skew-curved bridges.
5. Improvisation in design and construction processes as per the seismic response of skew-curved bridges will lead to hazard reduction during the earthquake events.

2.7 Research Objectives

After reviewing the previous studies and past performances of skewed and curved bridges, being limited to the bound given at the reference section, the following issues are identified to be studied for enhancing the understanding of seismic behaviours of skewed and horizontally curved bridges;

1. To investigate the mode shapes, time periods and natural frequency of the skew-curved bridges under free vibrations using finite element models.

2. To examine the contribution of each mode and their mass in affecting the response of the skew-curved bridges by studying the modal participation factor and mass participation factor.

3. To determine the variations of three principal moments along with the span for skew-curved bridges under longitudinal, transverse and vertical component of seismic excitations using Response Spectrum Analysis.

CHAPTER 3
METHODOLOGY AND BRIDGE MODELLING

3.1 Methodology

Methodology which has been followed to achieve the objectives of this dissertation has been discussed in this section. To perform modal analysis and response spectrum analysis of skew-curved bridges, 3-D finite element models have been modelled using the finite element program CSi Bridge. Modal analysis has been carried out first which is then followed by response spectrum analysis.

In modal analysis, the degree to which the mode shapes, time periods and mass participation factors of skew-curved bridges are affected have been investigated using finite element models.

Response Spectrum Analysis has been carried out under three directional components of seismic excitations. Three principal moments (i.e. out of plane bending moment, in-plane bending moment and longitudinal torsion) have been investigated for skew-curved bridges under these seismic excitations. Methodology of proposed work is conveyed in the figure 3.1

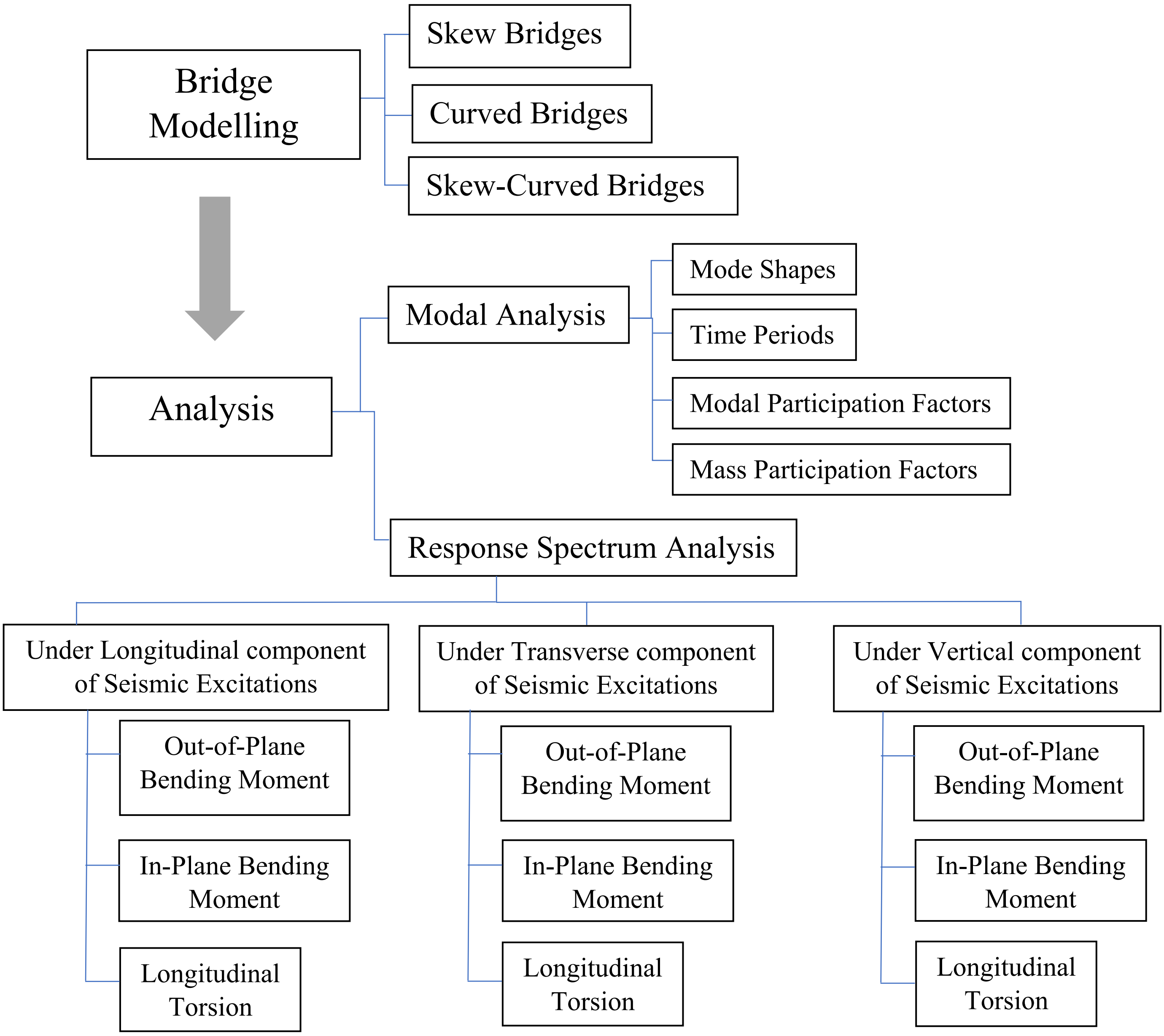


Figure 3.1 Methodology of proposed work

3.2 Bridge Modelling

3-D finite element models have been generated to perform analysis of skew-curved bridges under free and forced vibrations. Finite element models for several skew-curved bridge configurations taken for this study have been modelled with the help of finite element program CSi Bridge. This software offers the quick modelling of the bridge structures and provides the results for the static loads as well as for the dynamic loads such as earthquake loads. Description of benchmark bridge and their detailed modelling procedure has been discussed in the following sections.

3.3 Finite Element Method

Finite element method is a numerical approach for analysis of the structures. It is a computational approach which is used to obtain approximate results for problems of engineering. Problems are described by partial differential equation or can be formulated as functional minimization.

At present, finite element analysis is used at large extents in structural analysis. This method is developed after the intervention of the digital computers and is used in providing the solution for physical problems (such as an actual structure subjected to a force) of engineering analysis. The finite element analysis involves the various steps for the solution of the idealized mathematical model as shown in the figure 3.2. Physical problem is idealized as a mathematical model on the basis of the certain assumptions, from which the differential equation can be generated that governs the mathematical model. Mathematical model is solved using the finite element analysis. As this is a numerical approach, therefore it is necessary to check the obtained solution for accuracy. If the solution is not found satisfactory as per the accuracy criteria, the finite element analysis is repeated with refined parameters until the solution with sufficient accuracy is obtained.

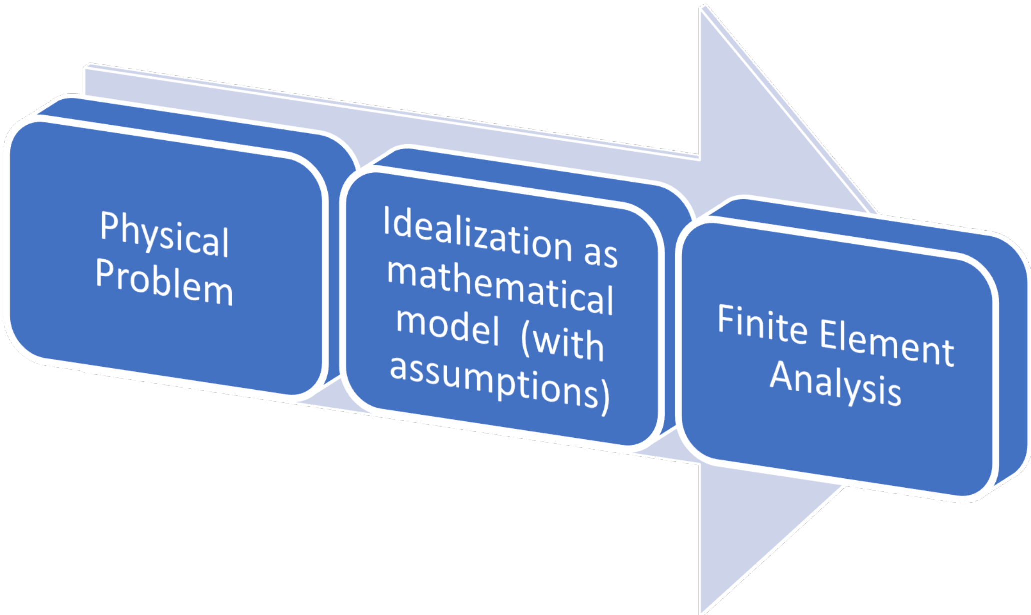
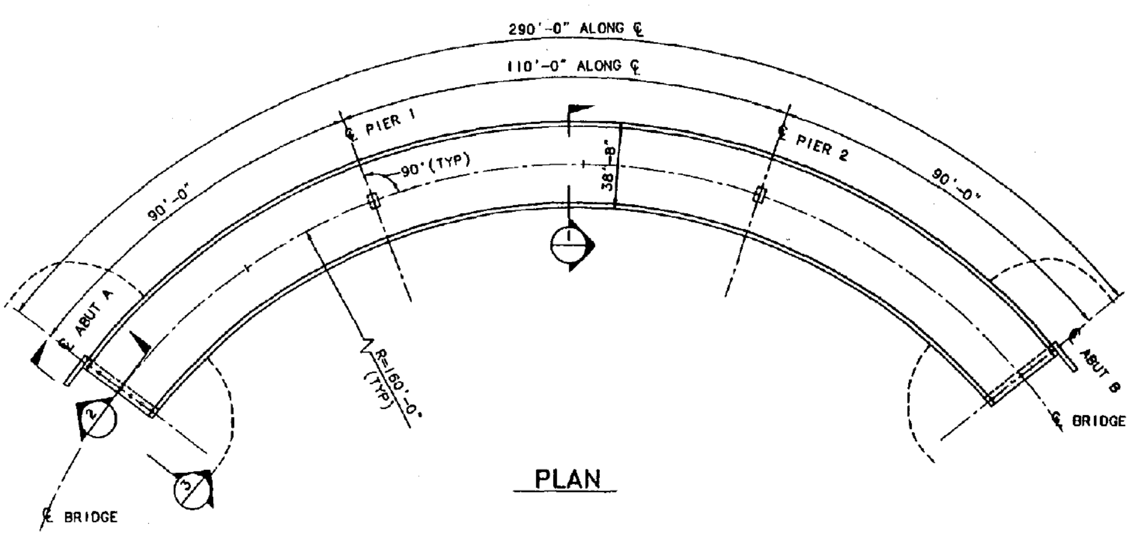


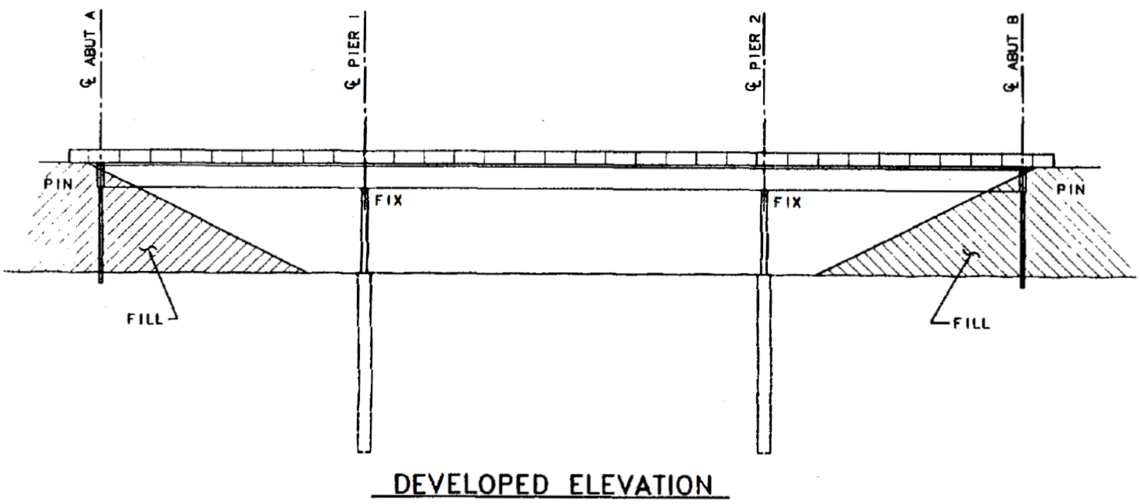
Figure 3.2 Phenomenon of solving the physical problem using finite element method

3.4 Description of the Benchmark Bridge

Benchmark bridge taken for this study is Example No. 6 of the FHWA series (FHWA, 1996-a). It is a three span curved RC box-girder bridge with a curvature angle (β) of 104°. Length of the first, second and third span is 27m, 34m and 27m respectively. Plan and elevation view of benchmark bridge is shown in figure 3.3



a) Plan view of the benchmark bridge



b) Elevation view of the benchmark bridge

Figure 3.3 Benchmark Bridge [93]

Intermediate bents with circular columns are supported on the drilled shaft foundation of diameter 8 feet. Bridge have diaphragm type abutments which are supported on seven pipe piles of 12m depth as shown in figure 3.4.

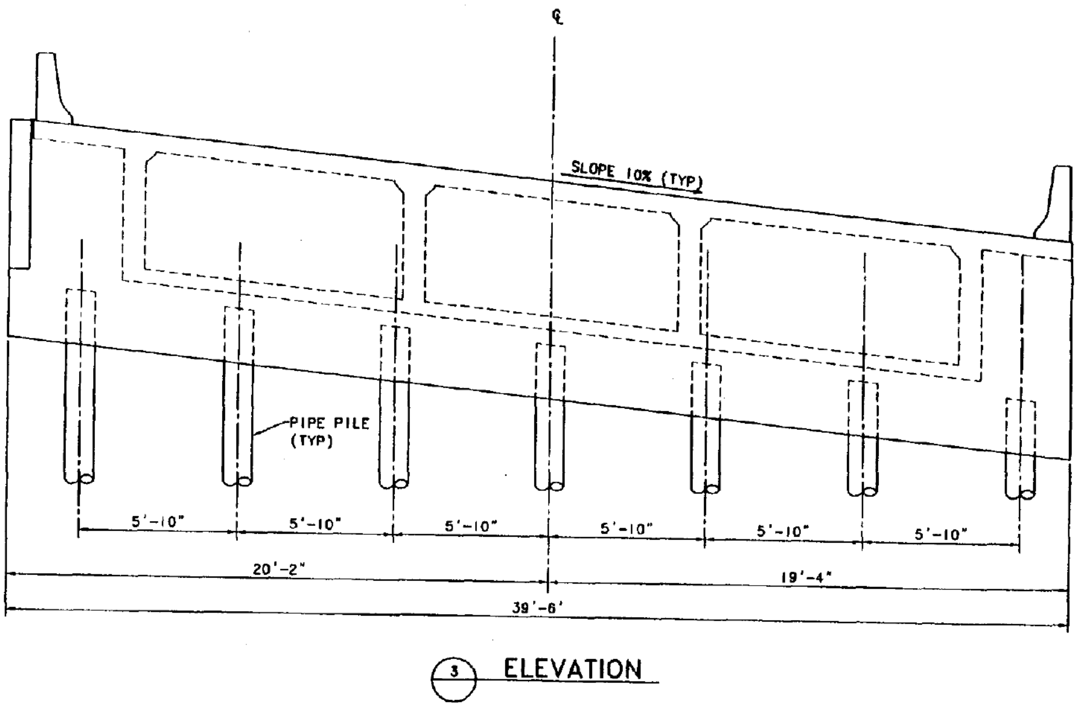


Figure 3.4 Abutment details of Benchmark Bridge [93]

Figure 3.5 shows the details of the pipe pile and figure 3.6 shows the cross section through the bridge with an elevation of intermediate bent.

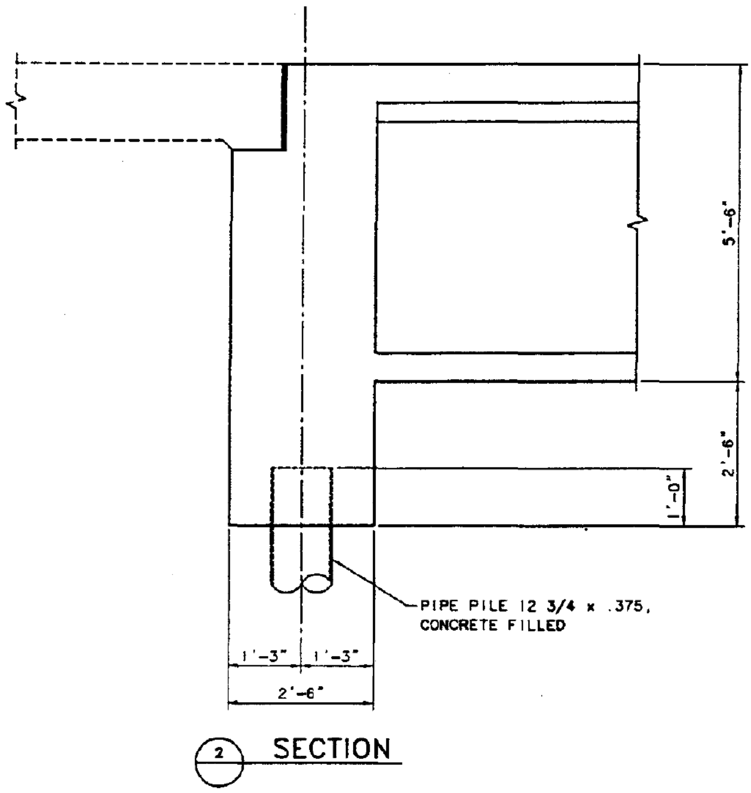


Figure 3.5 Details of pipe pile [93]

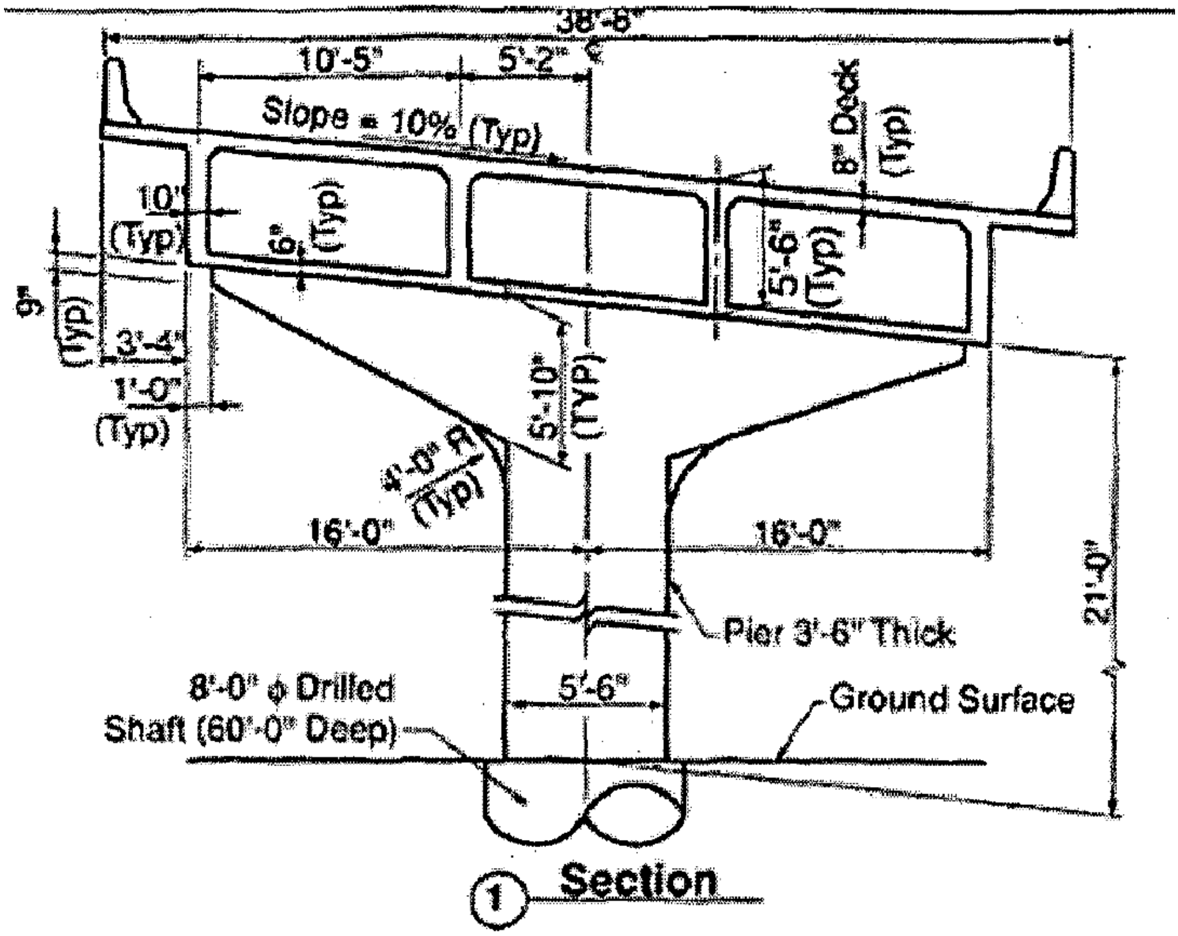


Figure 3.6 Cross section with an elevation of intermediate beam [94]

3.5 Modelling in CSi Bridge

Finite element models of the bridge have been developed in CSi Bridge which offers the modelling of bridges with easy procedure as compared to SAP 2000. With variation of skew angle (θ) and curvature angle (β) with constant centre line length of bridge, total 20 number of bridge models have been generated. Skew angle (θ) has been varied in the range between 0° and 60° at an interval of 15° whereas the curvature angle is varied as 0°, 30°, 60° and 90°.

3.5.1 Superstructure modelling of the bridge models

Superstructure of the bridge has been modelled as shell elements. Maximum meshing size of 0.3m has been assigned, therefore total number of shell elements between 35000 to 100000 has been found which varies with the variation of the bridge configuration. Mesh size has been chosen by performing mesh sensitivity analysis. Modal analysis has been performed with different mesh sizes, and their respective %age error and time taken to complete analysis for that particular mesh size is shown in figure 3.7.

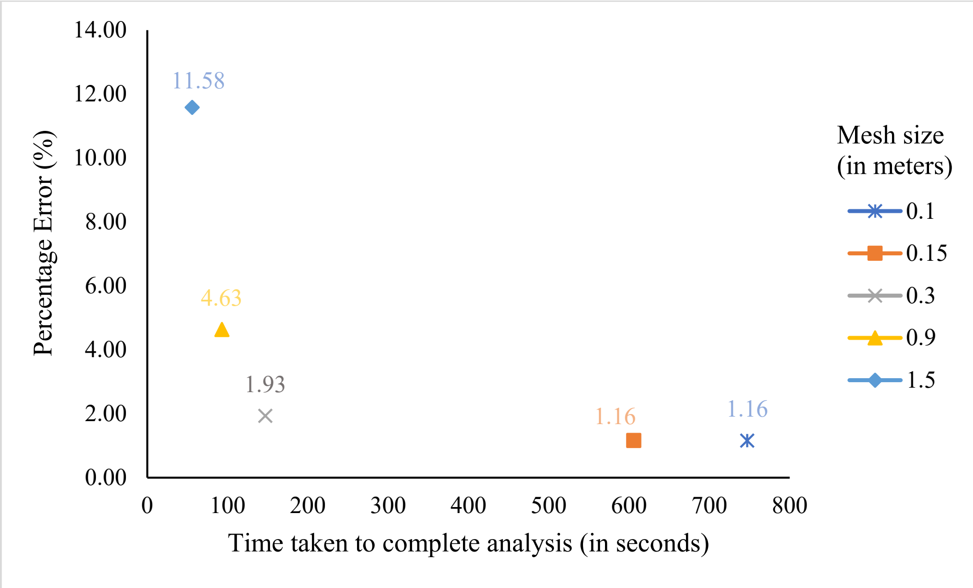


Figure 3.7 Percentage Error versus Analysis Time graph for different mesh sizes

Decrease in the mesh size will increase the number of nodes, and this increase in number of nodes increase the accuracy of results as shown in figure 3.7. Very small difference has been noticed in percentage error for the mesh size of 0.1, 0.15m and 0.3m, whereas the difference in time taken for analysis is very large. Hence, the mesh size of 0.3m has been opted.

Three diaphragms of 9 inches (228mm) have been provided at the middle of each span and two exterior diaphragms of 30 inches (762mm) thickness have been provided at both abutments. Self-weight of the superstructure is automatically calculated by the software. Since the wearing coat and traffic barrier has not been modelled, therefore for taking the load of wearing coat and traffic barrier, the additional live load of $2.59 kN/m^2$ has been applied as uniformly distributed load (UDL) on top of the deck slab. Three-dimensional model for bridge configuration having curvature angle (β) of 60° and skew angle (θ) of 45° is shown in the figure 3.8.

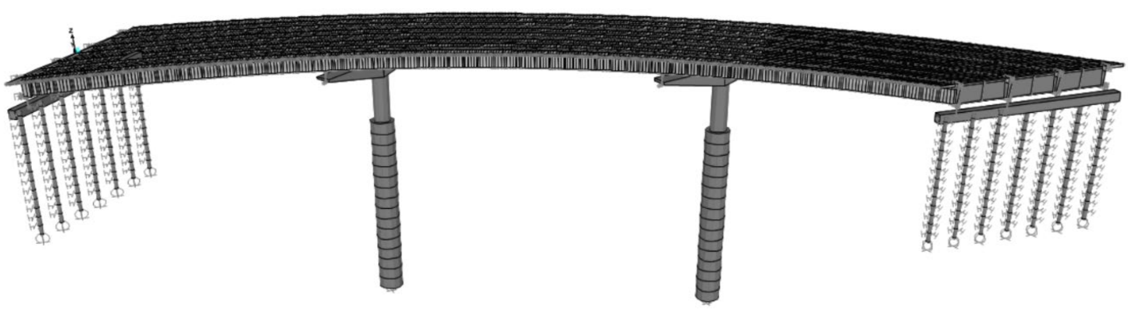


Figure 3.8 3-D model for bridge configuration having curvature angle, β=60° and skew angle, θ=45°

3.5.2 Bent modelling of the bridge models

Intermediate bents of the bridge have been modelled as three-dimensional frame elements as shown in the figure 3.9. Bents consists of two parts i.e. bent cap and the column. Different frame elements have been used to model each part. Non-prismatic frame elements have been used to model the tapered portion of the bent.

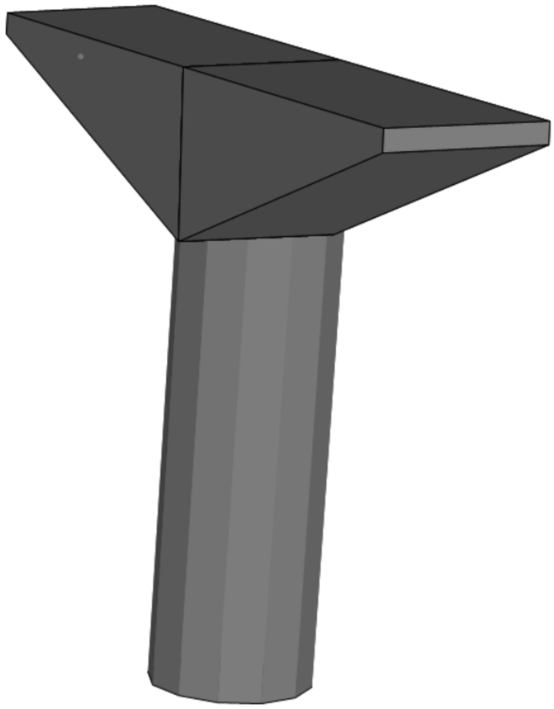


Figure 3.9 Bent of the bridge

3.5.3 Drilled Shaft modelling

Piers are supported on drilled shaft foundation. Using 3-D frame elements, the pier shafts have been modelled and flexibility of the foundation has been modelled using soil springs along the shaft. 60 feet deep drilled shaft has diameter of 8 feet and each shaft has been meshed into 16 elements as shown in figure 3.10. 15 pairs of soil springs have been used for modelling the lateral passive resistance of the foundation soil. Equivalent linear stiffness of soil springs (k_i) has been determined using the following equation;

$$k_i = k_h.D.H_i$$

Where, H_i is the tributary length of the pile

k_h is the soil modulus in kN/m^3 which can be calculated as;

$$k_h = n_h \left(\frac{z}{D}\right)$$

In this equation n_h is depth independent subgrade reaction coefficient in kN/m^3, z is the depth below ground level in *meters* and D is the diameter of pile in *meters*.

Modulus of subgrade reaction is taken as $6000kN/m^3$ for the soil. No reduction factor has been applied for the subgrade reaction, as the pile is single. Translational degree of freedom of the pier tip in vertical direction has been restrained.

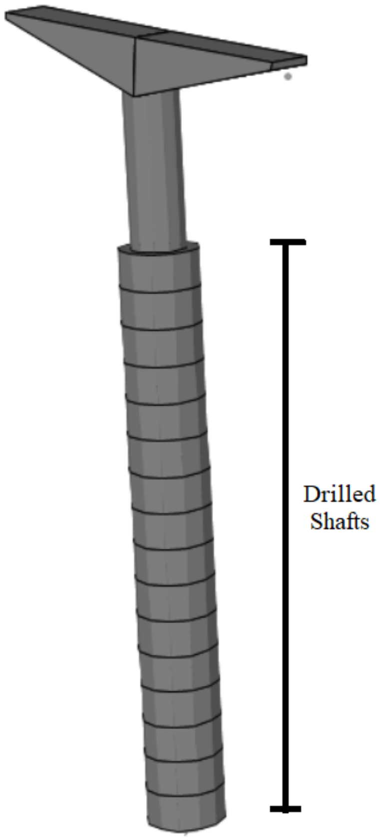


Figure 3.10 Drilled Shafts

3.5.4 Abutment Modelling of the Bridge

Diaphragm-type abutment has been provided at the abutments as shown. Lateral stiffness of the foundation soil has been modelled using 13 soil springs as shown in figure 3.11. Depth of each pile is 12m and the embedment in this case is only one foot as shown in figure 3.12.

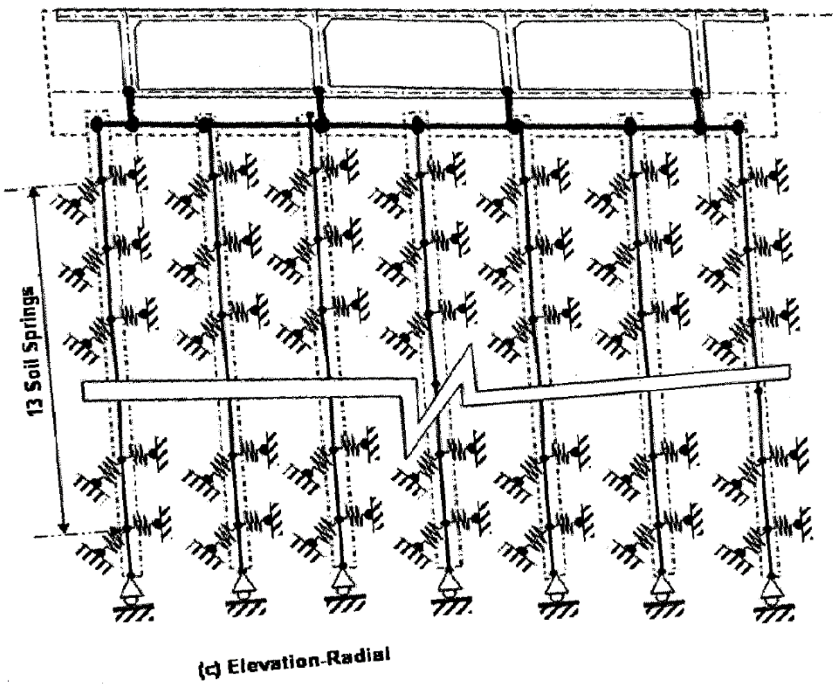


Figure 3.11 Diaphragm type abutment details [94]

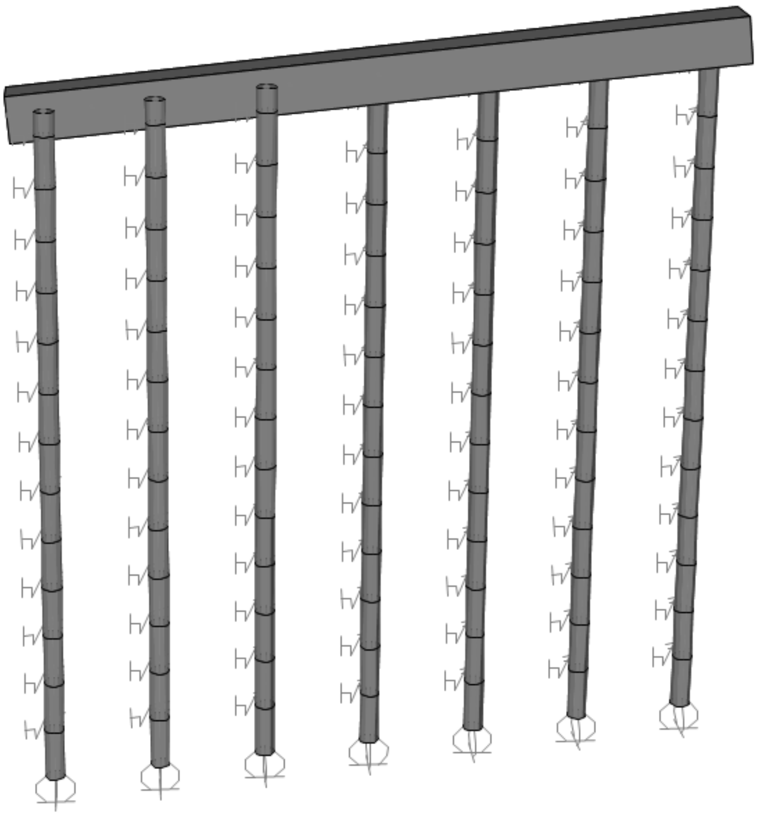


Figure 3.12 Modelling Details of 13 soil springs used for accounting the behaviour of lateral stiffness of the soil

Same soil properties of the soil have been used as that of the pier shaft. Abutment piles have been provided in group, therefore modulus of subgrade reaction of 0.7 has been used. Discrete soil spring stiffness k_i (kN/m) can be determined same as the stiffness of the pier shaft. Gap link elements (k_{gap}) have been used for modelling the behaviour of gap between abutment and the backfill as shown in figure 3.13. Stiffness of gap element (k_{gap}) and backfill element (k_{bw}) is $298000 kN/m$ and $2980 kN/m$ respectively. Stiffness of the gap will be activated only when the gap closes. To account for the response of backfill soil, multilinear plastic links (k_{bw}) have been used as shown in figure 3.13.

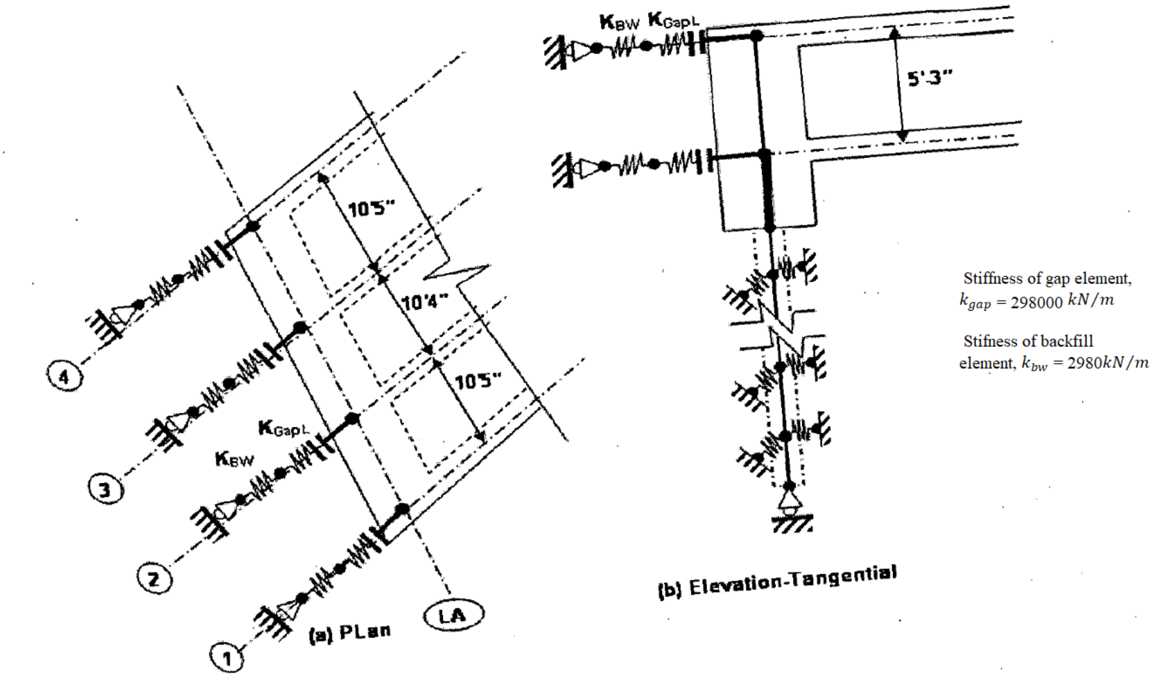


Figure 3.13 Modelling details of gap element and backfill element [94]

3.6 3-D Finite Element Models for various Bridge Configurations

3-D models have been generated by changing the degree of skewness and curvature angle of benchmark bridge, whereas the span length has been kept constant. Curvature angle has been varied as 0°, 30°, 60° and 120°. For each curvature angle skew angle has been varied as 0°, 15°, 30°, 45° and 60°. Total 20 number of bridge configurations has been modelled. Figure 3.14 shows the various bridge configurations that has been taken for this study.

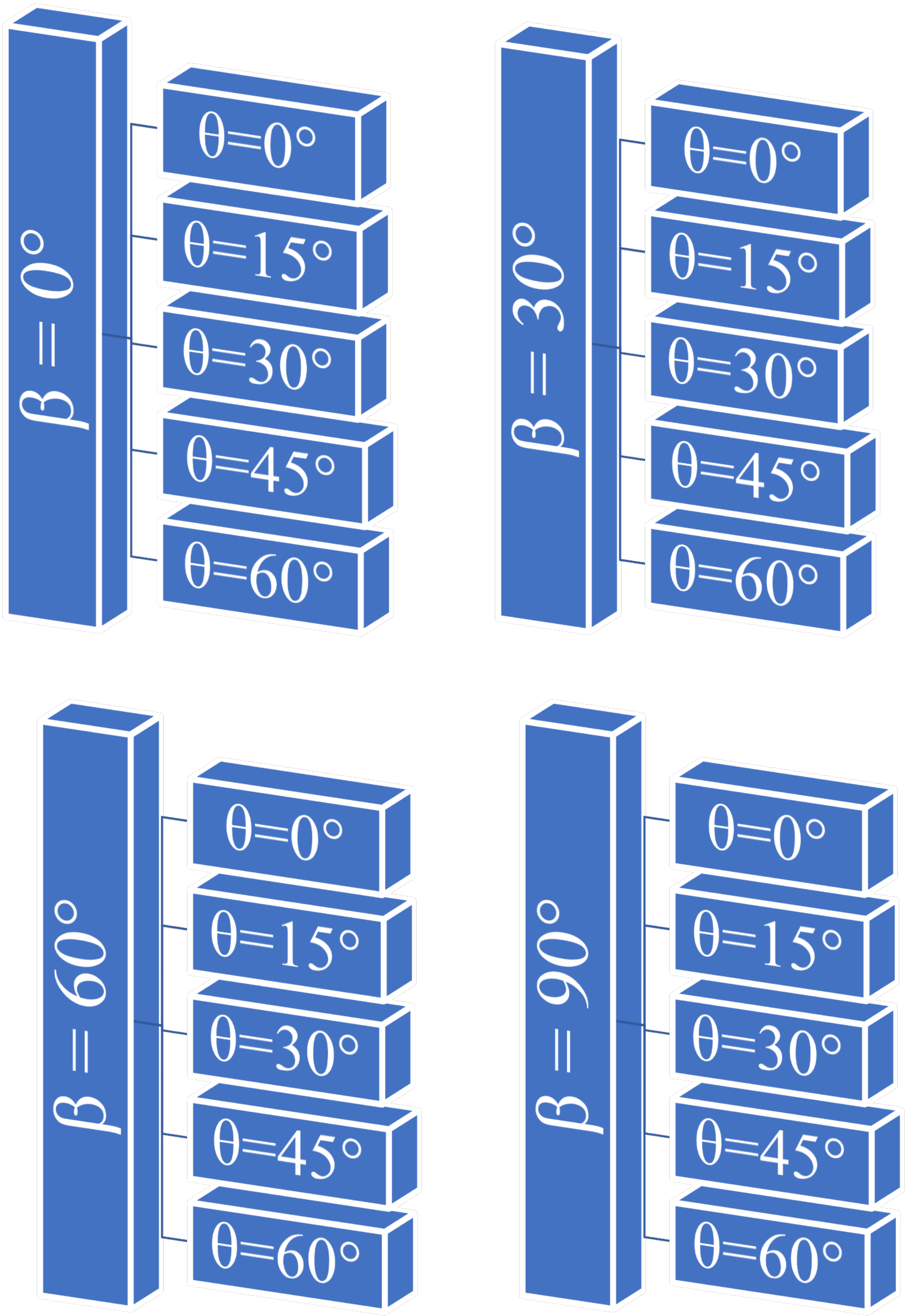


Figure 3.14 Detail of Skew-Curved Geometries

3-D models have been generated in CSi Bridge which are shown in this section. Figure 3.15 shows the 3-D model of the bridge having curvature angle (β) of 0° and skew angle (θ) of 0° i.e. a straight bridge configuration. Figure 3.16 shows the variation of skew angles for the bridge having curvature angle of 0°. Curvature angle of 0° signifies that the bridge deck is having no curvature, whereas skew angle of 0° indicates the case of no skewness.

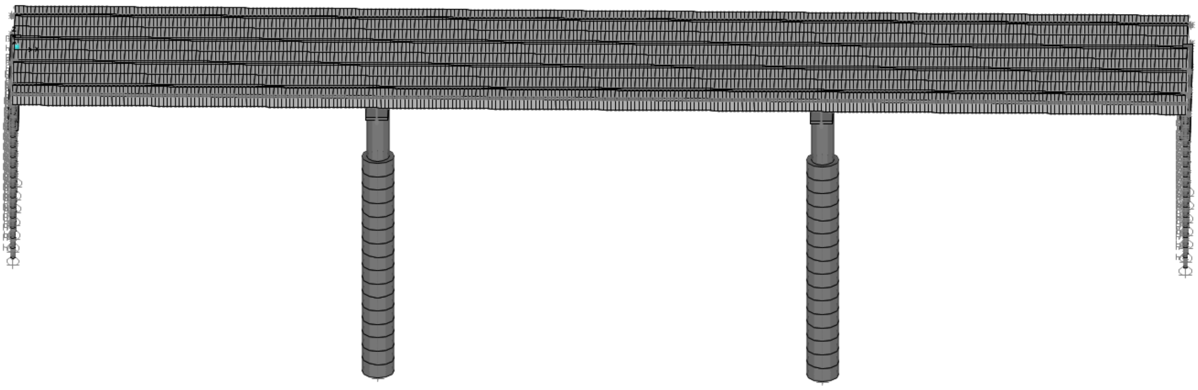
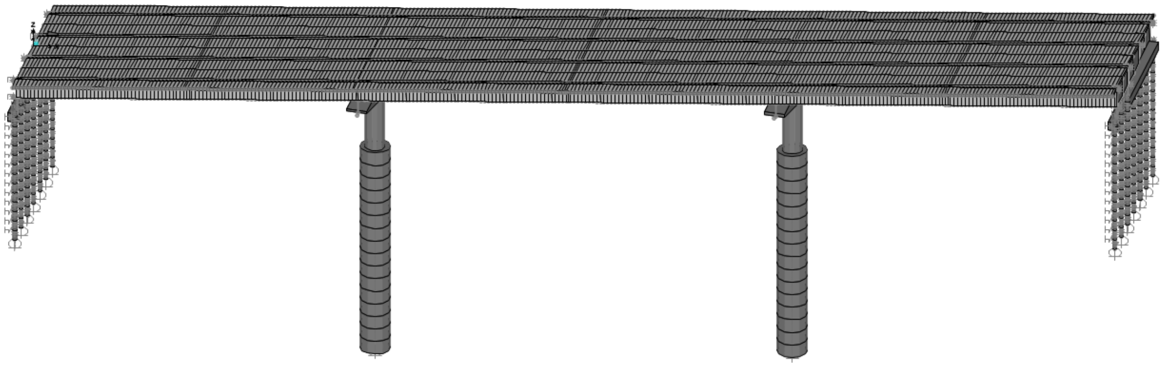
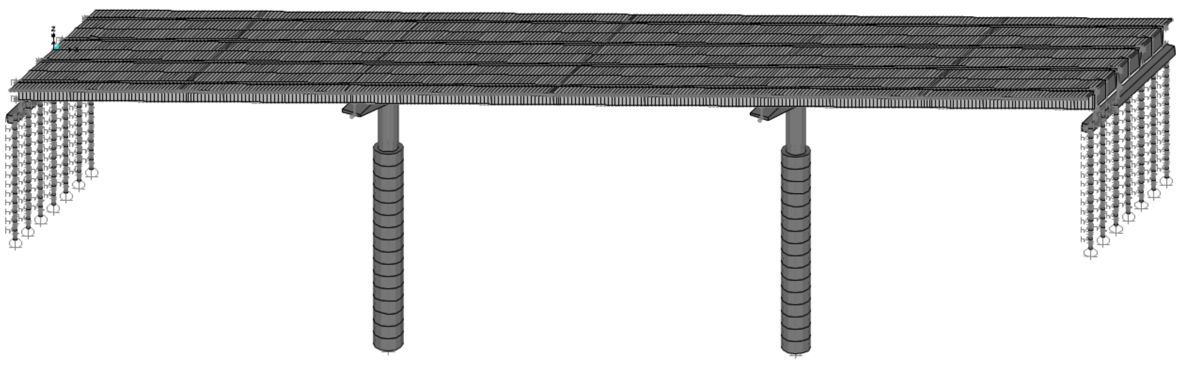


Figure 3.15 3-D model of bridge for configuration of β=0° and θ=0° i.e. a straight bridge configuration



β=0° and θ=15°



β=0° and θ=30°

β=0° and θ=45°

β=0° and θ=60°

Figure 3.16 3-D Bridge models for the configuration of β=0° with varying skew angles (θ)

3-D bridge model for the configuration of β=30° and θ=0° is shown in the figure 3.17 and bridge models with variation of the skew angle (θ) for curvature angle (β) of 30° is given away in the figure 3.18.

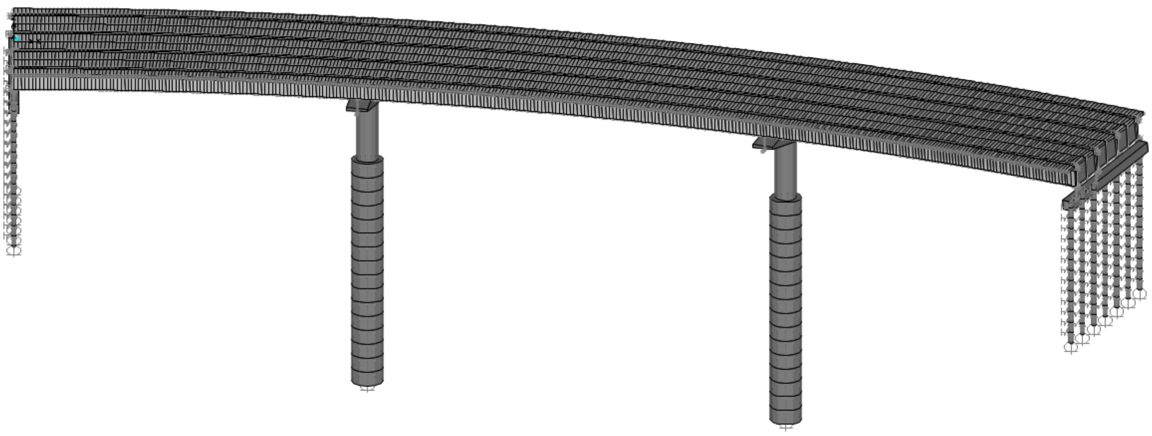
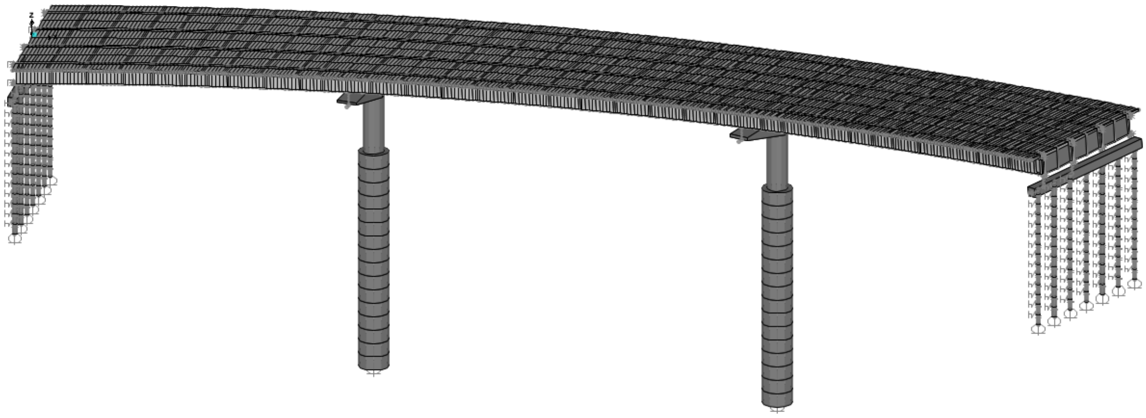


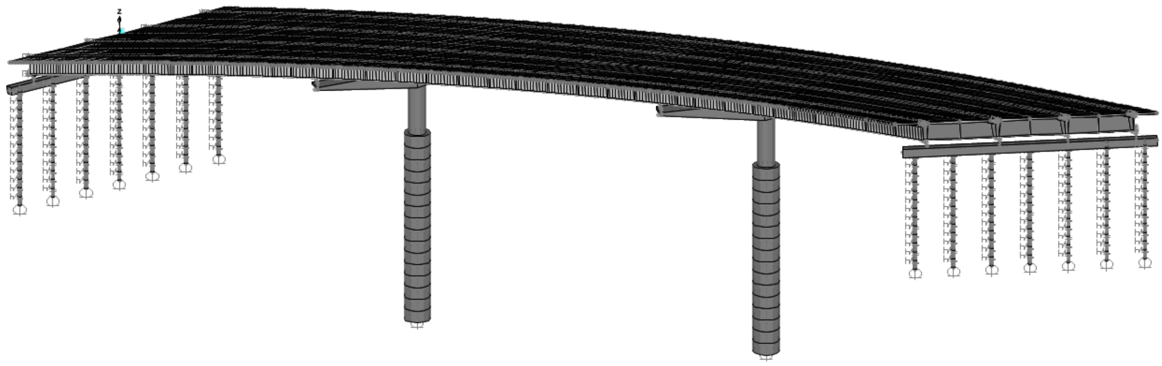
Figure 3.17 3-D model of bridge for configuration of β=30° and θ=0°



β=30° and θ=15°

β=30° and θ=30°

β=30° and θ=45°



β=30° and θ=60°

Figure 3.18 3-D Bridge models for the configuration of β=30° with varying skew angles (θ)

3-D bridge model for the configuration of β=60° and θ=0° is shown in the figure 3.19. Figure 3.20 shows bridge models with variation of the skew angle (θ) for curvature angle (β) of 60°.

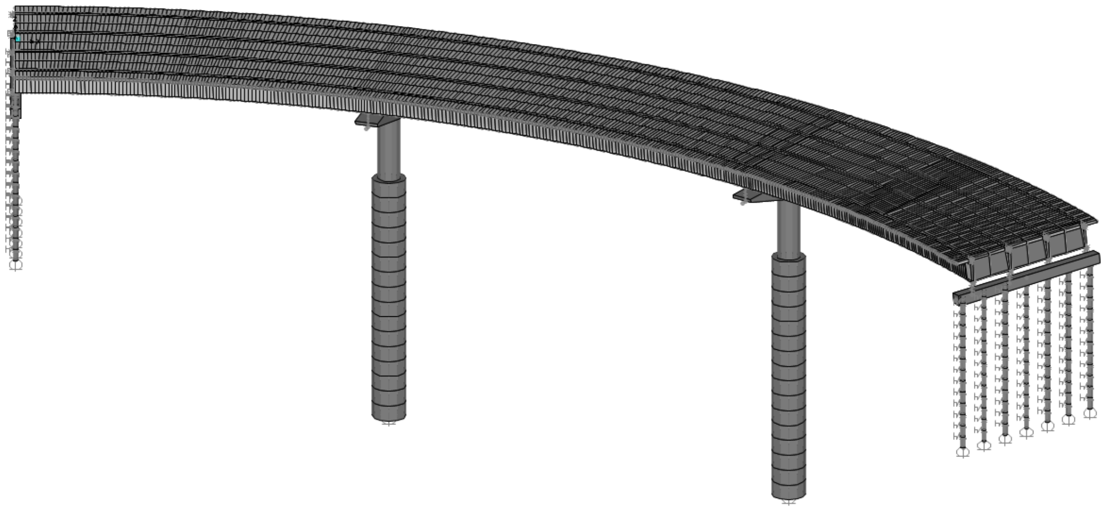
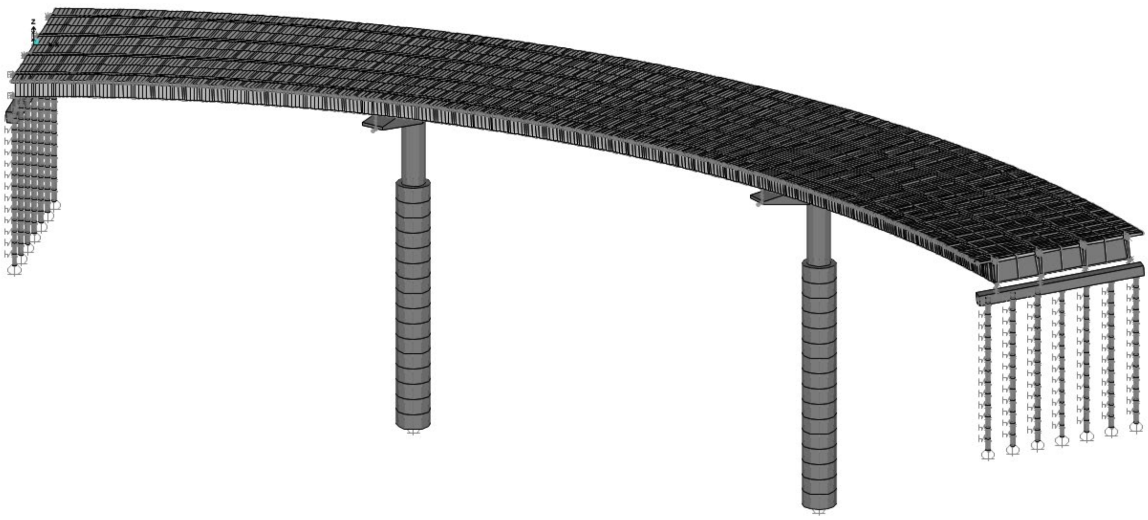
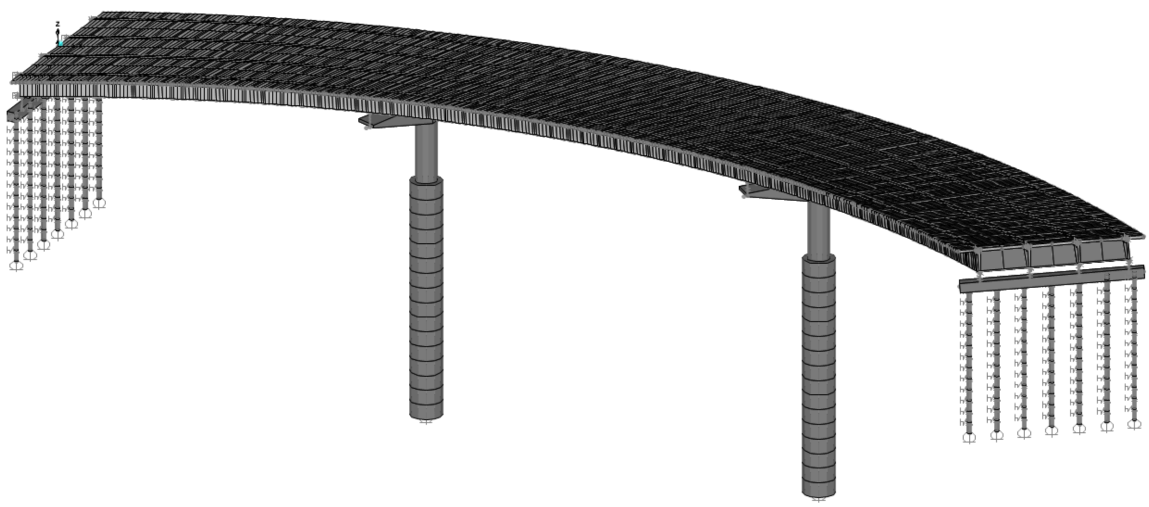


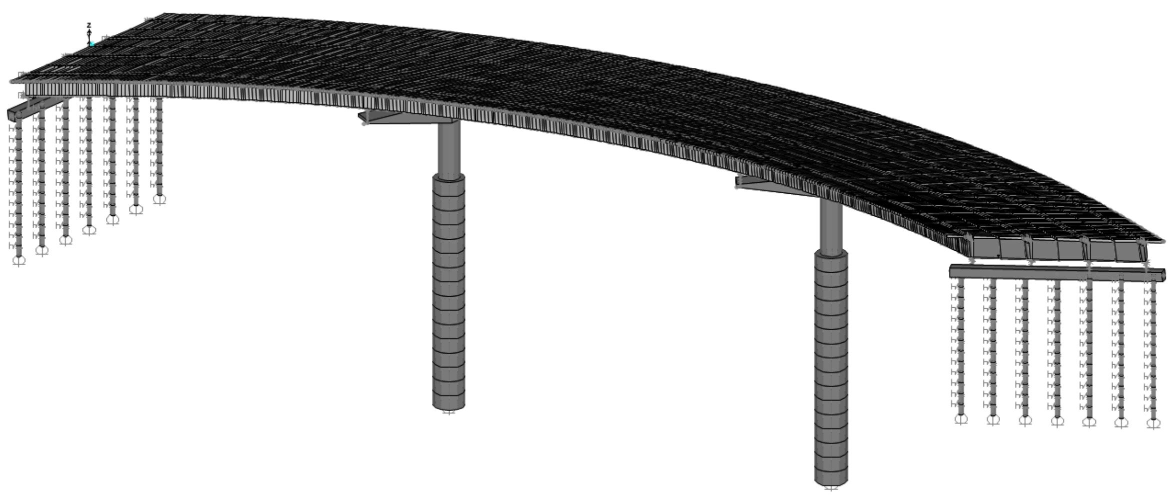
Figure 3.19 3-D model of bridge for configuration of β=60° and θ=0°



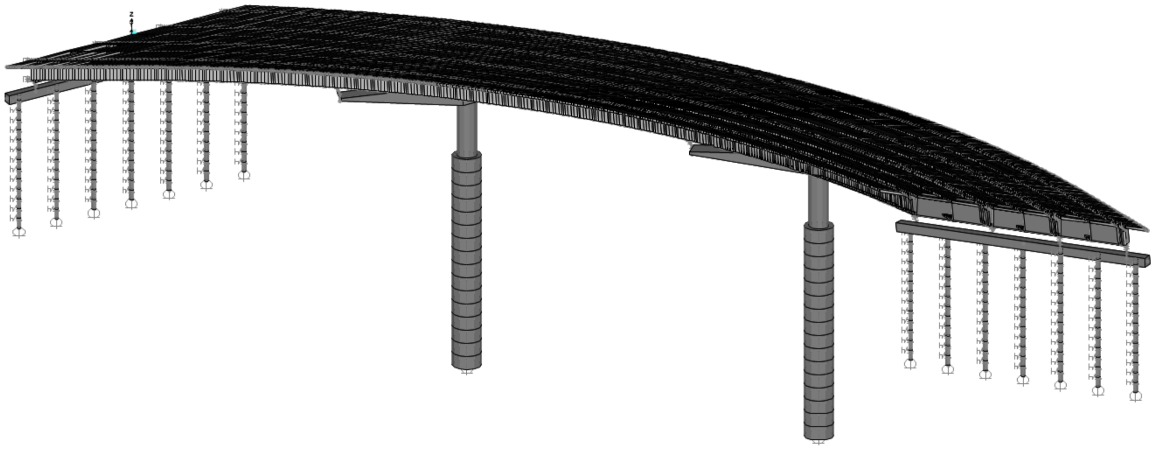
β=60° and θ=15°



β=60° and θ=30°



β=60° and θ=45°

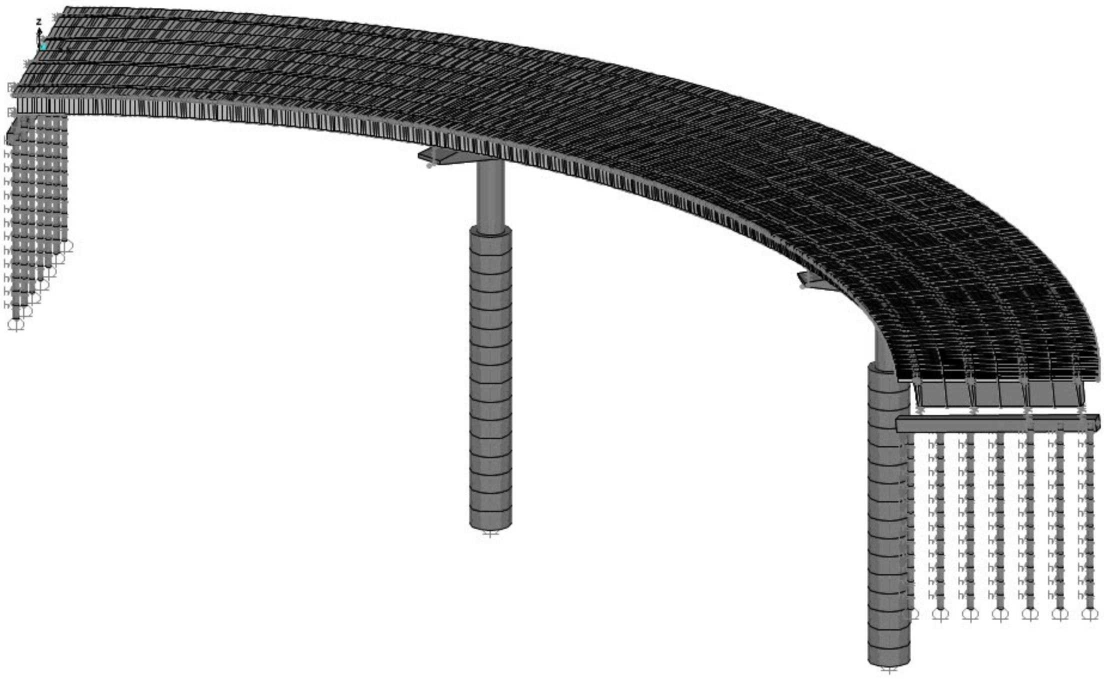


β=60° and θ=60°

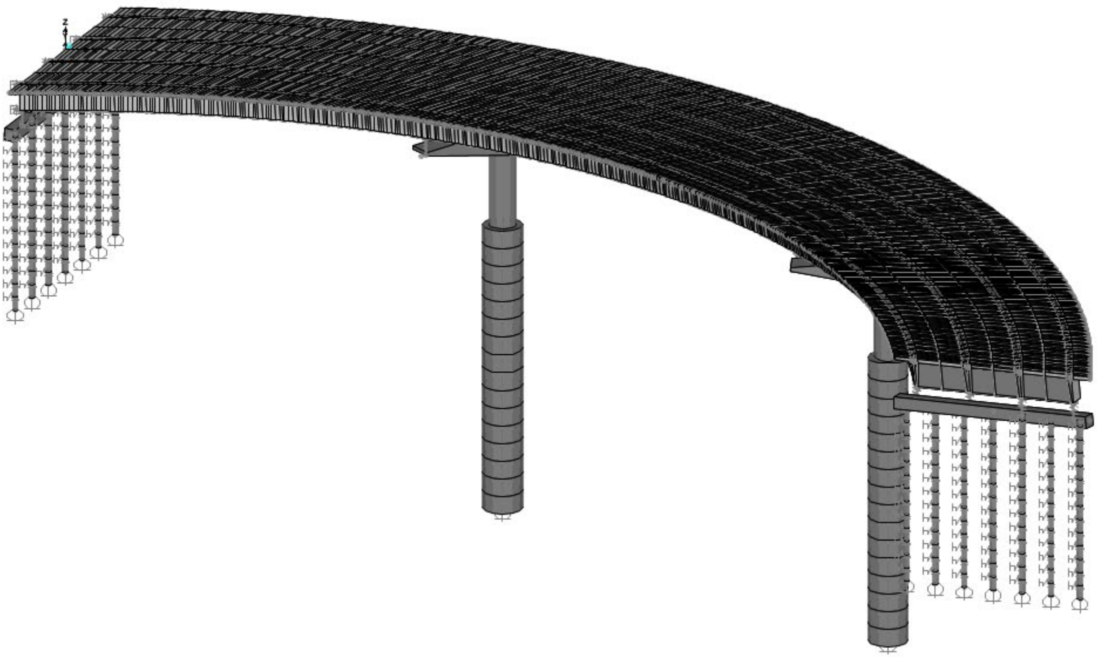
Figure 3.20 3-D Bridge models for the configuration of β=60° with varying skew angles (θ)

3-D bridge model for the configuration of β=90° and θ=0° is shown in the figure 3.21. Figure 3.22 shows bridge models with variation of the skew angle (θ) for curvature angle (β) of 90°.

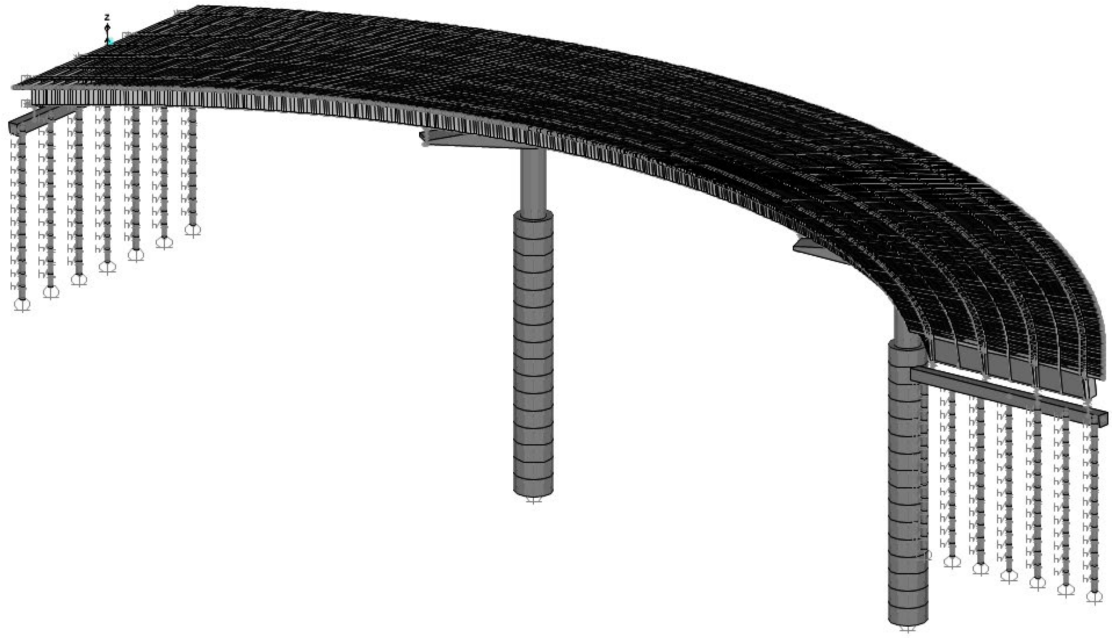
Figure 3.21 3-D model of bridge for configuration of β=90° and θ=0°



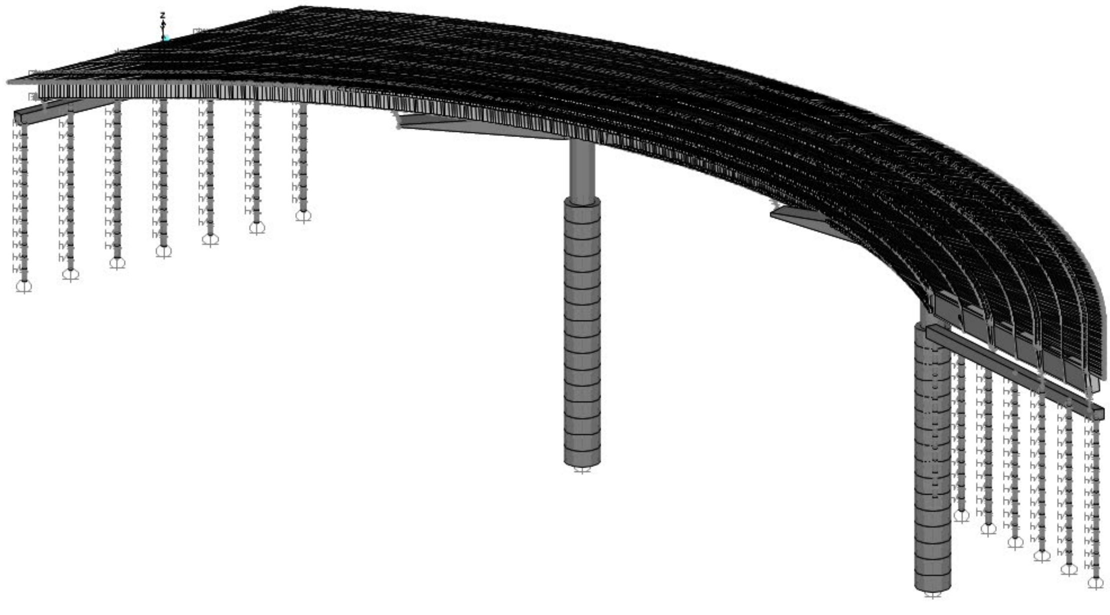
β=90° and θ=15°



β=90° and θ=30°



β=90° and θ=45°



β=90° and θ=60°

Figure 3.22 3-D Bridge models for the configuration of β=90° with varying skew angles (θ)

CHAPTER 4
MODAL ANALYSIS

4.1 Modal Analysis

Modal behaviour of the structure is expressed in terms of mass participation factors, mode shapes, natural frequencies, time periods etc. To calculate the aforementioned factors, it is essential to perform the modal analysis. As modal analysis is analysis of the structure under action of free vibrations, it is also known as free vibration analysis.

Modal behaviour of each bridge model has been studied by performing the modal analysis. After the removal of the loads such as live load, moving vehicular load etc. the bridge structures accomplish free vibrations. It is necessary to know the natural frequency of these vibrations, as if the natural frequency of the structure matches the frequency of forced vibrations then the resonance may occur which can cause destruction. Resonance is the phenomenon of amplification which occurs when frequency of periodically applied force is in harmonic proportion to natural frequency of the structure.

In this chapter, the modal behaviour of the bridges having combined skewness and curvature has been explained in brief.

4.2 Parameters of modal analysis

To explain the modal behaviour of the bridge models, the various parameters such as mode shapes, natural frequencies, time period and mass participation factor has been studied by performing modal analysis.

4.2.1 Mode Shapes

When subjected to a vibration, the structure can take different shapes and this shape during the different modes are called mode shape and each mode shape have their corresponding natural frequency and time period. Generally, mode shape is the shape at which free vibration occurs. The response at those corresponding frequencies depends upon the damping characteristics of the components. The vibrational modes of the bridge models have been categorized as;

a) Vertical vibrational modes: Modes in which either out of plane deformation or torsional deformation in the longitudinal direction has been observed are categorized under this category.

These vibrational modes are termed as out of plane bending modes and longitudinal torsional modes.

b) Horizontal vibrational modes: Horizontal vibrational modes have been further classified as;

i) in-plane vibrational modes i.e. the modes in which in-plane (perpendicular to longitudinal axis) movement of the deck has been observed and

ii) longitudinal vibrational modes i.e. the modes in which the movement of bridge deck has been observed along its longitudinal axis.

4.2.2 Time Period and Natural Frequency

Frequency can be defined as the number of times an event happens per unit of time. Natural frequency of the structure can be defined as that frequency of the structure at which structure oscillates under the influence of free vibrations. Natural frequency can also be defined as the rate at which an object vibrates when subjected to free vibration and this vibrating structure may have single or multiple natural frequencies. Natural frequency of the structure is different from forced frequencies (i.e. frequency of the structure when it is subjected to forced vibrations) of the structure.

Natural frequency can be expressed as;

$$f = \frac{\omega}{2\pi}$$

Where, ω is the angular frequency and is given by;

$$\omega = \sqrt{\frac{k}{m}}$$

In the above equation k is the stiffness, and m is the mass.

Time taken to complete one complete cycle of vibration is known as time period. Time period is inversely proportional to the natural frequency that can be expressed mathematically as:

$$T = \frac{1}{f}$$

4.2.3 Modal Participation Factor and Mass Participation Factor

Modal participation factors are the scalars that measure the interaction between modes and directional excitation for a particular reference frame. Larger value of modal participation factor specifies a stronger contribution to the structure's dynamic response.

Mass participation factor signifies the percentage of the structure's mass that will contribute in specific mode. Modes with greater mass participation are most likely to get excited whereas the modes having lower mass participation will not be more significant. Total number of modes that are needed to be extracted can be determined on the basis of mass participation factor. 90% of the effective mass is a good number.

4.3 Validation of Modal Analysis Results

Modal analysis has been carried out for the various bridge configurations having different angles of skewness and curvature. In this study, the bridge configurations with curvature angle varying in the range between 0° to 90° and with skew angles of 0° to 60° has been taken. 3-D models of these bridge configurations have been generated in CSi Bridge. Results of the modal analysis has been validated with the results of the source thesis [94]. Table 4.1 shows comparison of time periods obtained in present analysis and the time periods obtained in the source thesis for bridge configuration having curvature angle (β) of 0° and skew angle (θ) of 0° i.e. a straight bridge configuration. Similarly, table 4.2 shows the comparison of time periods for bridge configuration having curvature angle (β) of 90° and skew angle (θ) of 0°.

Table 4.1. Comparison of the Time Periods of first In-Plane, Longitudinal and Out of Plane Mode from present analysis with standard results of [94] for bridge configuration having β=0° and θ=0°

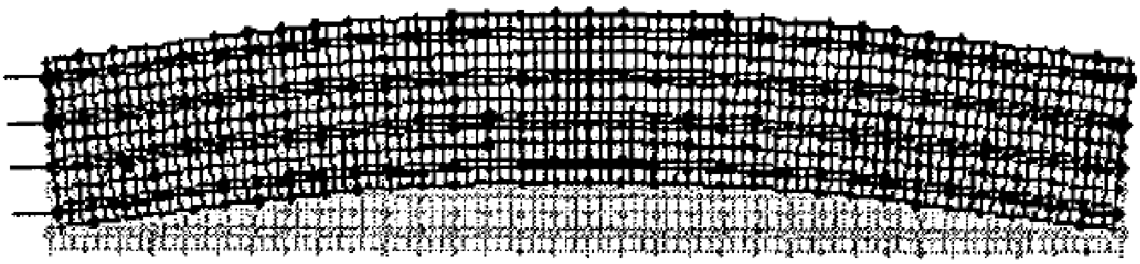
Mode	**Time Period in Present Analysis** (seconds)	**Time Period in [94]** (seconds)	**Difference** (in percentage)
1st In-Plane Mode	0.499	0.517	-3.48
1st Longitudinal Mode	0.322	0.319	0.99
1st Out of Plane Mode	0.254	0.259	-1.65

Table 4.2. Comparison of the Time Periods of first In-Plane, Longitudinal and Out of Plane Mode from present analysis with standard results of [94] for bridge configuration having β=90° and θ=0°

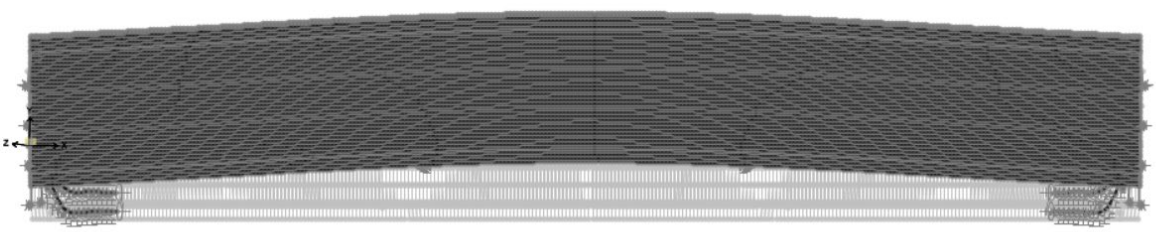
Mode	**Time Period in Present Analysis** (seconds)	**Time Period in [94]** (seconds)	**Difference** (in percentage)
1st In-Plane Mode	0.41	0.428	-4.20
1st Longitudinal Mode	0.339	0.356	-4.77
1st Out of Plane Mode	0.271	0.277	-2.16

Excellent coherence of the mode shapes described in the thesis [94] and the mode shapes obtained in the present modal analysis for aforementioned bridge configurations is shown in figure 4.1 and figure 4.2. Comparison of first in-plane, first longitudinal, and first out of plane mode shape is shown in figure 4.1(a), 4.1(b), and 4.1(c) respectively for straight bridge configuration. Similarly, comparison of these above-mentioned mode shapes for bridge configuration with β=90° and θ=0° is shown in figure 4.2(a), 4.2(b) and 4.2(c).

Comparison of mode shapes for bridge having curvature angle (β) of 0° and skew angle (θ)of 0° i.e. straight bridge configuration

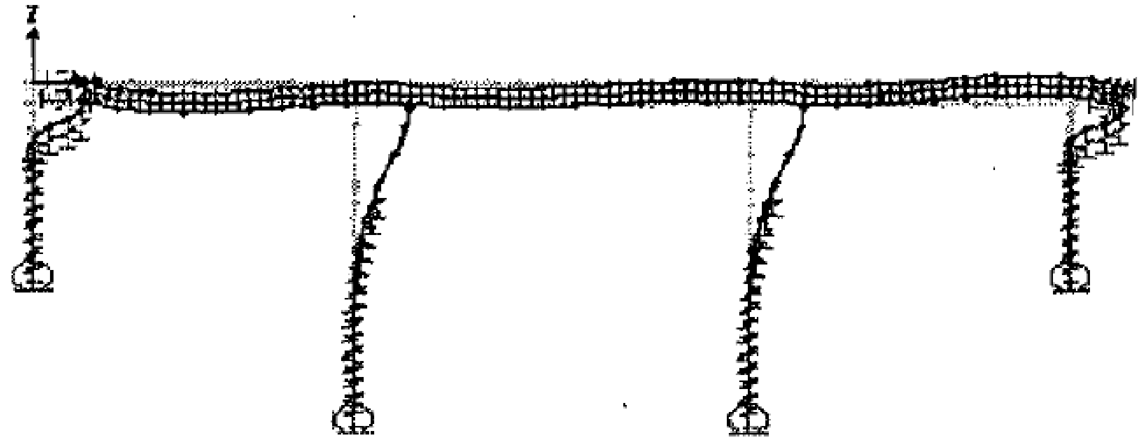


1st in-plane mode shape in [94]

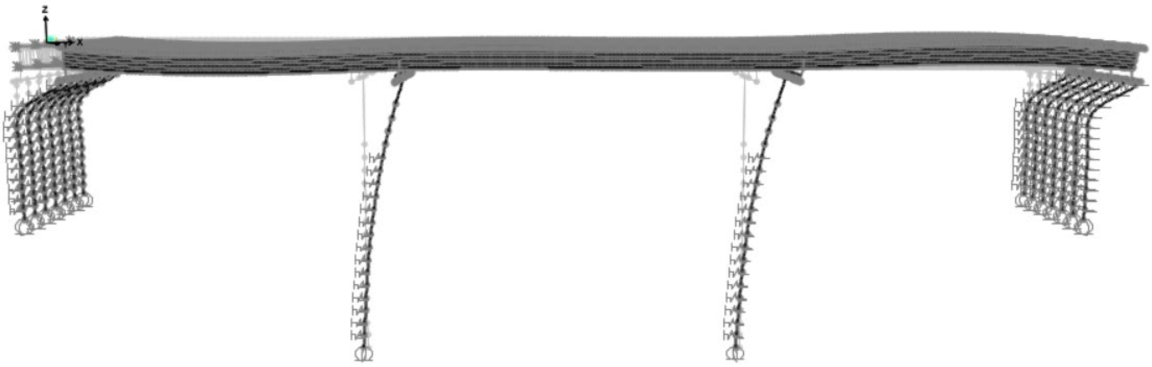


1st in-plane mode shape in present analysis

a) Comparison of first in-plane mode shape for β=0° and θ=0°

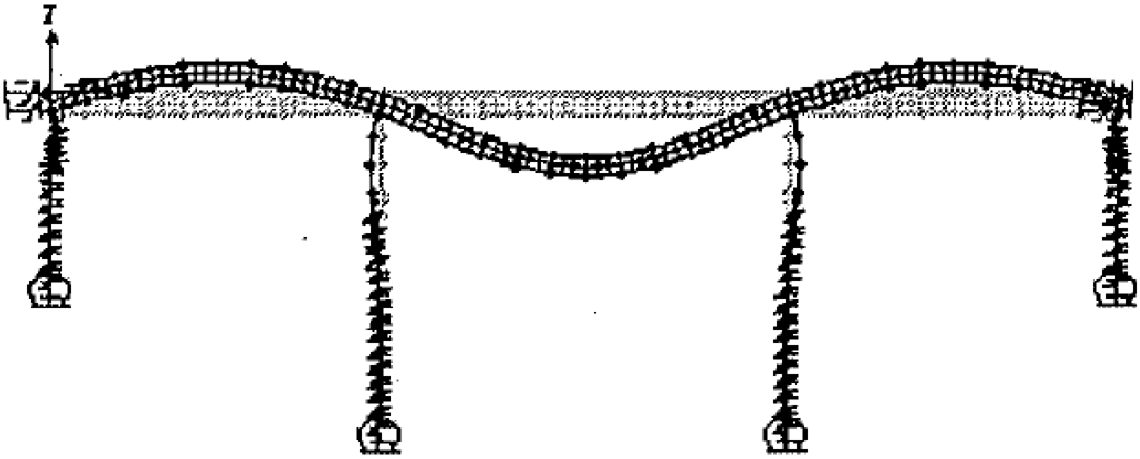


1st longitudinal mode shape in [94]

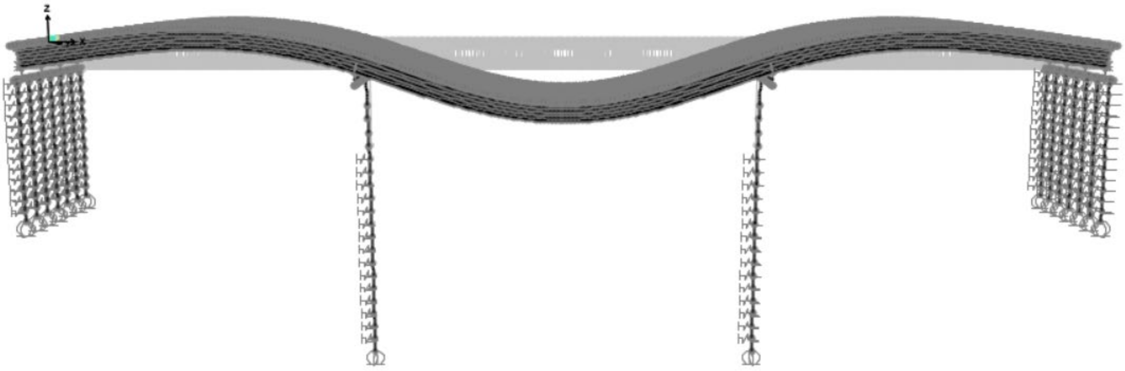


1st longitudinal mode shape in present analysis

b) Comparison of first longitudinal mode shape for β=0° and θ=0°



1st out-of-plane mode shape in [94]

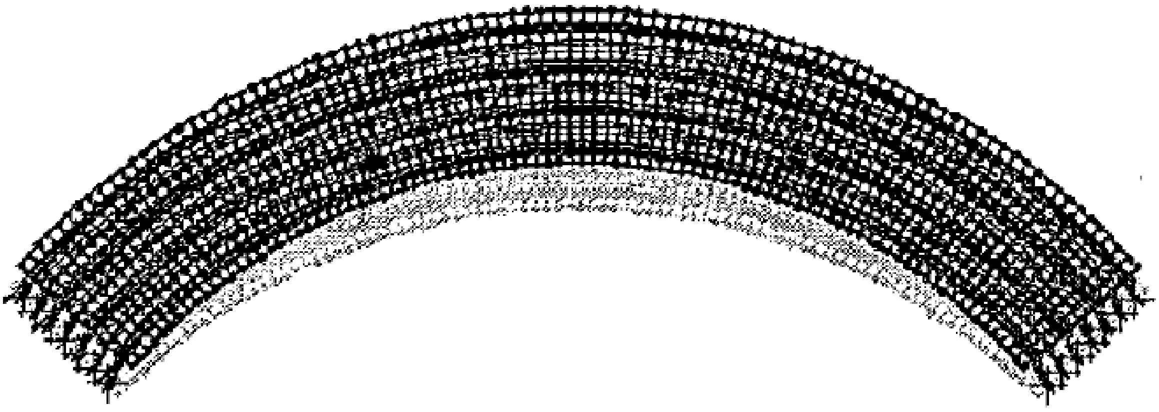


1st out-of-plane mode shape in present analysis

c) Comparison of first out-of-plane mode shape for β=0° and θ=0°

Figure 4.1 Comparison of first in-plane, first longitudinal and first out-of-plane mode shape for bridge configuration with curvature angle, β=0° and skew angle, θ=0°

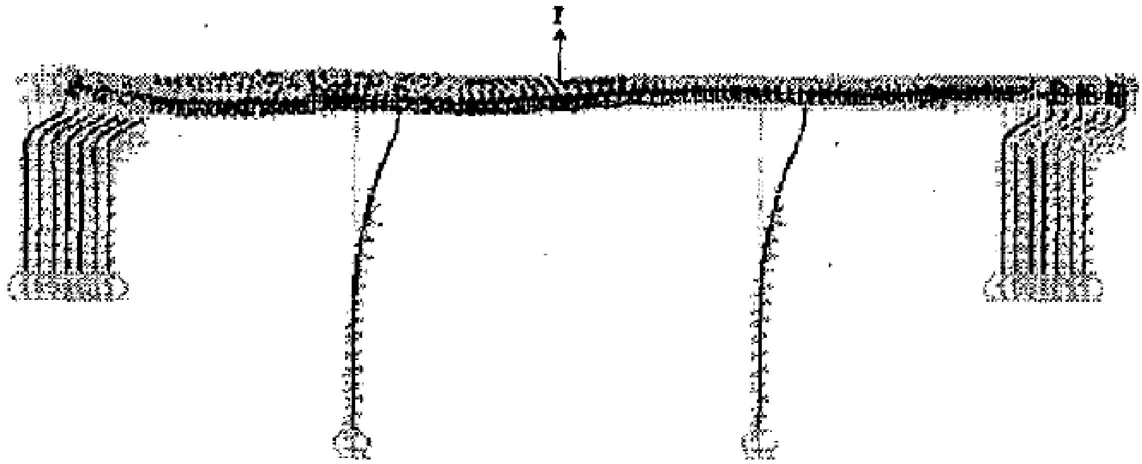
Comparison of mode shapes for bridge having curvature angle (β) of 90° and skew angle (θ)of 0°



1st in-plane mode shape in [94]

1st in-plane mode shape in present analysis

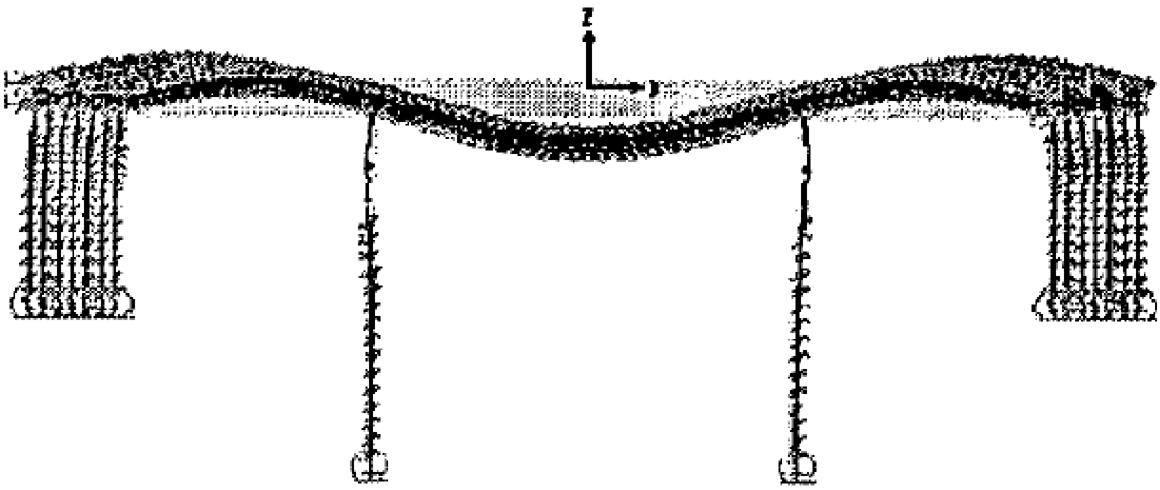
a) Comparison of first in-plane mode shape for β=90° and θ=0°



1st longitudinal mode shape in [94]

1st longitudinal mode shape in present analysis

b) Comparison of first longitudinal mode shape for β=90° and θ=0°



1st out-of-plane mode shape in [94]

1st out-of-plane mode shape in present analysis

c) Comparison of first out-of-plane mode shape for β=0° and θ=0°

Figure 4.2 Comparison of first in-plane, first longitudinal and first out-of-plane mode shape for bridge configuration with curvature angle, β=90° and skew angle, θ=0°

4.4 Modal Behaviour of Skew-Curve Bridges

This study investigates the influence of combined skewness and curvature on modal behaviour of three-span reinforced concrete box-girder bridge. Modal behaviour of the bridges with such configuration has been explained on the basis of parameters such as; natural frequency, time period, mass participation factor and mode shape.

4.4.1 Effect of combined Skewness and Curvature on Time Period

From past studies, observation has been made that skewness as well as curvature affects the natural time period of a bridge. This study attempts to analyze the influence of combined curvature and skewness on modal behavior of three span RC box-girder bridge. Ratio of time periods of horizontal and vertical vibrational modes for all bridge configurations with respect to the time periods of straight bridge have been presented. Results shows that highest value of time period has been occurred for in-plane vibration mode, closely followed by longitudinal and out of plane vibration modes in all bridge configurations.

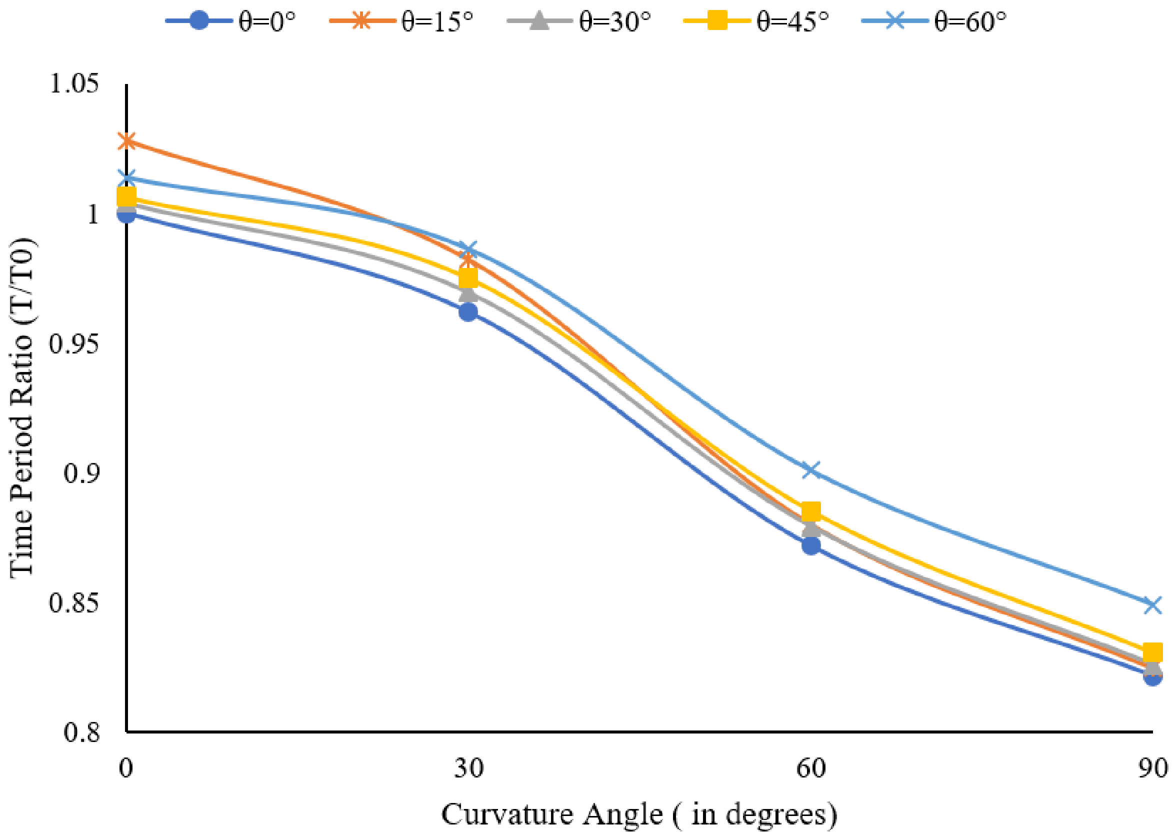


Figure 4.3. Time Periods Ratio of 1st In-Plane mode for various bridge configurations

Figure 4.3 shows the ratios of the time periods of first in-plane vibration mode with respect to the time period of the straight bridge for the same mode. In general, time period of first in-plane mode decreases with increase in curvature angle because of decrease in flexibility of the bridge-deck for in-plane bending due to arching action which increases with increase in curvature. As the curvature angle changes from 0° to 90°, maximum percentage difference of -17.84% (decrease) has been observed in time period ratios for bridges having no skewness. However, increase in skew angle from 0° to 60° causes the increase in time period ratios for first in-plane mode usually, as shown in Figure 4.3. Maximum percentage difference of 1.2% (increase) has been noticed in time period ratios with increase in skew angle from 0° to 60° for bridges having no curvature. Hence, the least time period ratio has been noticed for the bridge with curvature angle of 90° and skew angle of 0°. In case of skew-curved bridges, time period has been noticed to decrease with increase in deck-curvature for a particular skew angle. Thus, a conclusion can be made that introducing skewness in horizontally curved bridges will increase the time period of the bridge structure.

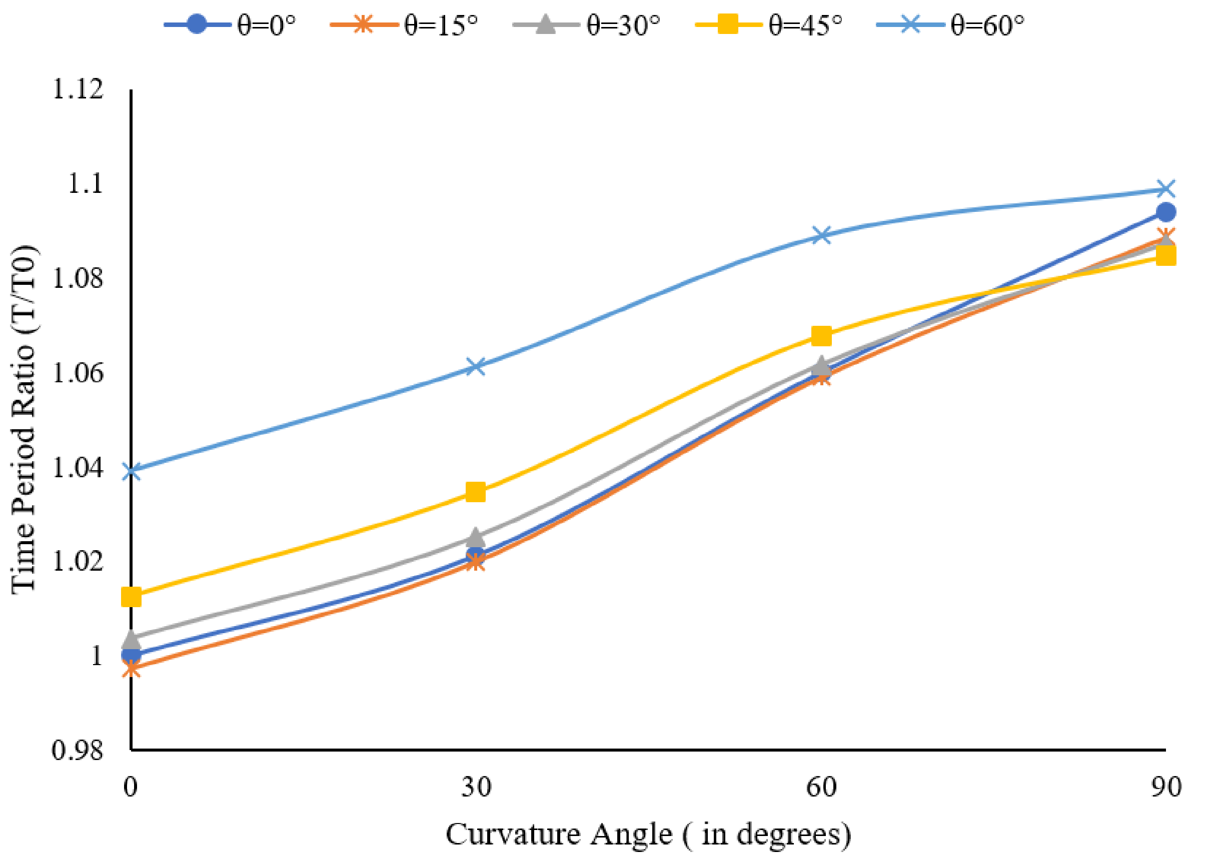


Figure 4.4. Time Periods Ratio of 1st Longitudinal mode for various bridge configurations

Figure 4.4 shows the time periods ratios for first longitudinal mode with respect to the time period of straight bridge for the same mode. Usually, time period ratios of this mode have been observed to increase with increase in skewness and curvature. The maximum difference of 9.9% has been noticed between the time periods ratios for the straight bridge and bridge having curvature angle of 90° and skew angle of 60°. However, skew angle has minor role in controlling the longitudinal time period for highly curved bridges.

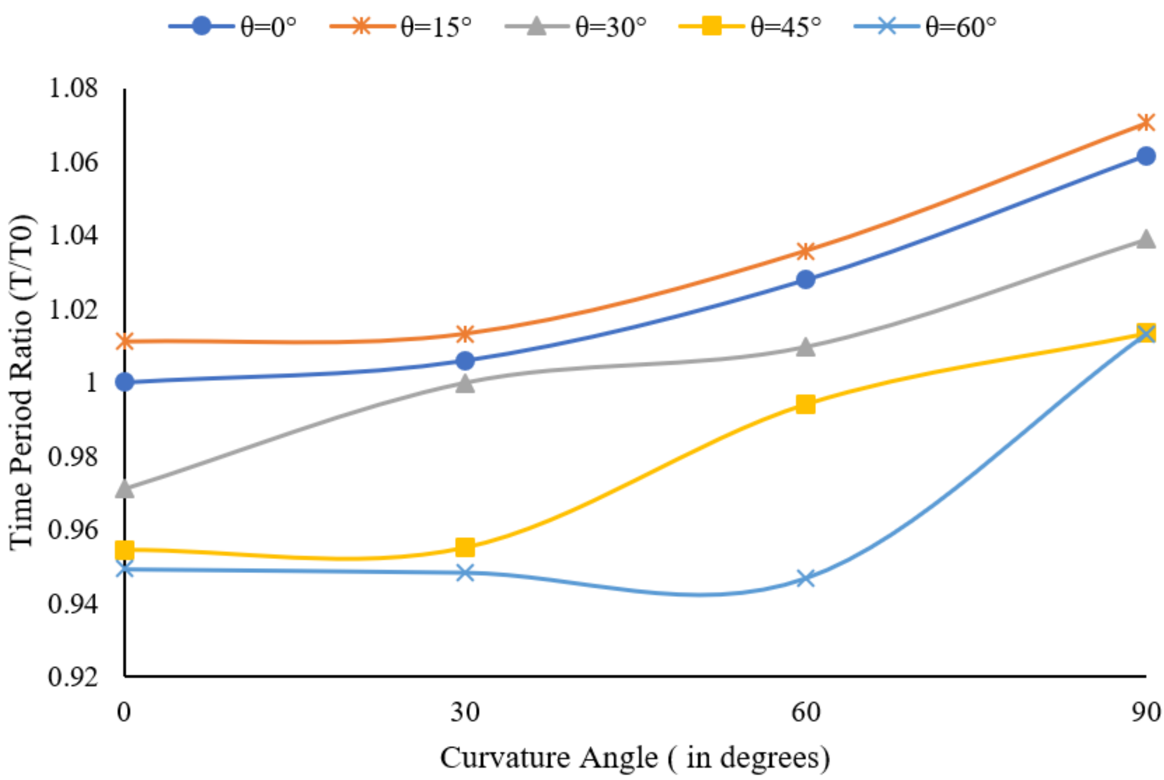


Figure 4.5. Time Periods Ratio of 1st Out of Plane mode for various bridge configurations

For any particular skew angle, with increase in curvature angle, time period ratios have been found to increase whereas noticed to decrease with increase in skew angle (Figure 4.5). Generally, it has been observed that time period for out of plane vibration lags behind the first mode of in-plane and longitudinal vibrations, however for skew-curve bridges as geometry becomes complex, in few cases time period of second in-plane mode also preceded first out of plane mode.

4.4.2 Effect of mode participation factor on Skew-Curved bridges

Mode participation factor shows that how strongly a particular mode will affect the dynamic behavior of the structure. Mode participation factors of the first in-plane, first longitudinal and third out of plane vibration mode have been discussed in this section. First and second out of plane vibration modes have very less values of mode participation factor which indicates that these modes are not affecting strongly in overall behavior of the structure, whereas the mode participation factor of third out of plane has been noticed to affect the dynamic behavior of the bridges significantly. Therefore, results of mode participation factor of third out of plane vibration modes have been discussed instead of first and second out of plane vibration modes.

Variations of the mode participation factor with change in configuration of the bridges is shown in Figure 4.6, 4.7 and 4.8.

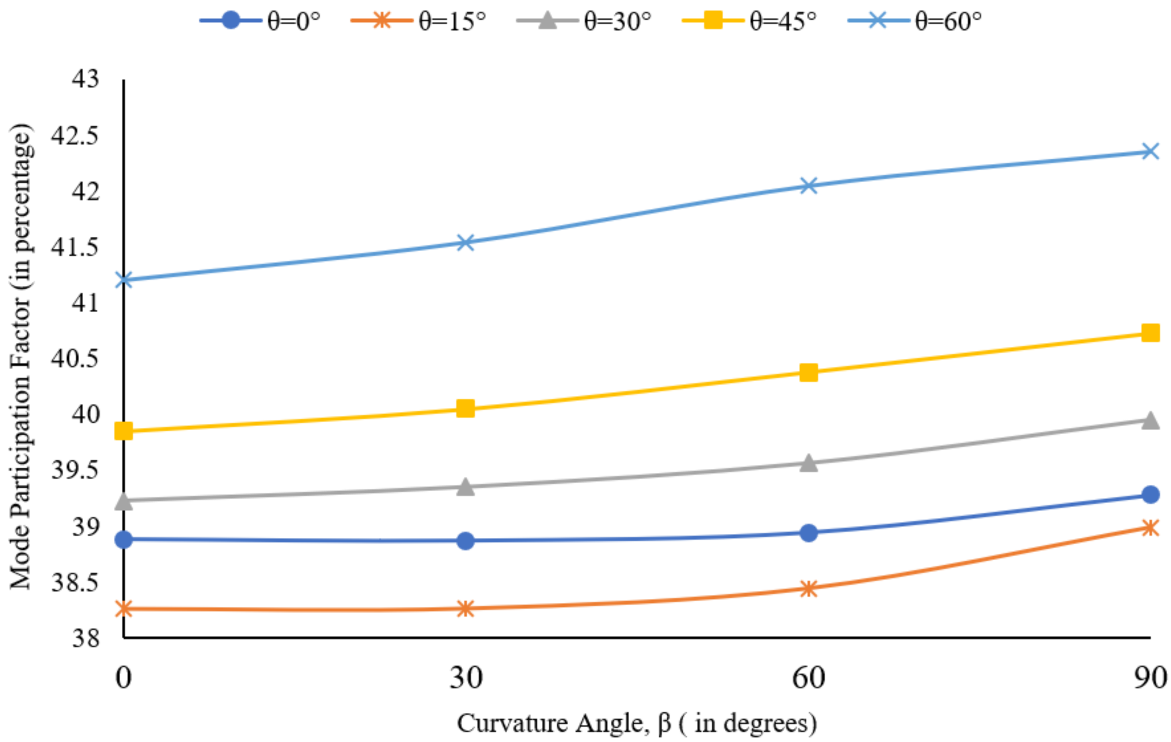


Figure 4.6. Mode Participation Factor of first In-Plane Mode for various bridge configurations

Mode participation factor of the first in-plane vibration mode is about 38% for straight bridge configuration which generally increases with increase in skew and curvature angle as shown in Figure 4.6. Maximum contribution of in-plane vibration mode is 42.35% which have occurred for the bridge model with combination of curvature angle of 90° with 60° skew angle. Hence, with increase in skewness and curvature, the first in-plane mode will significantly influence the structure's dynamic behavior, as compared to straight bridge.

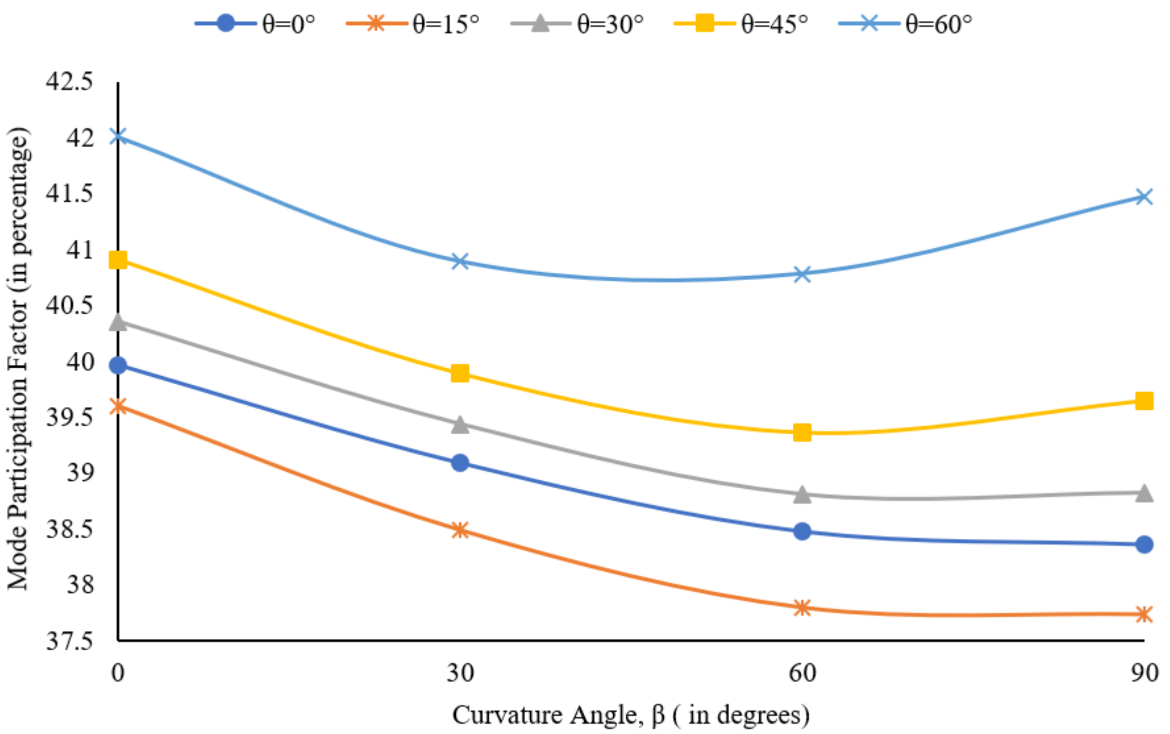


Figure 4.7. Mode Participation Factor of first Longitudinal Mode for various bridge configurations

Figure 4.7 shows the mode participation factors of the first longitudinal mode for different bridge configurations. In case of straight bridge, mode participation factor is 39.97%. Usually, the mode participation factors have been noticed to decrease with increase in curvature angle, whereas it has been observed to increase with increase in skew angle for this vibration mode. This means that as the curvature increases, the first longitudinal mode will not significantly influence structure's dynamic behavior as compared to the case of straight bridge. The least mode participation factor has been observed for the bridge configuration with curvature angle of 90° and skew angle of 15°.

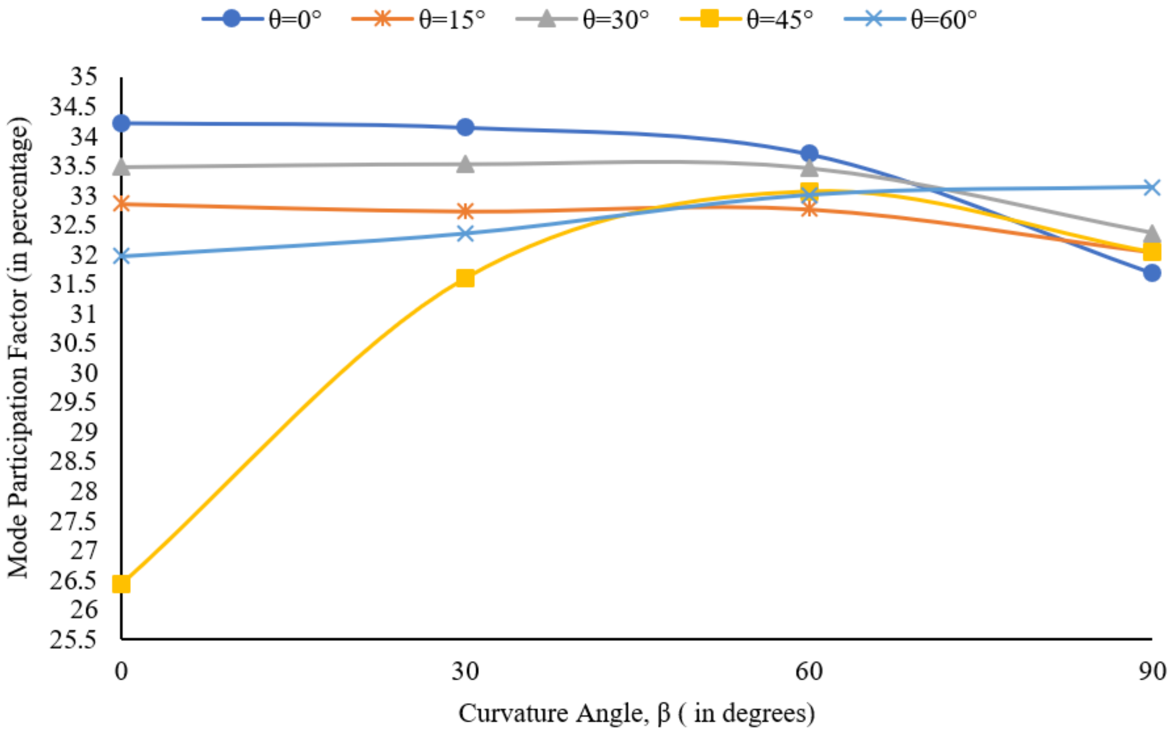
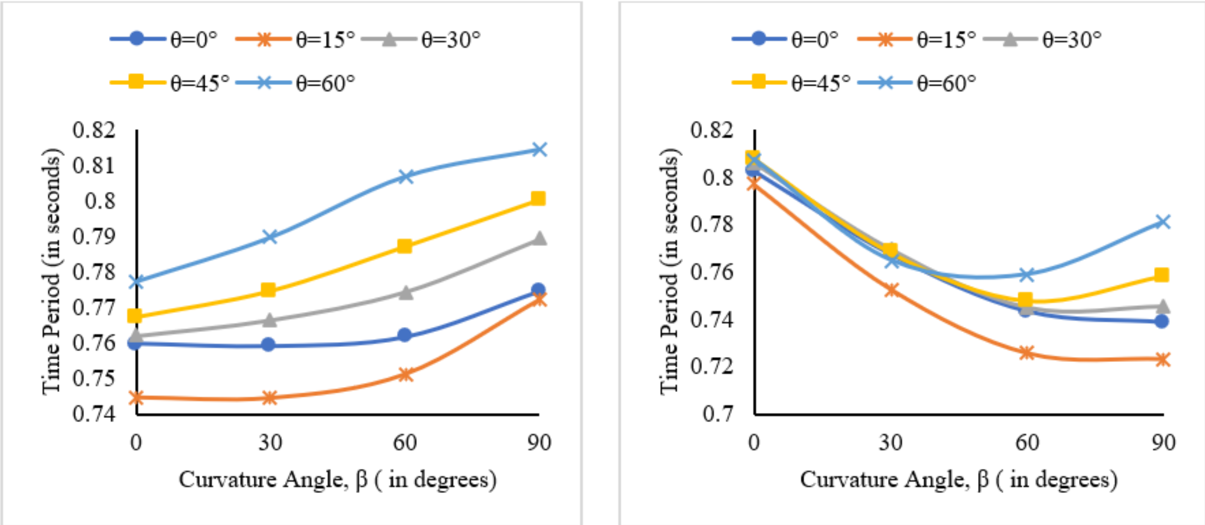


Figure 4.8. Mode Participation Factor of third Out of Plane Mode for various bridge configurations

First and second out of plane vibration modes have very less value of mode participation factor which shows that these vibration modes have very less contribution in affecting the dynamic behavior of the bridge structures. However, the third out of plane vibration mode has been found to participate significantly in affecting the dynamic behavior of the bridge structure for straight bridge as well as for skew-curve bridge configurations. For straight bridge configuration, mode participation factor of third out of plane vibration mode is 34.22% (Figure 4.8). However, for the combination of curvature and skew angle, the variations in mode participation factor have not been observed in symmetric order. Moreover, in general with increase in skew or curvature angle, the mode participation factor of third out of plane vibration mode has been observed to decrease or have very less changes.

4.4.3 Effect Mass Participation Ratios on Skew-Curved Bridges

Mass participation ratio signifies the amount of the structure's total mass which participates in stimulating the structure's particular mode. Ratio of mass participation can be estimated by squaring the participation factor of a particular mode and divide it by the structure's total joint masses [12]. Mass participation ratios of different vibrational modes i.e. first in-plane, first longitudinal and third out of plane vibration mode have been deliberated in the current section. 1^{st} and 2^{nd} out of plane vibrational modes have been noticed to rarely excite the structure's mass, as the mass participation ratio is very small. Therefore, results of modal mass participation ratios for 3rd out of plane vibrational modes have been deliberated instead of the first two out of plane vibrational modes. Figure 4.9 and 4.10 conveys the variation trend of the modal mass participation ratios with change of skew-curved bridge geometries.



a. Mass Participation Ratios of 1st In-Plane Vibrational Mode for various skew-curved bridge geometries

b. Mass Participation Ratios of 1st Longitudinal Vibrational Mode for various skew-curved bridge configurations

Figure 4.9 Mass Participation Ratios for Horizontal Vibrational Modes

Mass excitation of 76% has been caused by the 1st in-plane for straight bridge geometry and usually become higher for larger skew and curvature angle as conveyed by figure 4.9(a). Mass participation ratio has been noticed to be highest (i.e. 81%) for bridge having curvature angle (β) of 90° and skew angle (θ) of 60°. Hence, the contribution of first in-plane mode in exciting the mass of the structure is more than the contribution in case of straight bridges which signifies the lower contribution of higher in-plane vibrational modes in exciting the effective mass.

80% of the mass excitation has been noticed to cause by the first longitudinal vibrational mode for straight bridge configurations (Figure 4.9b). Usually, the mass participation ratios have been noted to increases with increase in skewness, however it gets reduced with increase in deck curvature for this vibrational mode. This signifies that contribution of 1st longitudinal mode in exciting the structure's mass will decreases with increase in curvature angle. The least value of mass participation ratio has been observed for bridge having curvature angle (β) of 90° & skew angle (θ) of 15°.

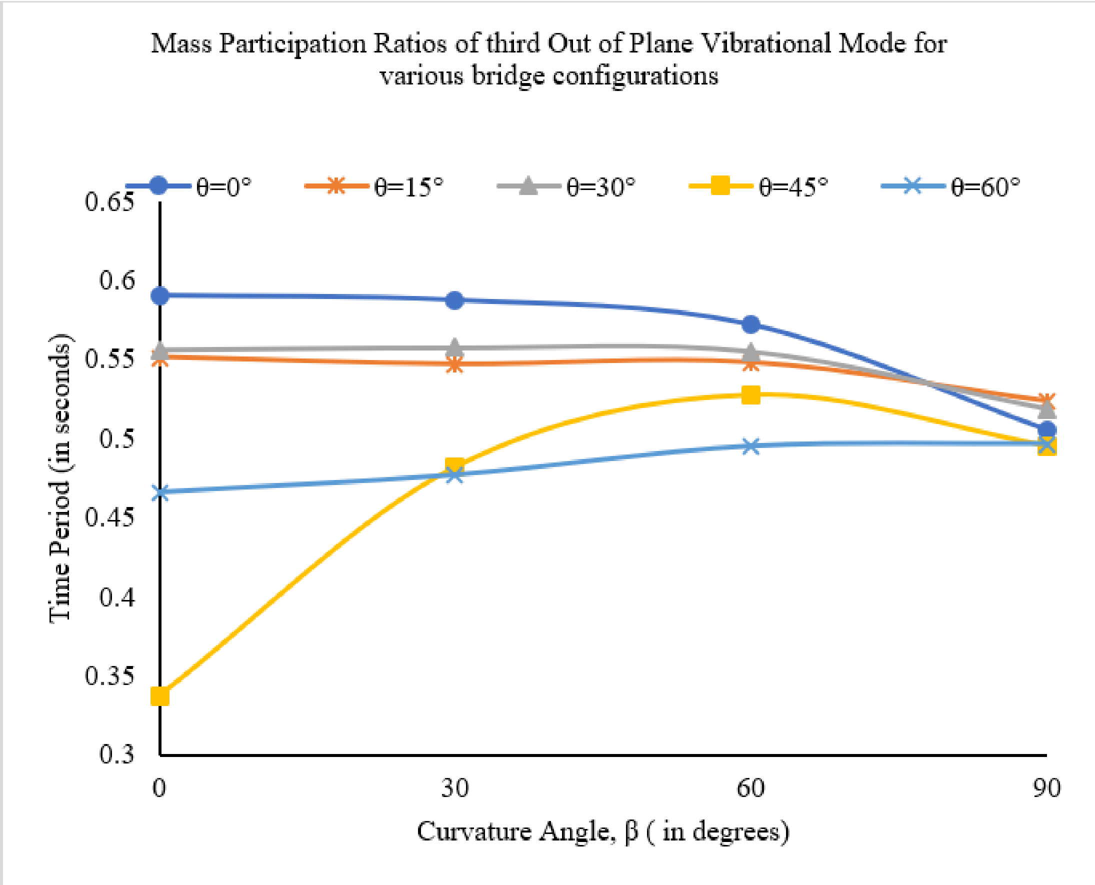


Figure 4.10 Mass Participation Ratios for Vertical Vibration Modes

First two out of plane vibrational modes shows very less contribution in exciting the mass of the bridge structures. Whereas, 3rd out of plane vibrational mode greatly excite structure's mass for straight bridge and skew-curved bridge configurations. Mass participation ratio of 59% has been noted for 3rd out of plane vibrational mode in straight bridge configuration. However, the variations of mass participation ratios have been noticed in unsymmetrical order for skew-curved bridges. Moreover, in general with increase in skewness or curvature, the mass participation ratio of 3rd out of plane vibrational mode has been observed to reduce or have very small changes.

CHAPTER 5

SEISMIC ANALYSIS

5.1 Seismic Analysis

Seismic analysis is the part of structural analysis in which structure's response is calculated, when the structure is subjected to ground motions. In the process of structure designing, it is necessary to perform seismic analysis of the structure which are to be constructed in earthquake prone areas. Some of the common methods that are used to perform seismic analysis of the structure are;

i) Seismic Coefficient Method (SCA)
ii) Response Spectrum Method (RSM)
iii) Time History Method (THM)
iv) Nonlinear Pushover Analysis (NPA)

In this study, Response spectrum analysis has been carried out for all the bridge configurations with varying skewness and curvature using CSi Bridge.

5.2 Response Spectrum

The possible earthquakes the place of construction can be represented by the code specified or site specific designed spectral accelerations. Design response spectrum of the AASHTO 2007 has been used as input for response spectrum analysis. To perform response spectrum analysis, the design acceleration response spectra with scaling factor of 0.2g has been applied in vertical direction and 0.3g has been applied for both the horizontal directions i.e. longitudinal and transverse direction.

Design acceleration spectrum is the average of several earthquake motions. Values of member forces and displacement is calculated directly for individual mode. Maximum responses of the individual modes can be combined using CQC (complete quadratic combination) method and SRSS (square root of the sum of the squares) method to calculate maximum structural member forces, displacements and moments. In this study, maximum values of modal response have been combined using CQC method to obtain the peak value of force or displacement.

Soil has been classified as medium soil site. Values of S_{DS} (design earthquake response spectral acceleration coefficient at 0.2 second period) and S_{D1} (design earthquake response spectral acceleration coefficient at 1.0 second period) has been found to be 2.5 and 1.44 respectively. Graph for define function of response spectrum as per AASHTO 2007 is shown in figure 5.1.

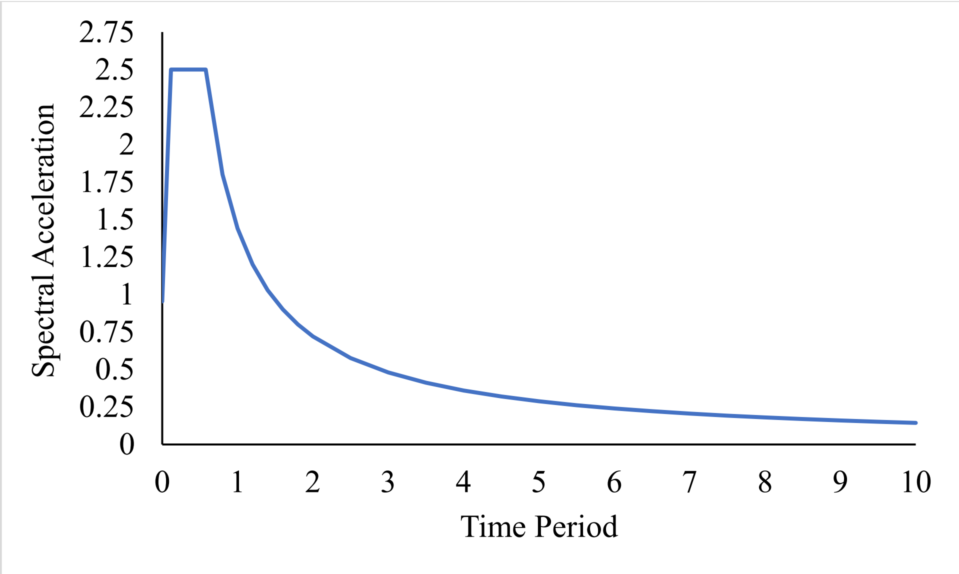


Figure 5.1 Response Spectrum AASHTO 2007 Function Graph

5.3 Seismic behaviour of irregular bridges

Seismic elastic behaviour of the skew-curved bridges has been presented in this section. Effect of both skewness and curvature on torsion and bending moment about both horizontal and vertical axis has been studied. Results have been obtained using CQC modal combination and SRSS directional combination rules. Three principal moment components of the bridge deck are named as out-of-plane bending moment, in-plane bending moment and the longitudinal torsion. Results which have been obtained after applying the above defined response spectrum function in horizontal (longitudinal and transverse) and vertical directions individually are discussed in this section. On the basis of these results, the seismic behaviour of skew-curved bridges has been discussed.

In this study, curvature angle of 0°, 30°, 60° & 90° and skew angle of 0°, 15°, 30°, 45° & 60° has been taken. Seismic behaviour of bridge configuration with combination of these skew angle and curvature angle has been studied. There are two cases when the bridge configuration will not be skew-curved bridge configuration; i) when the skew angle is 0° and ii) when the curvature angle is 0°. Curvature angle of 0° signifies that the bridge deck is having no curvature i.e. the bridge deck is straight. So, when the combination of any skew angle will be made with curvature angle of 0°, then it will be the skew bridge configuration and not the skew-curved bridge configuration. Similarly, when the skew angle will be zero i.e. there will be no skewness then the combination of any curvature angle with skew angle of 0° will be the curved bridge configuration and not the skew-curved bridge configuration. With respect to these perspectives, the results have been categorised accordingly in the following sections.

5.3.1 Seismic Behaviour of Skew Bridges

Skew bridges are the bridges in which the angle between the bridge deck and the substructure part of the bridge (i.e. pier and/or abutment) is other than 90° i.e. the bridge deck and the substructure are not perpendicular to each other. As discussed above that curvature angle of 0° signifies the straight bridge deck configuration. Therefore, the combination of any skew angle with curvature angle of 0° will represent skew bridge geometry. Results of response spectrum analysis for curvature angle of 0° with combination of various skew angles i.e. 0°, 15°, 30°, 45° and 60° has been discussed in this section.

5.3.1.1 Out-of-Plane Bending Moment

Flexural moment demand of the deck about the radial axis has been termed as *out-of-plane bending moment*. Variation of out-of-plane bending moment along with the span length of skew bridges under different components of seismic excitations is shown in figure 5.2, 5.3 and 5.4. It has been observed that both longitudinal and transverse excitations generate a large amount of bending moment at the supports of the skew bridge, whereas vertical excitations cause large moment at both supports as well as at bridge spans.

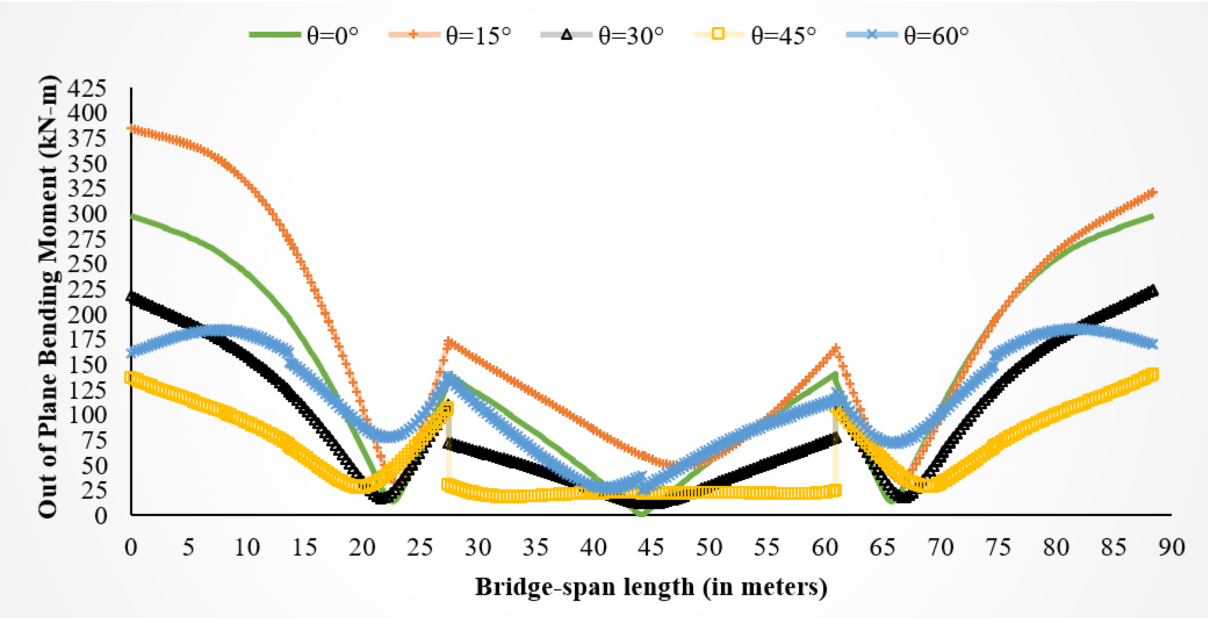


Figure 5.2 Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 0° with different Skew Angles under Longitudinal Excitations

Under longitudinal excitations, general observation has been made that out-of-plane bending moment has least value at the midpoint of the mid-span which is also the midpoint of the whole bridge length.

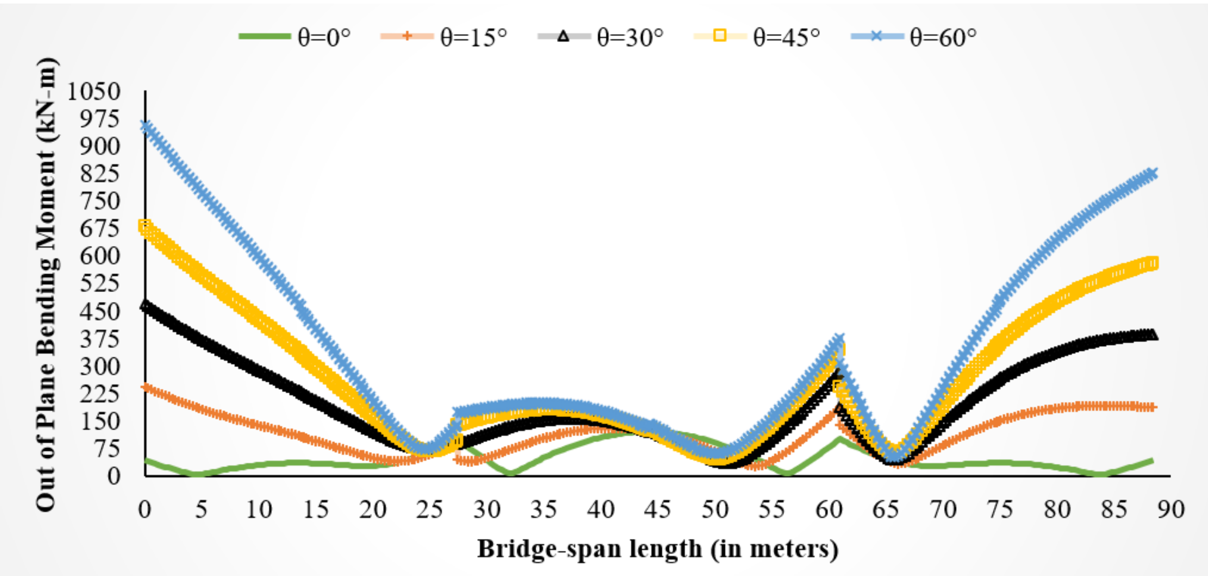


Figure 5.3 Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 0° with different Skew Angles under Transverse Excitations

For straight bridge configuration i.e. curvature angle (β) of 0° and skew angle (θ) of 0°, very less out-of-plane bending moment has been observed under transverse excitations. However, moment increases with increase in the skewness of bridge-deck under transverse and vertical components of seismic excitations as shown in figure 5.3 and 5.4 respectively.

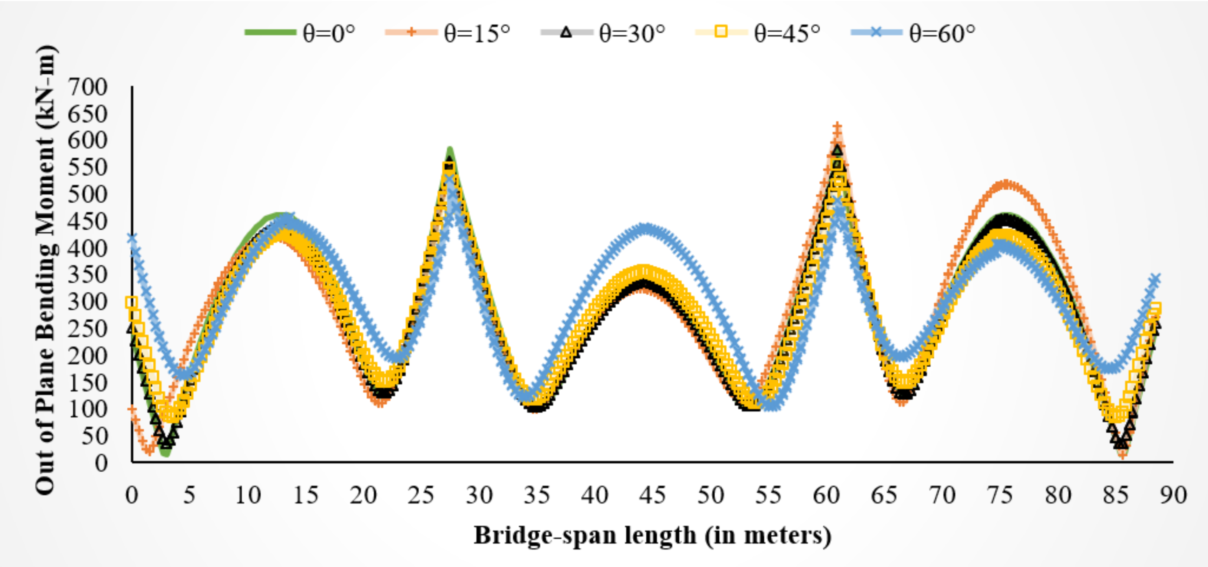


Figure 5.4 Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 0° with different Skew Angles under Vertical Excitations

5.3.1.2 In-Plane Bending Moment

Flexural moment demand of the bridge deck about the vertical axis has been termed as *in-plane bending moment*. In-plane bending moment can be generated by longitudinal, transverse and vertical components of the seismic excitations. In-plane bending moment at the abutments has not been observed to be zero as the in-plane movement and rotation of the bridge has not been restrained.

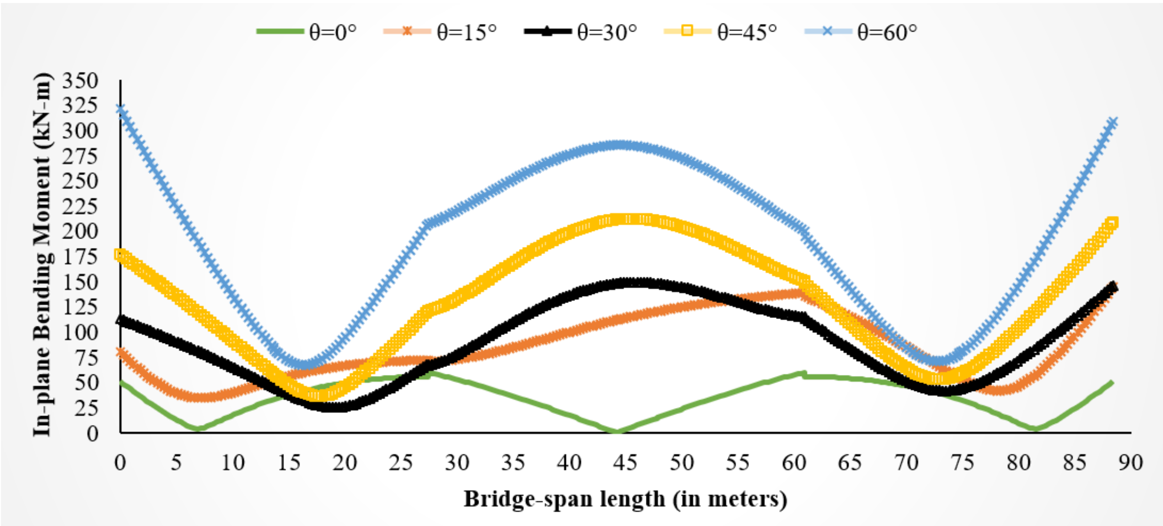


Figure 5.5 In-plane Bending Moment for bridge models having Curvature Angle (β) of 0° with different Skew Angles under Longitudinal Excitations

It has been observed that in-plane bending moment of skew bridge increases with increase in skew angle as shown in figure 5.5. In case of straight bridge configuration very less amount of in-plane bending moment has been observed under longitudinal excitations. Also, a reverse trend of variation at midpoint of the mid-span has been observed in straight bridge configuration.

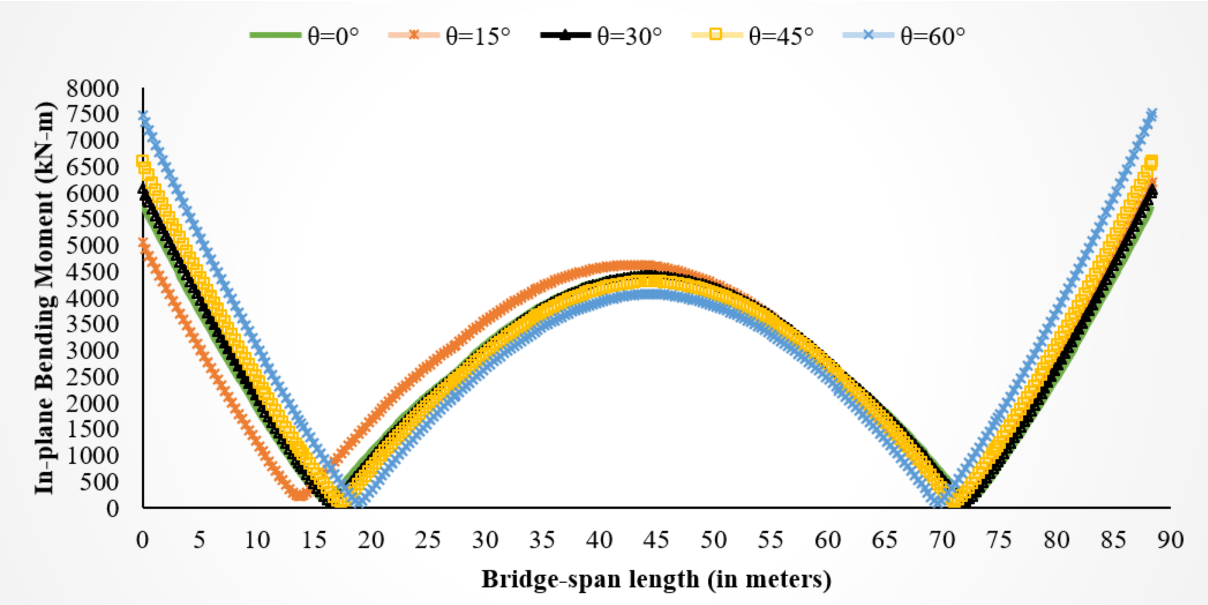


Figure 5.6 In-plane Bending Moment for bridge models having Curvature Angle (β) of 0° with different Skew Angles under Transverse Excitations

Usually, the in-plane bending moment of the skew bridges under transverse components of seismic excitations has been observed to be decreased with increase in skew angle as shown in figure 5.6. Maximum value of in-plane bending moment has been observed at the abutments for any particular skew angle.

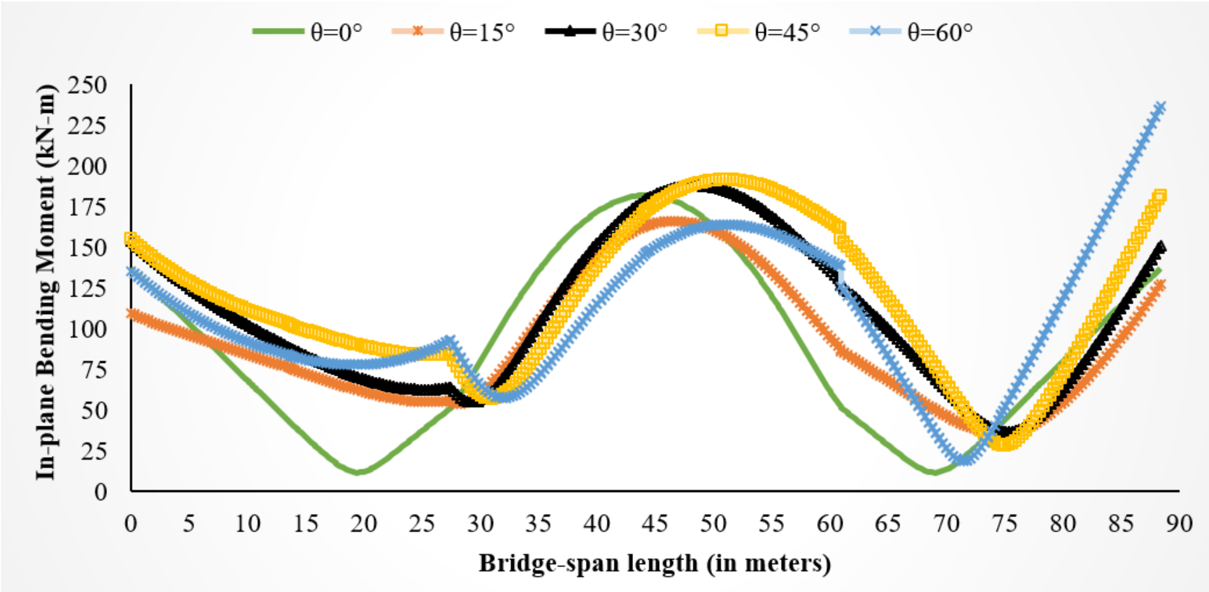


Figure 5.7 In-plane Bending Moment for bridge models having Curvature Angle (β) of 0° with different Skew Angles under Vertical Excitations

Usually, in-plane bending moment has been observed to increase with increase in skewness under vertical component of seismic excitations as shown in figure 5.7. Though, no general trend for variation of in-plane bending moment over the length of the span has been observed.

5.3.1.3 Longitudinal Torsion

Moment demand of the deck about the tangential axis has been termed as *longitudinal torsion*. Variation of longitudinal torsion over the span length under longitudinal, transverse and vertical components of seismic excitation is shown in figure 5.8, 5.9 and 5.10 respectively.

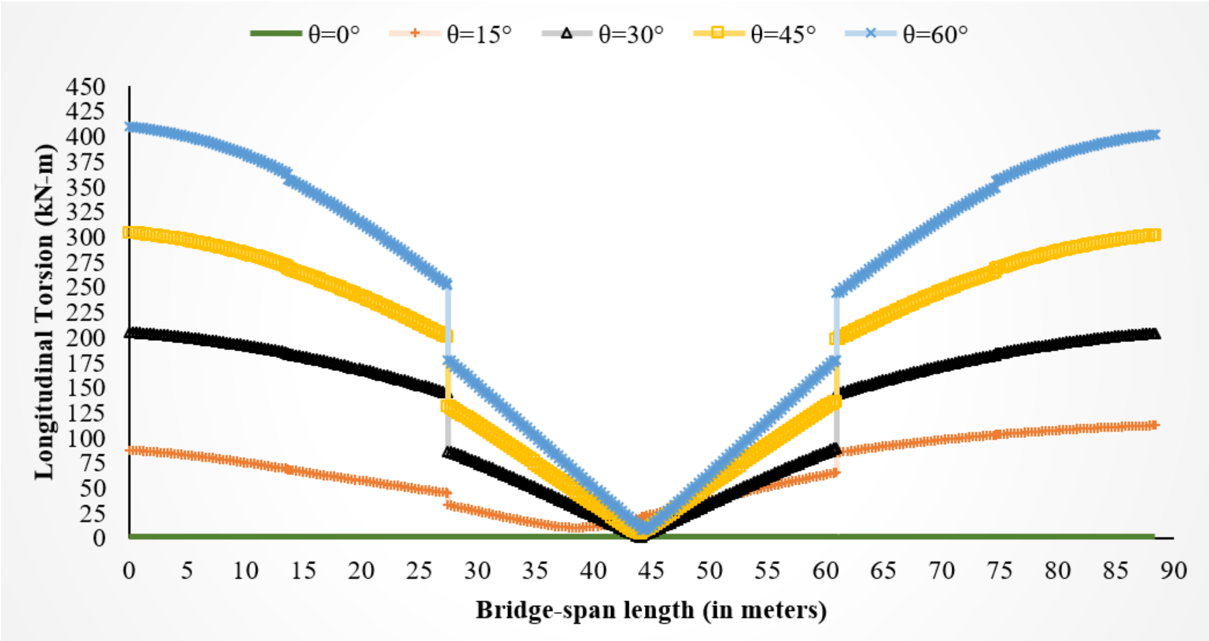


Figure 5.8 Longitudinal Torsion for bridge models having Curvature Angle (β) of 0° with different Skew Angles under Longitudinal Excitations

Figure 5.8 shows that longitudinal torsion increases with increase in degree of skewness in a pattern which indicates the amplification of longitudinal torsion at the location of internal bents and decreases to very less value at the midpoint of the bridge. Longitudinal torsion at abutments in case of θ=60° is 400 times (approx.) the longitudinal torsion in case of straight bridge configuration.

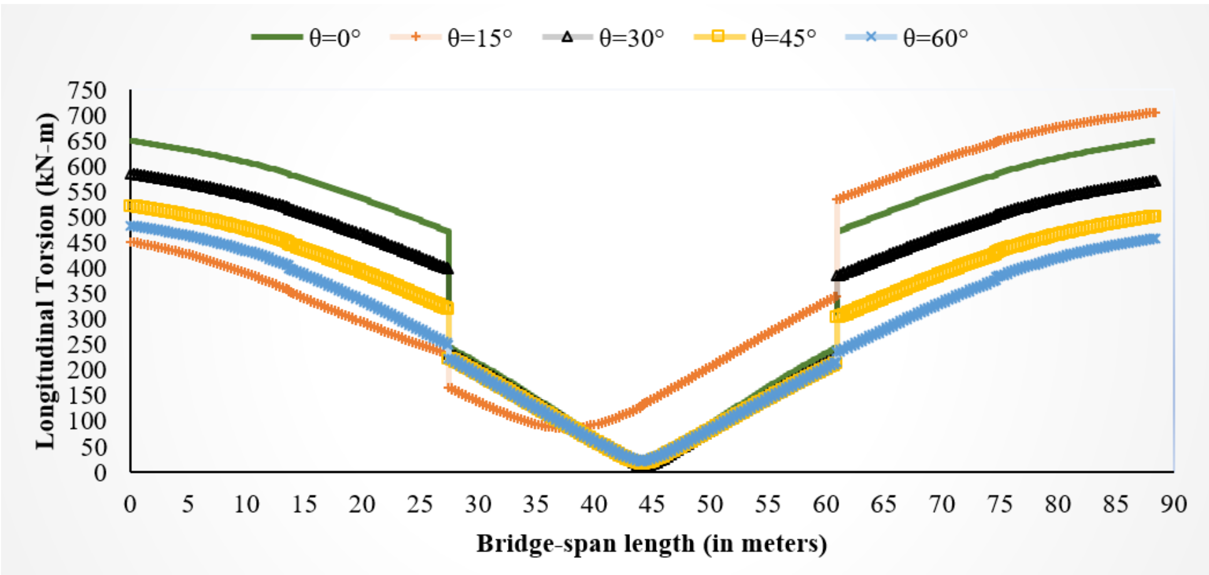


Figure 5.9 Longitudinal Torsion for bridge models having Curvature Angle (β) of 0° with different Skew Angles under Transverse Excitations

Usually, the decrease in longitudinal torsion has been observed with increase in skew angle under the influence of transverse component of the seismic excitations.

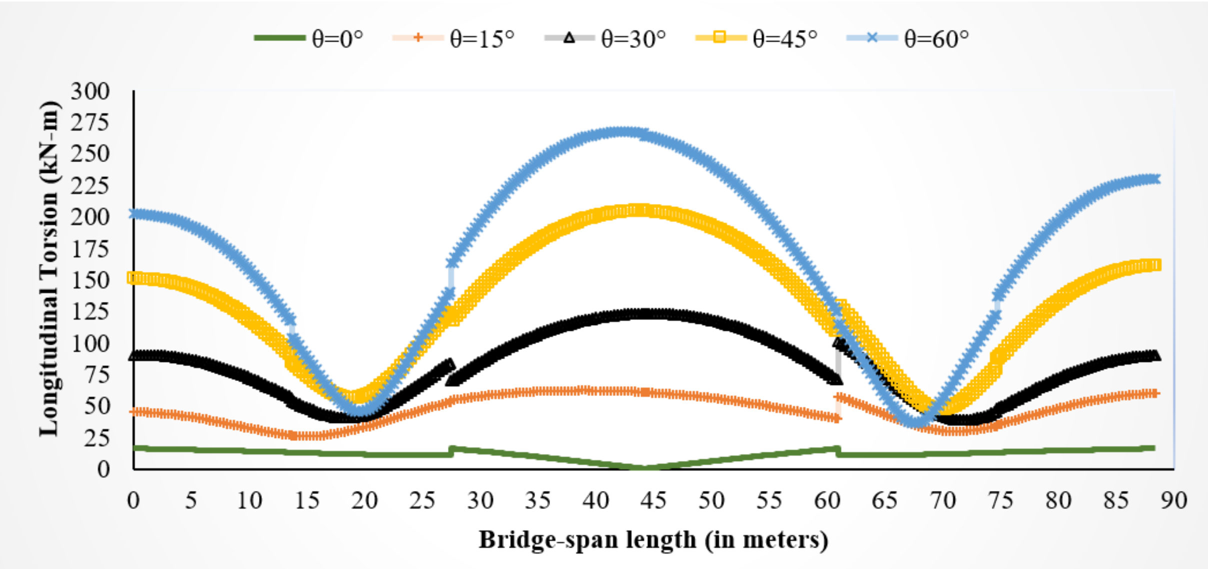


Figure 5.10 Longitudinal Torsion for bridge models having Curvature Angle (β) of 0° with different Skew Angles under Vertical Excitations

Pattern for variation of longitudinal torsion under the vertical component of seismic excitations is shown in figure 5.10 which represents that longitudinal torsion increases with increase in skew angle.

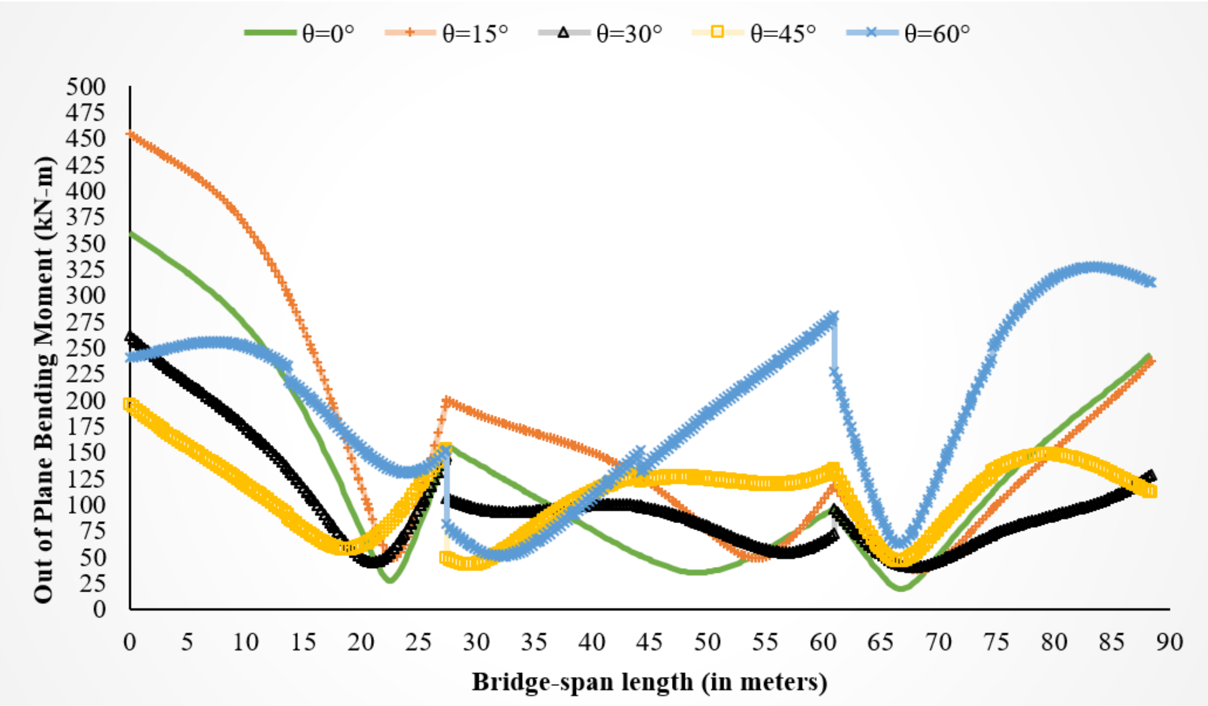
Diagram for longitudinal torsion under longitudinal, transverse and vertical component of seismic excitations shows that skew bridges experiences couple at intermediate bents' location and the magnitude of this couple will be equal to the amplification of moment at that section. Couple has been also experienced at the midpoint of the first and third span, whereas their magnitude is very small as compared to magnitude of couple at location of the bents. While, the magnitude of couple at intermediate bents under vertical component of seismic excitations is smaller as compared to the magnitude of couple at intermediate bents under longitudinal and transverse components of seismic excitations.

5.3.2 Seismic Behaviour of Skew-Curved Bridges

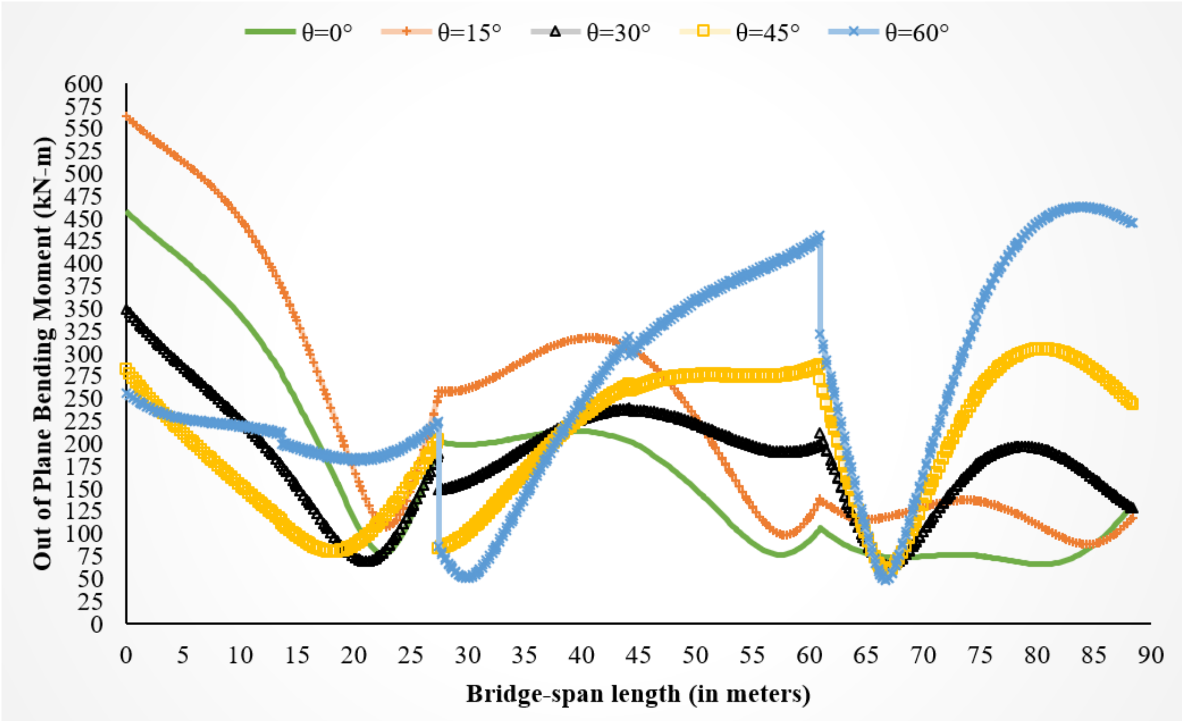
Bridges which are having horizontal curvature along with the skewness at the abutments are termed as skew-curved bridges. Results of response spectrum analysis for curvature angles (β) of 30°, 60°, 90° along with different skew angles has been studied. Variation of the three principal moments under three components of seismic excitations has been discussed.

5.3.2.1 Out-of-Plane Bending Moment

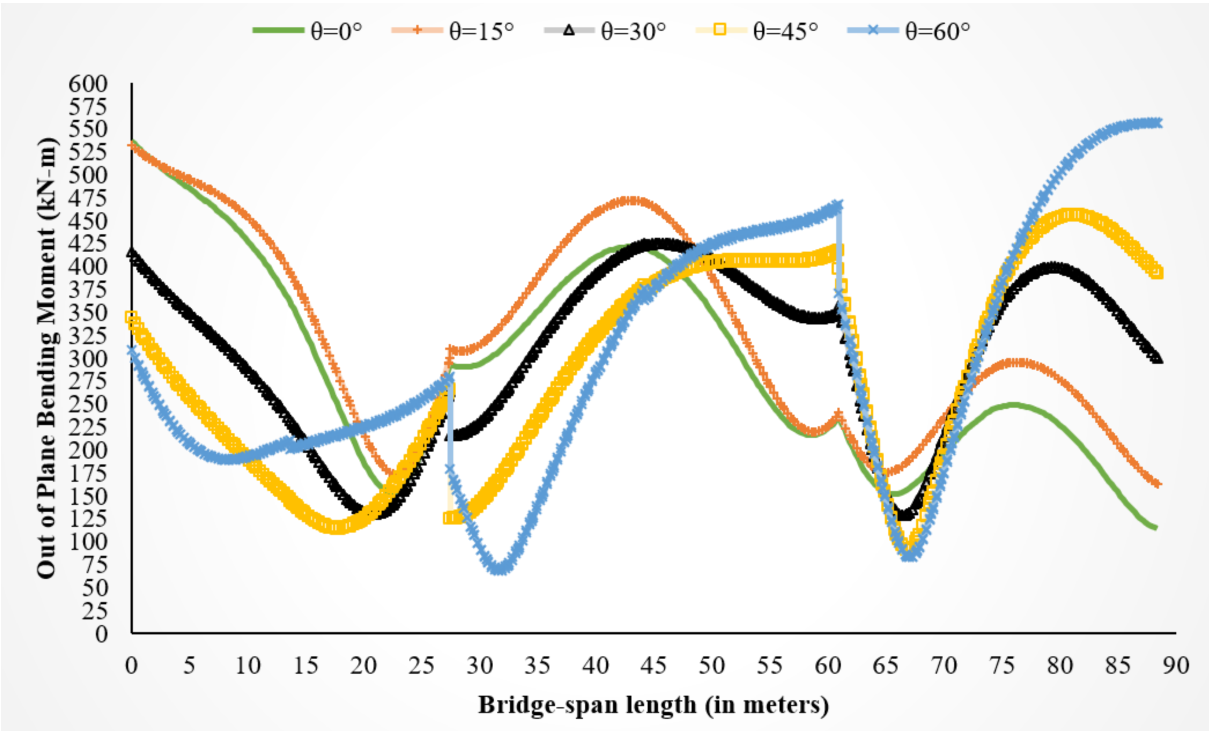
Flexural moment demand of the deck about the radial axis has been termed as *out-of-plane bending moment*. Out-of-plane bending moment under longitudinal component of seismic excitations for various curvature angles (i.e. 30°, 60° and 90°) is shown in figure 5.11.



a) Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 30° with different Skew Angles under Longitudinal Excitations



b) Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 60° with different Skew Angles under Longitudinal Excitations

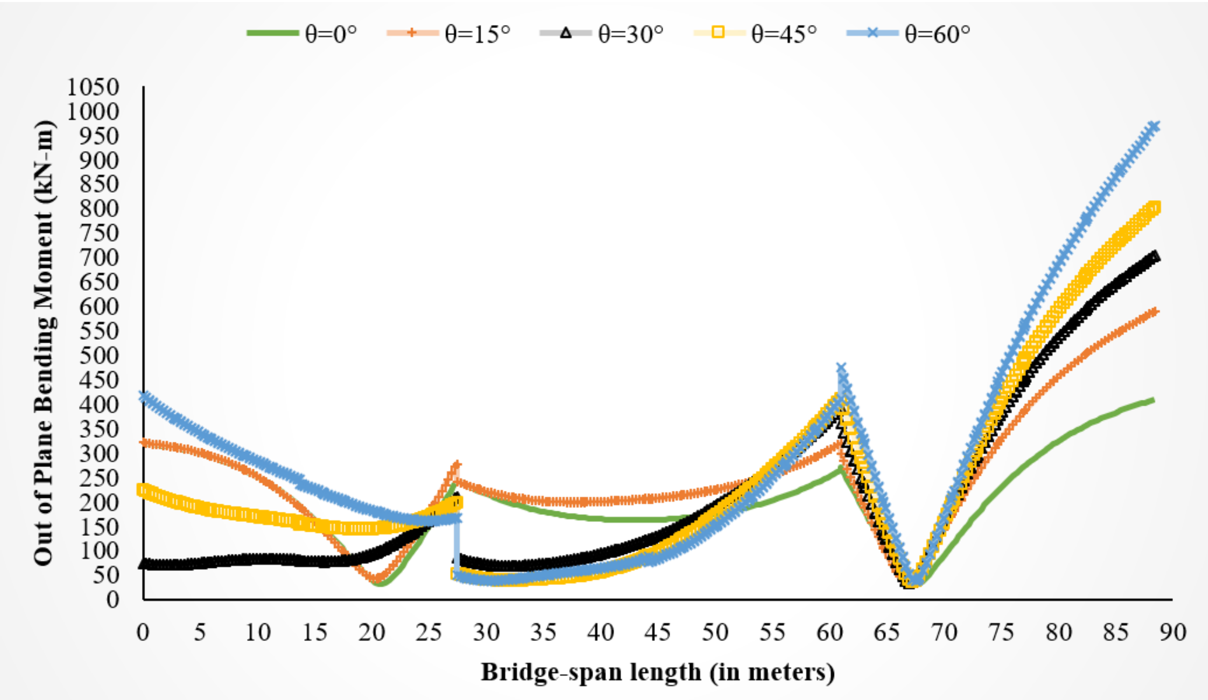


c) Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 90° with different Skew Angles under Longitudinal Excitations

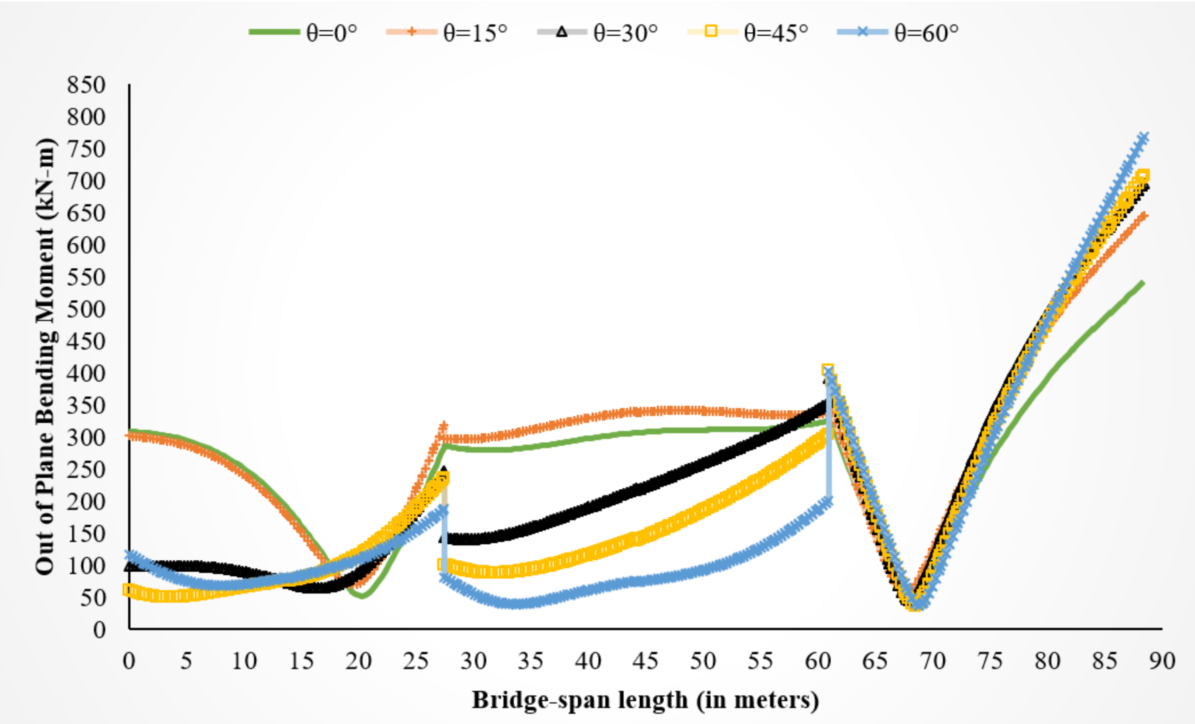
Figure 5.11 Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 30°, 60° and 90° with different Skew Angles under Longitudinal Excitations

When the skewness is induced to the curved bridge deck then the complex pattern of moment for various bridge geometries has been noticed as evident from figure 5.11. For any curvature angle, the couple has been experienced at intermediate bents for skew angle greater than or equal to 30°.

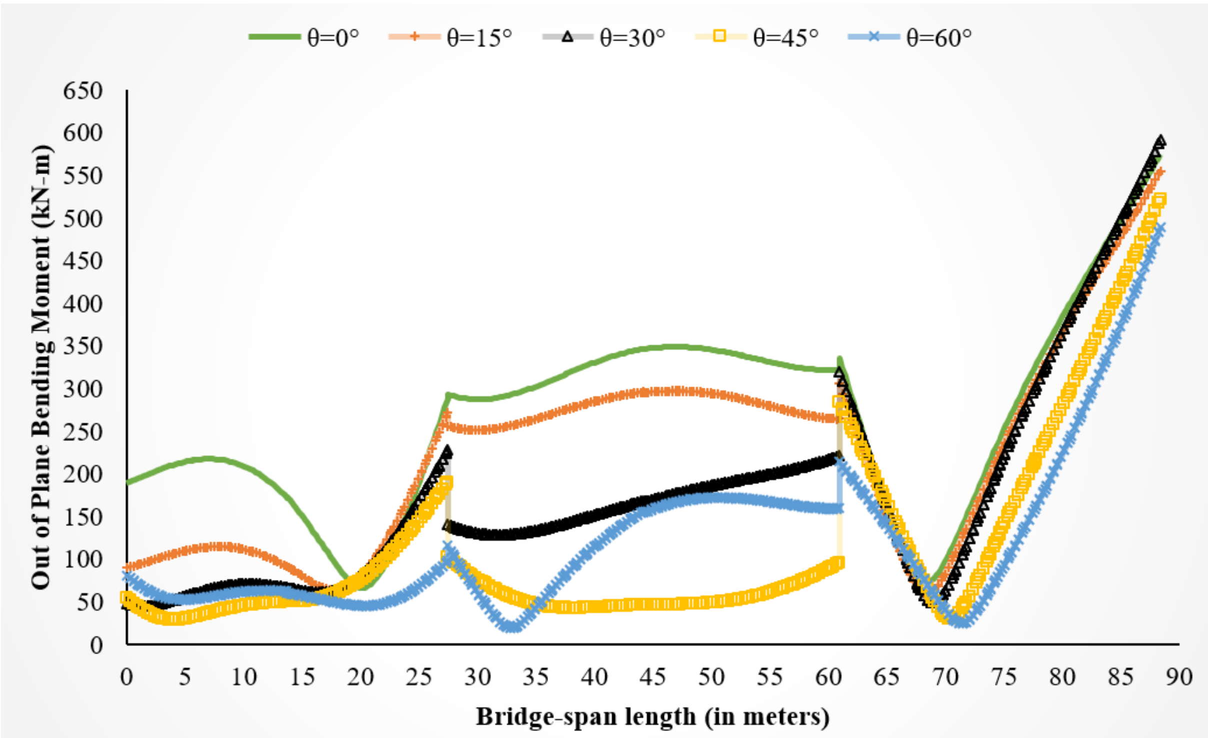
Out-of-plane bending moment under transverse component of seismic excitations for different curvature of bridge-deck (i.e. β=30°, β=60° and β=90°) is shown in figure 5.12.



a) Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 30° with different Skew Angles under Transverse Excitations



b) Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 60° with different Skew Angles under Transverse Excitations



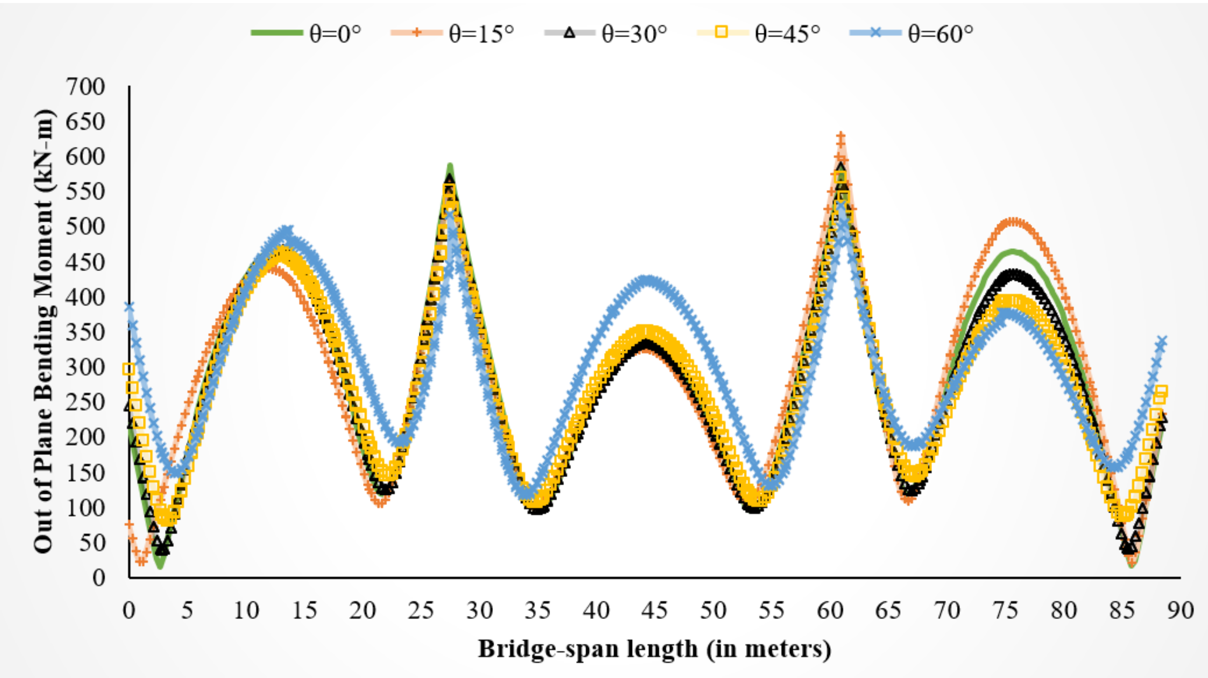
c) Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 90° with different Skew Angles under Transverse Excitations

Figure 5.12 Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 30°, 60° and 90° with different Skew Angles under Transverse Excitations

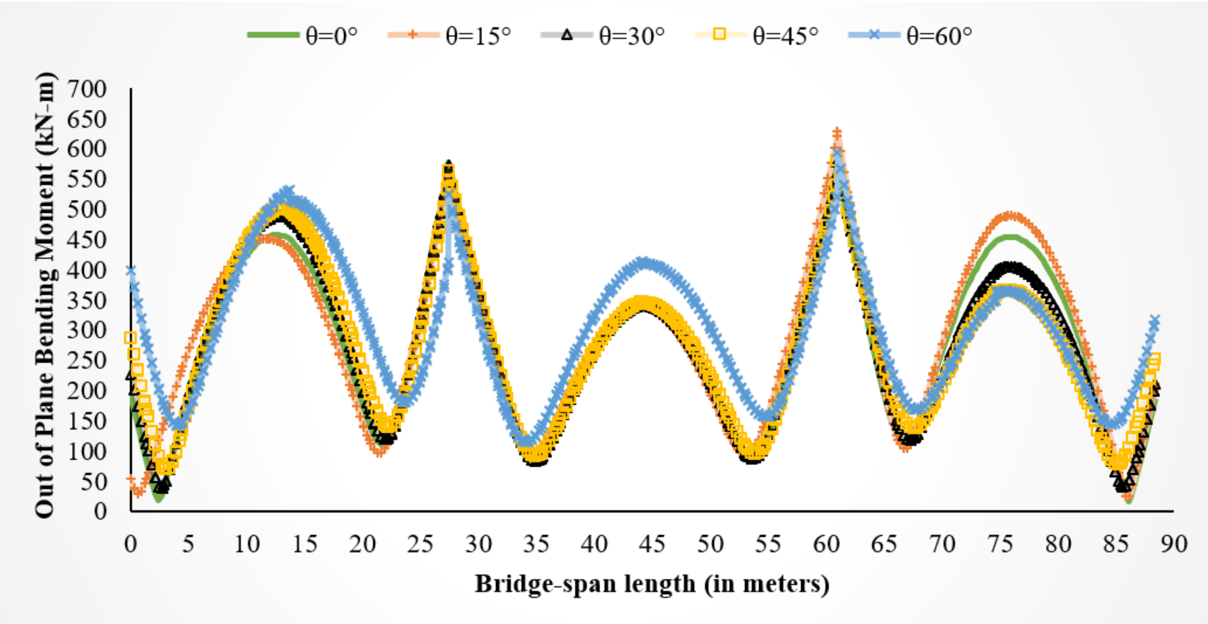
It has been noticed that skew-curved bridges generate higher moment demand under transverse component of seismic excitations towards the right side of the midpoint of the bridge as compared to the left side as shown in the figure 5.12. With increase in curvature angle, the out-of-plane bending moment at the end abutment gets reduced.

Skew-curved bridges has been noticed to experience couple at intermediate bents' location and this couple varies with change in curvature angle for a particular skew angle.

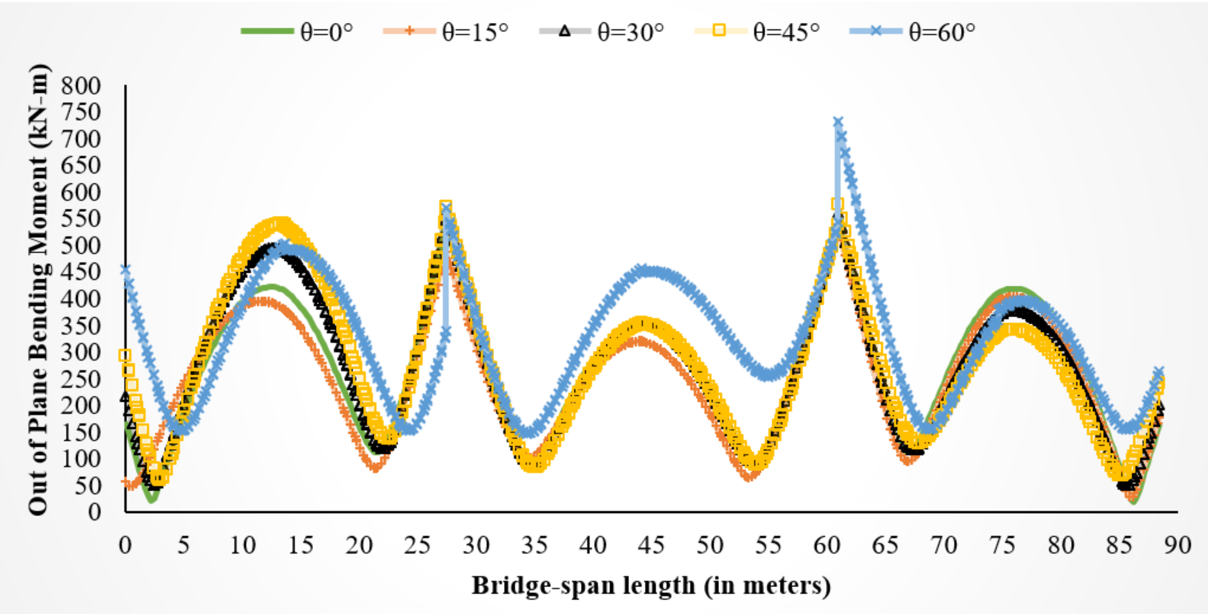
Out-of-plane bending moment under vertical component of seismic excitations for different curvature angle, β (i.e. 30°, 60° and 90°) is shown in figure 5.13.



a) Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 30° with different Skew Angles under Vertical Excitations



b) Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 60° with different Skew Angles under Vertical Excitations



c) Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 90° with different Skew Angles under Vertical Excitations

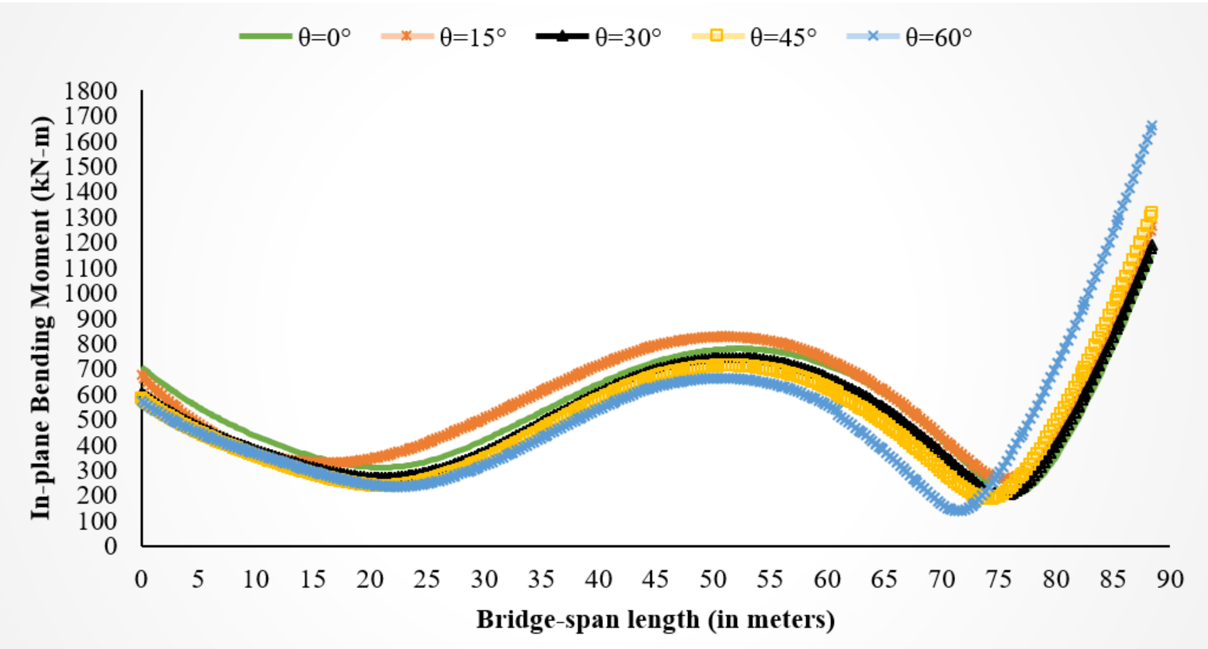
Figure 5.13 Out-of-Plane Bending Moment for bridge models having Curvature Angle (β) of 30°, 60° and 90° with different Skew Angles under Vertical Excitations

Increasing the degree of skewness causes the increase in out-of-plane bending moment towards the left portion of the midpoint of the bridge deck. However, an opposite trend has been noticed towards the right portion i.e. the moment has been noticed to decrease with increase in skewness along the right portion of the midpoint of the bridge as shown in the figure 5.13. Very slight difference has been observed in out-of-plane bending moment for skew angle of up to 45°, whether for skew angle of 60°, larger difference in moment demands has been noticed.

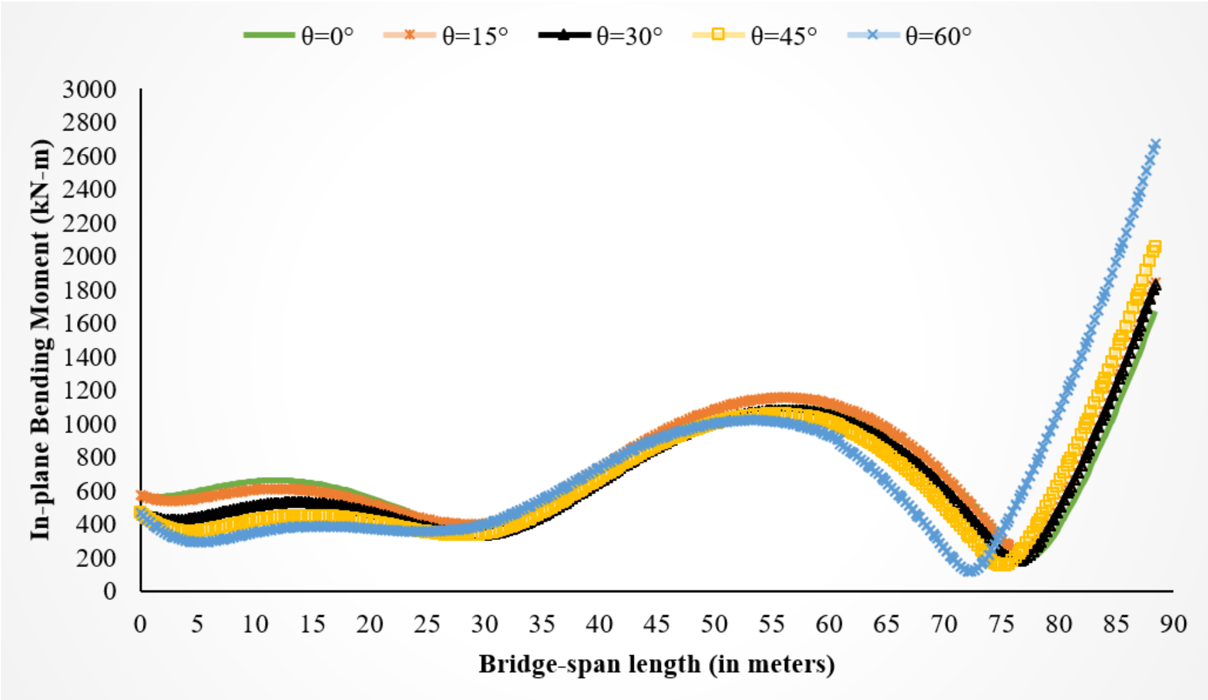
Out of the plane bending moment diagram for skew-curved bridges under vertical components of seismic excitations shows a parabolic curve which indicates that vertical components act as uniformly distributed load of different magnitude for different sections. However, for combination of larger skew angle, (i.e. θ=60°) with larger curvature angles (i.e. 60° and 90°), the couple has also been noticed at the bents.

5.3.2.2 In-plane Bending Moment

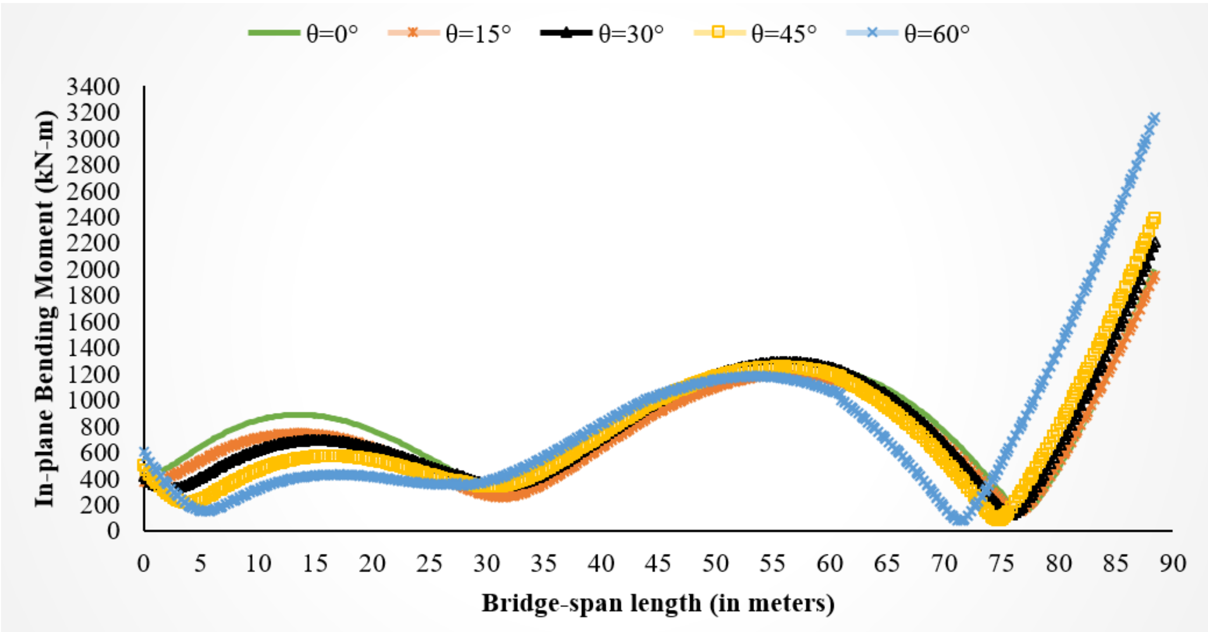
Flexural moment demand of the bridge deck about the vertical axis has been termed as *in-plane bending moment*. In-plane bending moment under longitudinal component of seismic excitations for β=30°, β=60° and β=90° is shown in figure 5.14(a), 5.14(b) and 5.14(c) respectively.



a) In-plane Bending Moment for bridge models having Curvature Angle (β) of 30° with different Skew Angles under Longitudinal Excitations



b) In-plane Bending Moment for bridge models having Curvature Angle (β) of 60° with different Skew Angles under Longitudinal Excitations

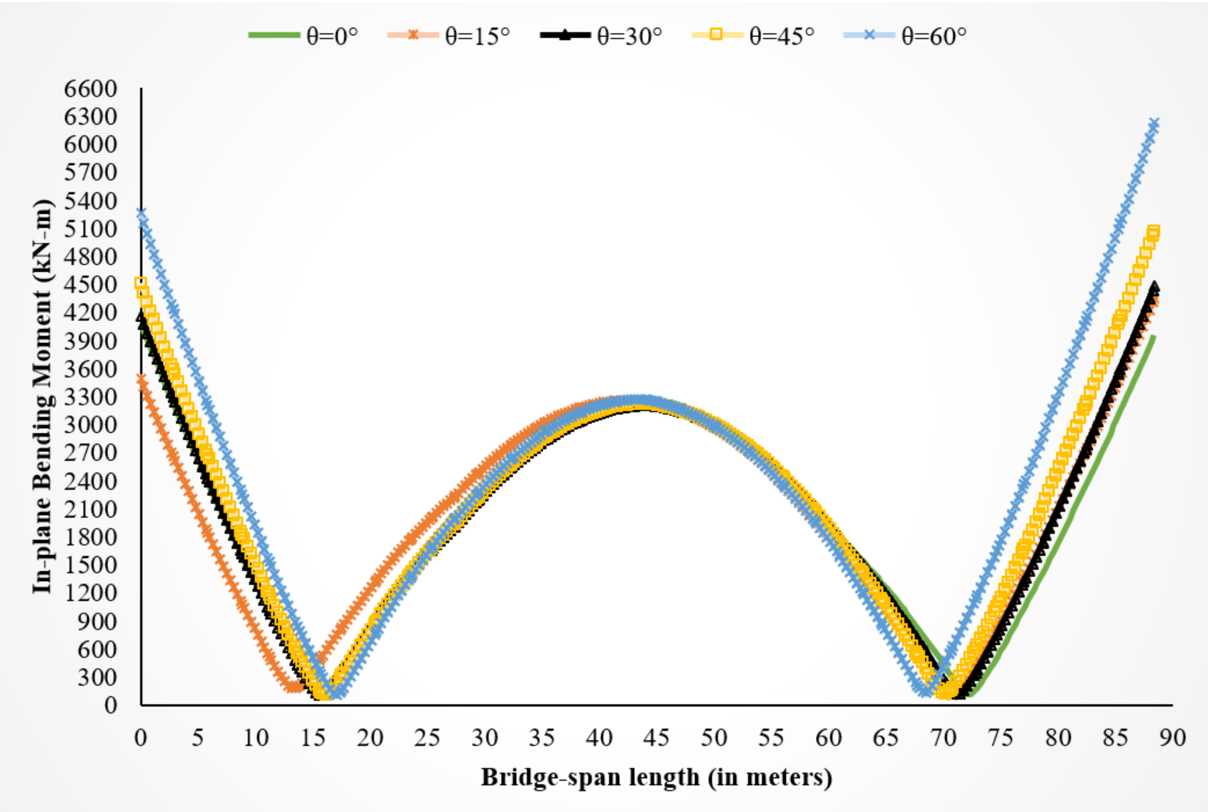


c) In-plane Bending Moment for bridge models having Curvature Angle (β) of 90° with different Skew Angles under Longitudinal Excitations

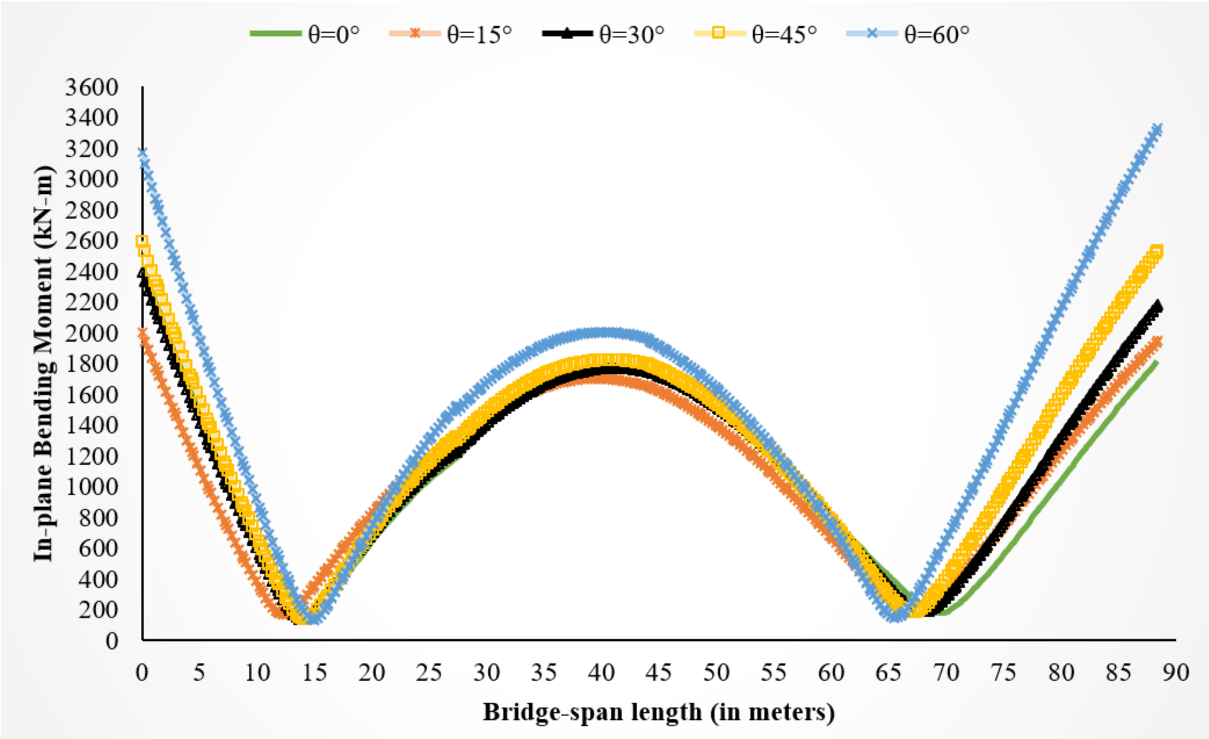
Figure 5.14 In-plane Bending Moment for bridge models having Curvature Angle (β) of 30°, 60° and 90° with different Skew Angles under Longitudinal Excitations

In case of skew-curved bridges, in-plane bending moment under longitudinal excitations has been noticed to increase at the end abutments of the bridge. However, the complex pattern of variation of in-plane bending moment has been noticed along the span length. Increasing the curvature of the bridge-deck significantly affect the moment demand of skew-curved bridges i.e. moment demand at the end abutments become higher with increase in curvature angle.

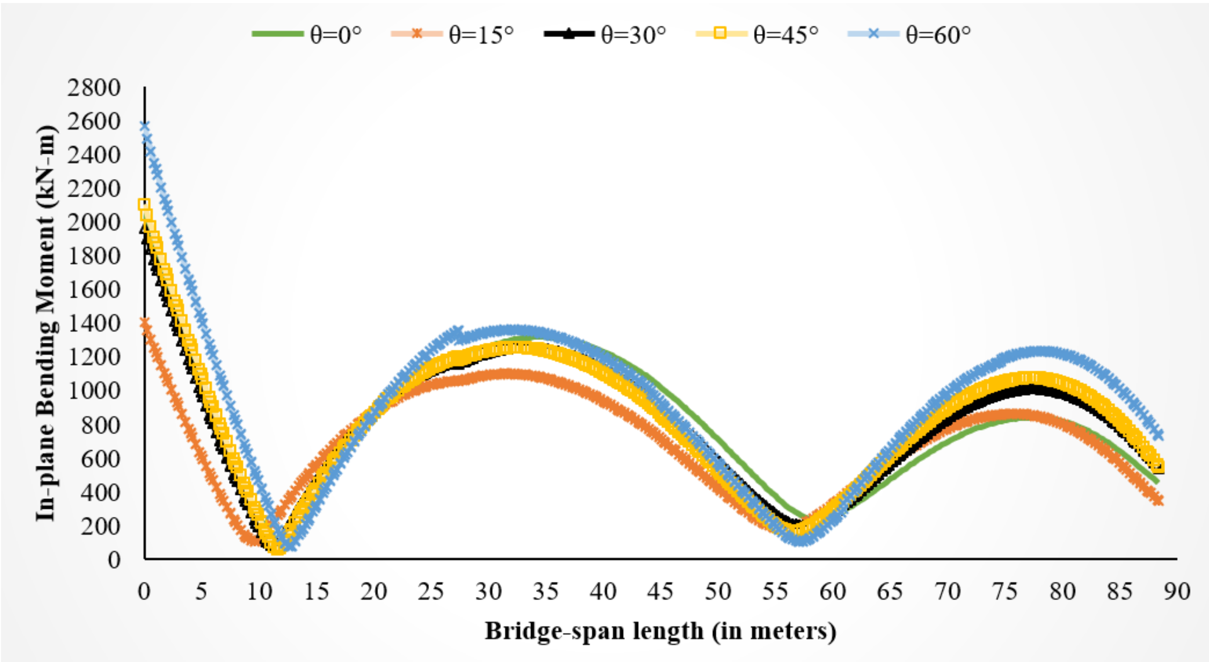
In-plane bending moment under transverse component of seismic excitations for various curvature angles (i.e. β=30°, β=60° and β=90°) is shown in figure 5.15.



a) In-plane Bending Moment for bridge models having Curvature Angle (β) of 30° with different Skew Angles under Transverse Excitations



b) In-plane Bending Moment for bridge models having Curvature Angle (β) of 60° with different Skew Angles under Transverse Excitations

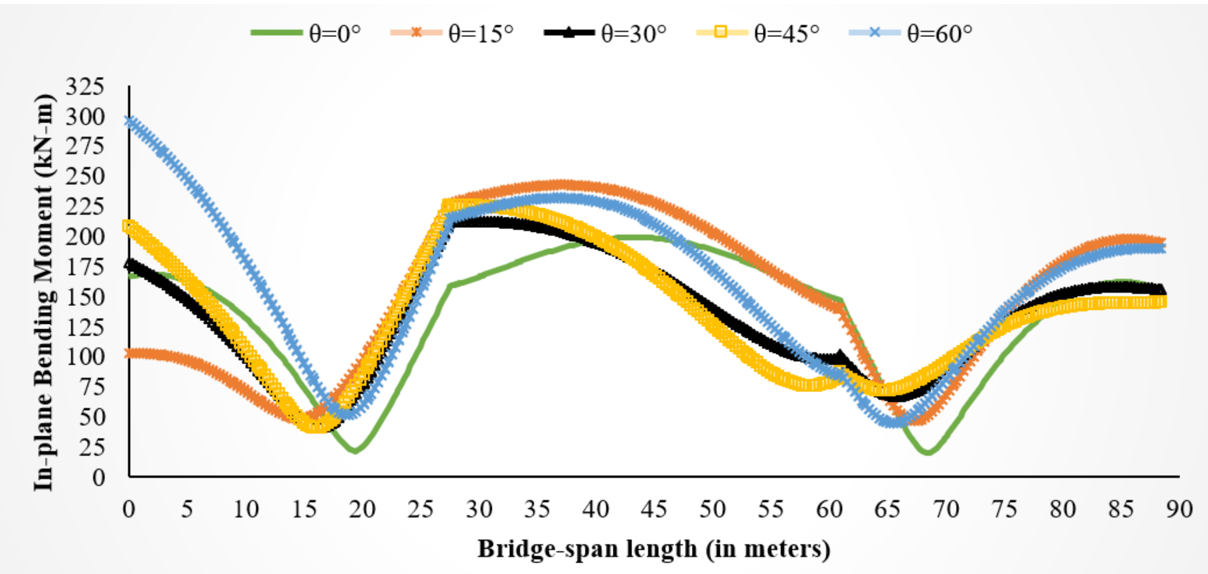


c) In-plane Bending Moment for bridge models having Curvature Angle (β) of 90° with different Skew Angles under Transverse Excitations

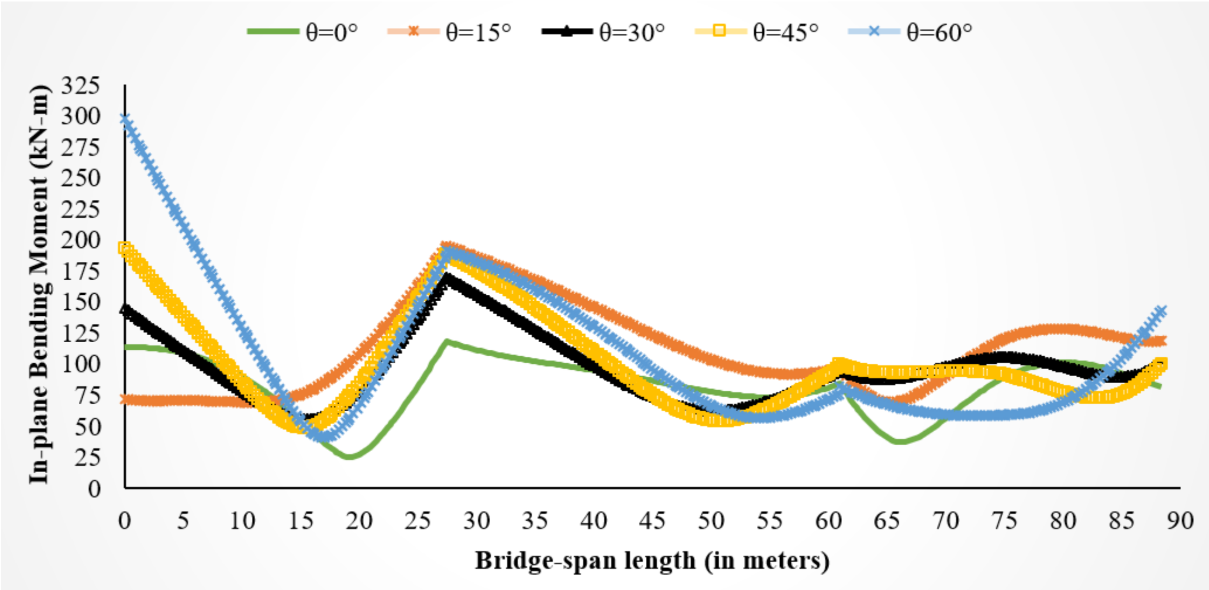
Figure 5.15 In-plane Bending Moment for bridge models having Curvature Angle (β) of 30°, 60° and 90° with different Skew Angles under Transverse Excitations

Both skewness and curvature affect the in-plane bending moment of the skew-curved bridges under transverse components of seismic excitations. In-plane bending moment becomes higher with increase in skewness, whereas moment demand decreases with variation in curvature of bridge deck from 30° to 90°. Same variation trend of in-plane bending moment has been observed for combination of skewed substructure elements with curvature angle of up to 60°. For higher curvature of the bridge deck i.e. for curvature angle of 90°, in-plane bending moment of third span has been noticed to be decreased which was increasing for curvature angle up to 60°.

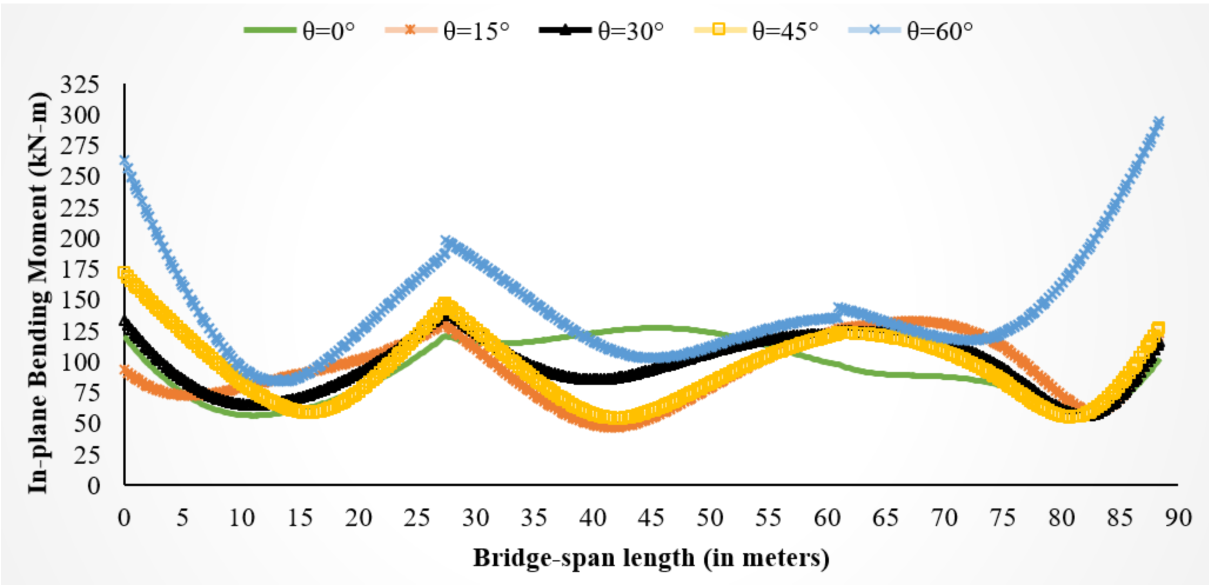
In-plane bending moment under vertical component of seismic excitations for variation of curvature angle from 30° to 90° is shown in figure 5.16.



a) In-plane Bending Moment for bridge models having Curvature Angle (β) of 30° with different Skew Angles under Vertical Excitations



b) In-plane Bending Moment for bridge models having Curvature Angle (β) of 60° with different Skew Angles under Vertical Excitations



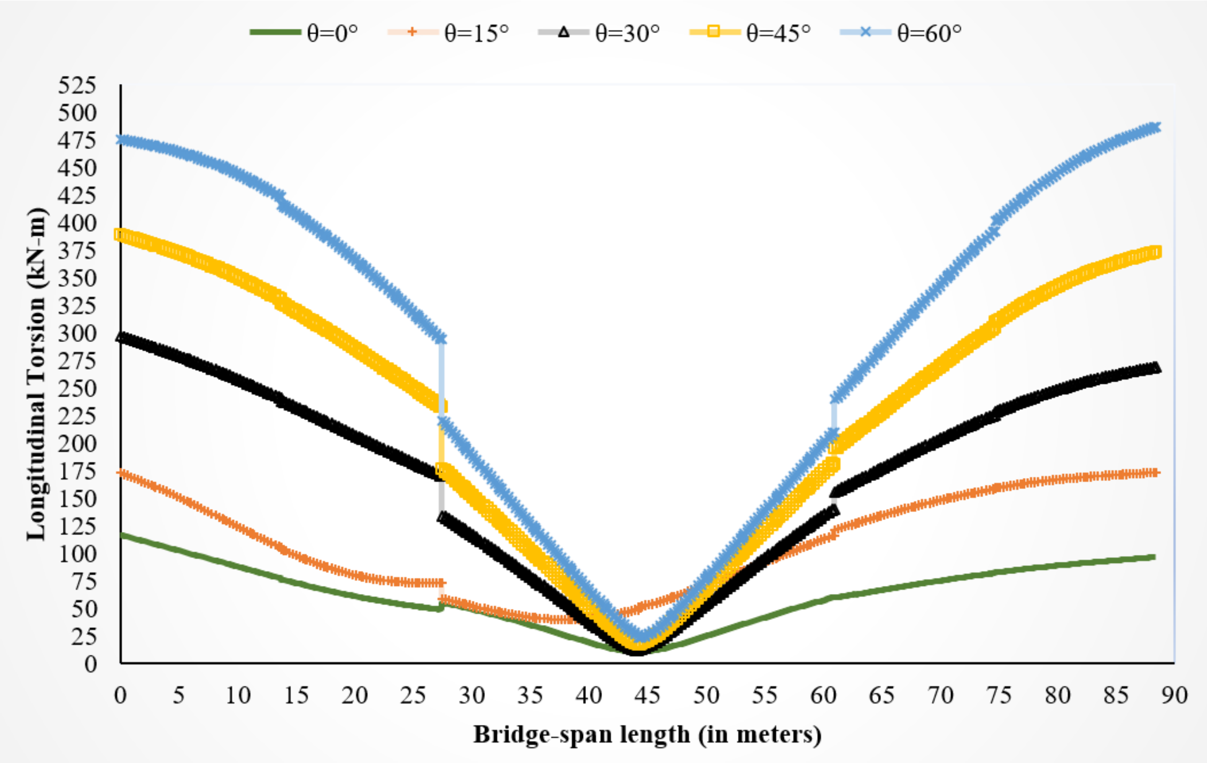
c) In-plane Bending Moment for bridge models having Curvature Angle (β) of 90° with different Skew Angles under Vertical Excitations

Figure 5.16 In-plane Bending Moment for bridge models having Curvature Angle (β) of 30°, 60° and 90° with different Skew Angles under Vertical Excitations

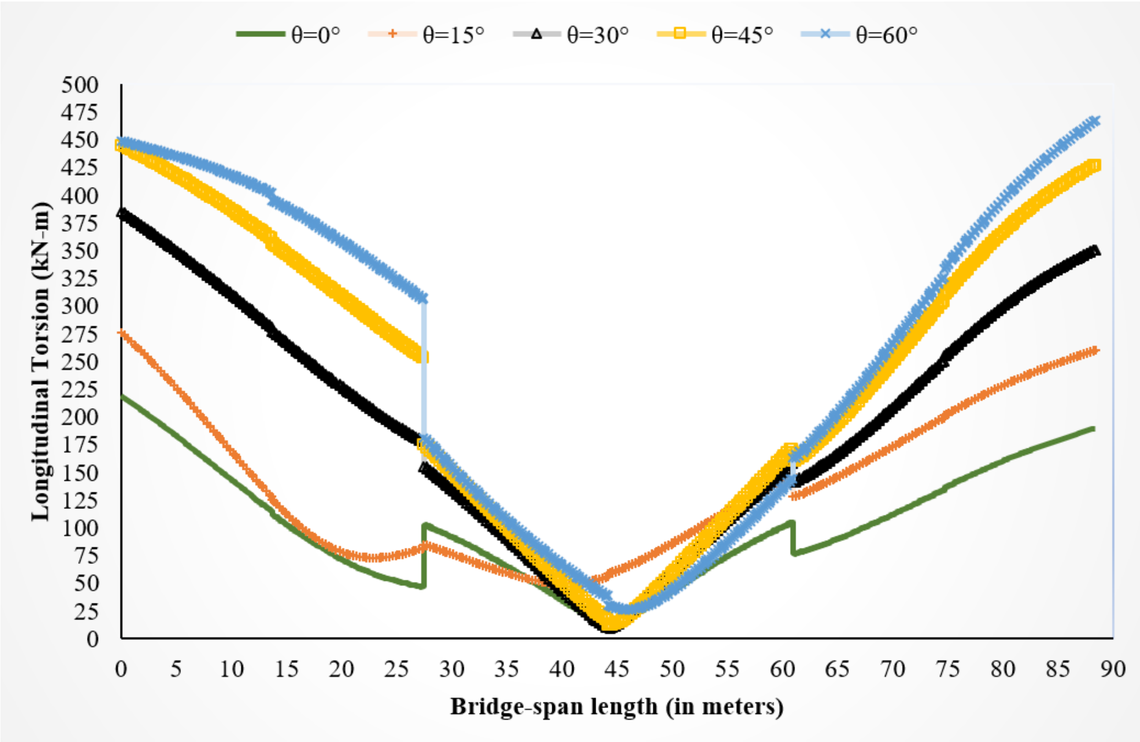
Usually, in-plane moment of the skew-curved bridges have been noticed to be decrease with increase in curvature angle as shown in figure 5.16. Whereas, the complex variation trend of in-plane bending moment has been observed for combination of various skew angles with any particular curvature angle.

5.3.2.3 Longitudinal Torsion

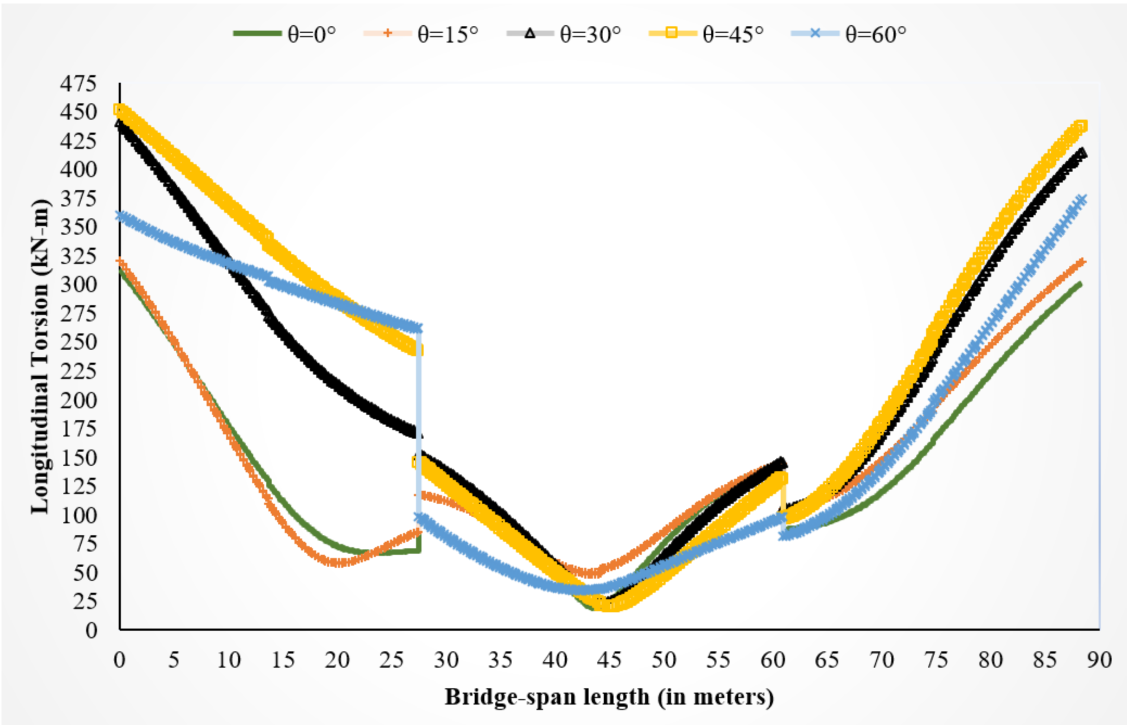
Moment demand of the deck about the tangential axis has been termed as *longitudinal torsion*. Longitudinal torsion under longitudinal component of seismic excitations for change in curvature angle from 30° to 90° is shown in figure 5.17.



a) Longitudinal Torsion for bridge models having Curvature Angle (β) of 30° with different Skew Angles under Longitudinal Excitations



b) Longitudinal Torsion for bridge models having Curvature Angle (β) of 60° with different Skew Angles under Longitudinal Excitations

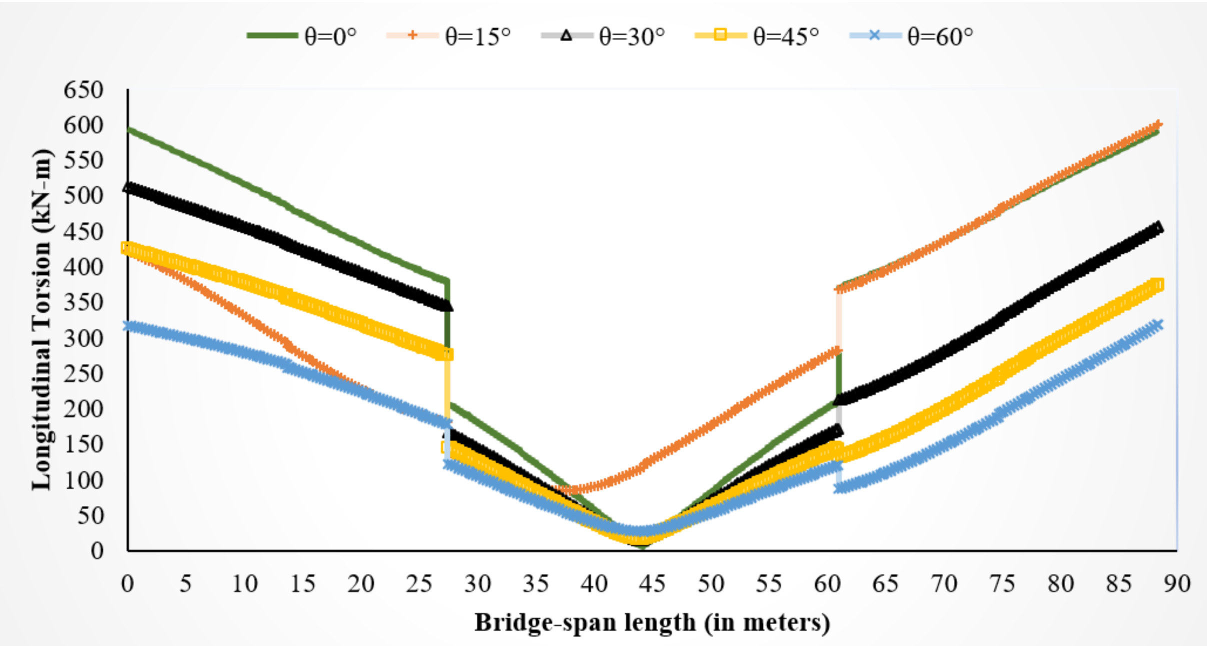


c) Longitudinal Torsion for bridge models having Curvature Angle (β) of 90° with different Skew Angles under Longitudinal Excitations

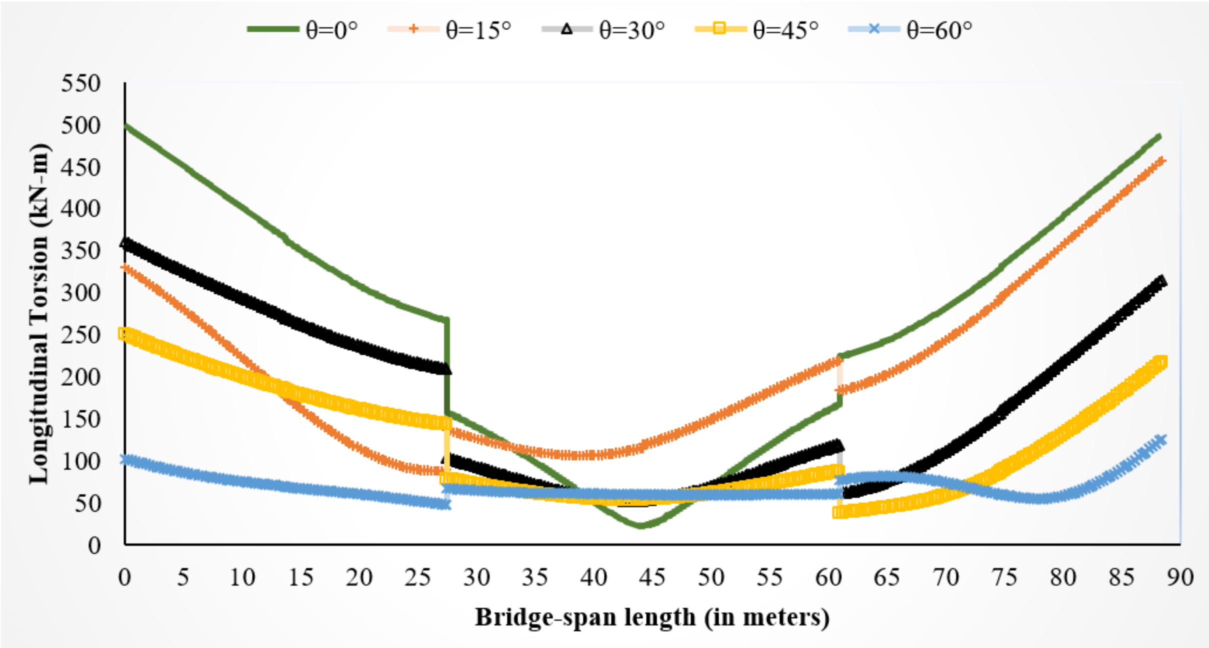
Figure 5.17 Longitudinal Torsion for bridge models having Curvature Angle (β) of 30°, 60° and 90° with different Skew Angles under Longitudinal Excitations

Increase in longitudinal torsional demand under longitudinal excitations has been noticed with variation of skew angle from 0° to 60°, for any constant curvature angle. However, the change in deck-curvature does not influence the behaviour of skew-curved bridges significantly as shown in figure 5.17.

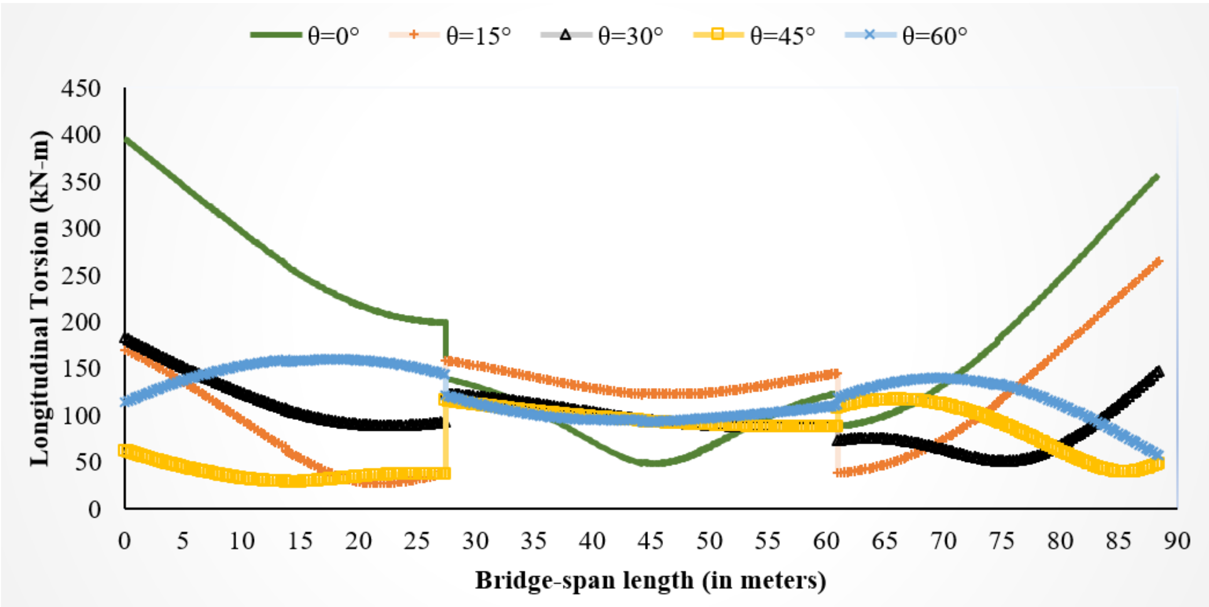
Longitudinal torsion under transverse component of seismic excitations for several curvature angles (i.e. from 30° to 90°) is shown in figure 5.18.



a) Longitudinal Torsion for bridge models having Curvature Angle (β) of 30° with different Skew Angles under Transverse Excitations



b) Longitudinal Torsion for bridge models having Curvature Angle (β) of 60° with different Skew Angles under Transverse Excitations

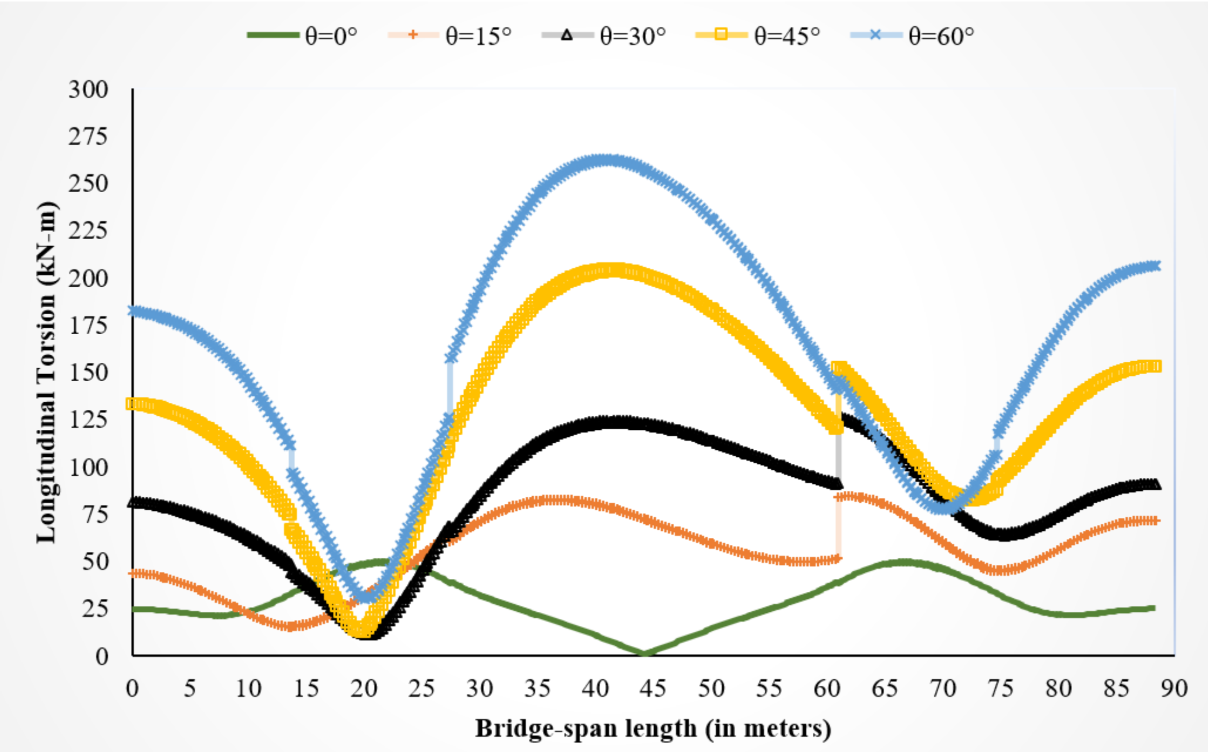


c) Longitudinal Torsion for bridge models having Curvature Angle (β) of 90° with different Skew Angles under Transverse Excitations

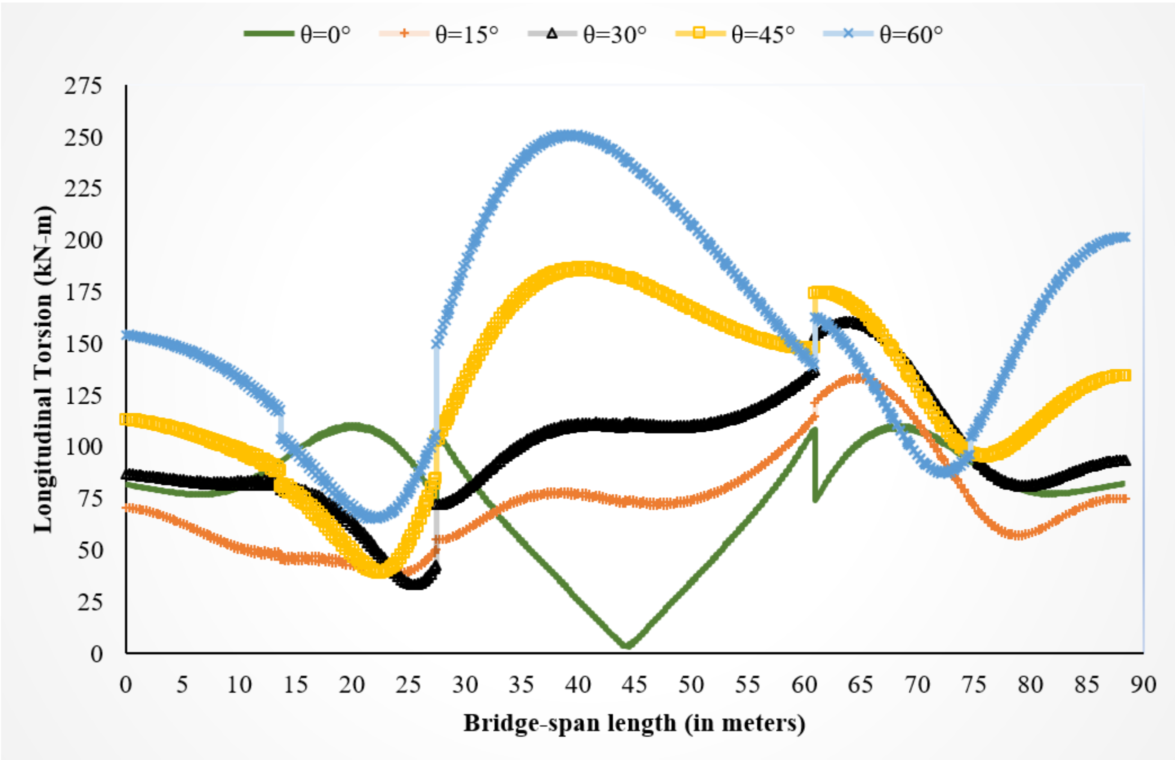
Figure 5.18 Longitudinal Torsion for bridge models having Curvature Angle (β) of 30°, 60° and 90° with different Skew Angles under Transverse Excitations

Usually it has been noticed that increase in degree of skewness and curvature of skew-curved bridges causes the decrease in longitudinal torsion under transverse excitations. However, this trend shows some complex behaviour for higher skew and curvature angles as shown in figure 5.18.

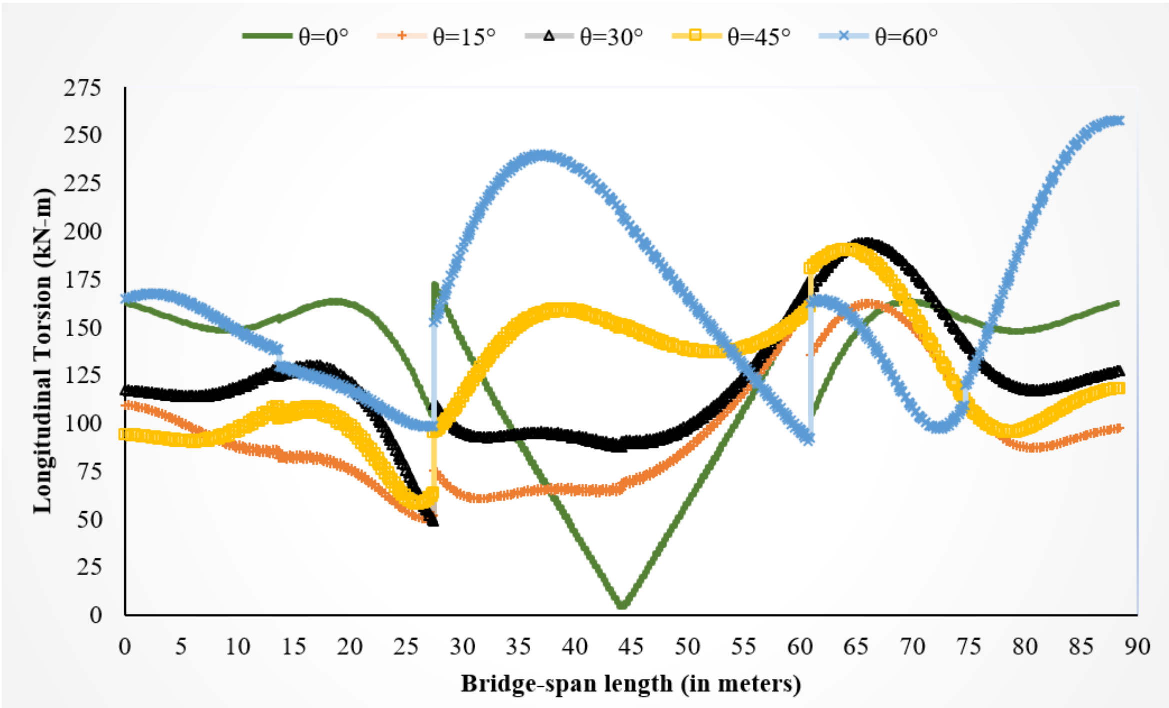
Longitudinal torsion under vertical component of seismic excitations for change in curvature angle from 30° to 90° is shown in figure 5.19(a), 5.19(b) and 5.19(c).



a) Longitudinal Torsion for bridge models having Curvature Angle (β) of 30° with different Skew Angles under Vertical Excitations



b) Longitudinal Torsion for bridge models having Curvature Angle (β) of 60° with different Skew Angles under Vertical Excitations



c) Longitudinal Torsion for bridge models having Curvature Angle (β) of 90° with different Skew Angles under Vertical Excitations

Figure 5.19 Longitudinal Torsion for bridge models having Curvature Angle (β) of 30°, 60° and 90° with different Skew Angles under Vertical Excitations

Complex variation trend of longitudinal torsion along with the span length of the bridge has been observed for combination of various skew angles with any particular curvature angle. With increase in curvature angle for any particular skew angle, decrease in longitudinal torsion has been observed as shown in figure 5.19. However, this decrease is very minor.

Figure 5.17, 5.18 and 5.19 conveys that in case of skew-curved bridges, couple has been experienced at intermediate bents under longitudinal, transverse and vertical components of seismic excitations.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this dissertation, seismic behaviour of skew-curved bridges has been studied under free and forced vibrations. Various skew-curved 3-D bridge models have been modelled in CSi Bridge. Skew angles of 0°, 15°, 30°, 45° and 60° has been taken and curvature angle has been varied as 0°, 30°, 60° and 90°. Modal analysis and Response Spectrum Analysis for the various skew-curved bridge configurations have been carried out using finite element analysis program CSiBridge. To facilitate the study of results for both modal and response spectrum analysis of skew-curved bridges, the changes have been made in the benchmark bridge which was a horizontally curved concrete box-girder bridge. Following conclusions have been drawn on the basis of these results;

1. Increase in curvature of the bridge deck leads to decrease the time period ratios of first horizontal (in-plane) vibration mode of the structure whereas increase in skew angle, increases the time period ratios.
2. For first longitudinal vibration mode, the time period ratios usually increase with increase in both skewness and curvature which signifies the decrease in natural frequency of the bridge structures. Therefore, stiffness of the structure should be increased to increase the natural frequency of the structure.
3. Modal analysis indicates time period ratios of horizontal vibration modes precedes the time period ratios of vertical vibration modes irrespective of skewness and curvature of the bridge.
4. Increase in skew angle causes the time period ratios to decrease usually in first out of plane vibration mode whereas increase in curvature angle causes increase in time period ratios of first out of plane vibration mode.
5. Mode participation factor of first in-plane vibration mode commonly increases with increase in skewness and curvature which signifies that this mode will contribute more significantly affect the dynamic behaviour of the structure as compared to the case of straight bridge configuration.
6. Mode participation factor of first longitudinal vibration mode decreases with the increase in deck-curvature whereas usually increases with increase in skew angle.

7. Usually, the mode participation factor of third out of plane vibration mode have very least changes with increase in curvature angle for any particular skew angle.
8. Mass participation ratio of first longitudinal vibrational mode usually increases as the skewness increases, whereas decreases as the deck-curvature increases.
9. Out-of-plane bending moment at mid span increases with increase curvature up to the curvature angle of 60° under longitudinal component of seismic excitations which reduces for curvature angle of 90°.
10. Out-of-plane bending moment of skew-curved bridges under transverse and vertical components of seismic excitations decreases with increase in skew angle for a certain angle of curvature. However, for combination of higher curvature with higher skewness, a different variation trend is noticed.
11. For a constant curvature angle, when skew angle is increased then in-plane bending moment under longitudinal component of seismic excitations decreases, whereas it increases under transverse component of seismic excitations.
12. When skew-curved bridges are subjected to vertical component of seismic excitations, then the in-plane bending moment does not varies linearly for various skew-curved bridge configuration and hence, forms a complex variation trend.
13. Longitudinal torsion of skew-curved bridges decreases with increase in skew angle for a particular curvature angle under all the three components (i.e. longitudinal, transverse and vertical) of seismic excitations, whereas the behaviour of bridge configuration having curvature angle of 90° and skew angle of 60° is different from all other bridge configurations.
14. Seismic behaviour for bridge geometries having higher deck-curvature along with the combination of higher skewness shows different behaviour than the other bridge configurations.
15. Usually, the moment demands increases as the bridge geometry become more complex i.e. the moment demands has been noticed to increase with increase in degree of skewness and curvature. However, if the decrease has been observed for any case, decrease was very less.

6.2 Recommendations for Future Work

Skew-curved bridges are the most important component of any transportation network. Thus, to ensure the safety of such kind of bridges, it is necessary to know their seismic behaviour.

Though, this study investigates the seismic behaviour of skew-curved bridges, but these results are limited to the three-span skew-curved bridges.

As an extension to this numerical study, the following research works have been recommended;

1. Seismic response of skew-curved bridges with positive skew angles has been investigated in this dissertation, which can be investigated for skew-curved bridges having negative skew angle, and combination of different skew angles at different abutments.
2. Time History Analysis should be performed on skew-curved bridges to investigate the seismic response of such bridges at different time intervals, as the response spectrum analysis gives only maximum response of the structure.
3. Base shear should be determined to investigate the base shear demand of skew-curved bridges.
4. Non-linear analysis should be performed to investigate the displacement behaviour of skew-curved bridges.
5. Parametric analysis which have been performed for three-span skew-curved bridges, can be extended to multi-span skew-curved bridges.

REFERENCE

1. Abdel-Mohti A. Seismic response assessment and recommendations for the design of skewed highway bridges (Doctoral dissertation), 2009.
2. Amjadian M, Kalantari A, Agrawal AK. Analytical study of the coupled motions of decks in skew bridges with the deck–abutment collision. Journal of Vibration and Control. 2018 Apr;24(7):1300-21.
3. Buckle I, Hube M, Chen G, Yen WH, Arias J. Structural performance of bridges in the offshore Maule earthquake of 27 February 2010. Earthquake Spectra. 2012 Jun;28(1_suppl1):533-52.
4. Kawashima K, Unjoh S, Hoshikuma JI, Kosa K. Damage of bridges due to the 2010 Maule, Chile, earthquake. Journal of Earthquake Engineering. 2011 Sep 1;15(7):1036-68.
5. Soleimani F, Yang CS, DesRoches R. The Effect of Superstructure Curvature on the Seismic Performance of Box-Girder Bridges with In-Span Hinges. InStructures Congress 2017 2017 (pp. 469-480).
6. Mangalathu S, Choi E, Park HC, Jeon JS. Probabilistic seismic vulnerability assessment of tall horizontally curved concrete bridges in California. Journal of Performance of Constructed Facilities. 2018 Dec 1;32(6):04018080..
7. Wilson T, Mahmoud H, Chen S. Seismic performance of skewed and curved reinforced concrete bridges in mountainous states. Engineering Structures. 2014 Jul 1;70:158-67.
8. Abdel-Mohti A, Pekcan G. Assessment of seismic performance of skew reinforced concrete box girder bridges. International Journal of Advanced structural engineering. 2013 Dec 1;5(1):1.
9. Rasouli SM, Mahmoodi M. Assessment the Effect of Skewness and Number of Spans in Seismic Behavior of Bridges with Continuous Multiple Spans Using MPA. KSCE Journal of Civil Engineering. 2018 Apr 1;22(4):1328-35.
10. Shamsabadi A. Three-dimensional nonlinear seismic soil-abutment-foundation-structureinteraction analysis of skewed bridges. University of Southern California; 2007.
11. Wu S. Investigation on the connection forces of shear keys in skewed bridges during earthquakes. Engineering Structures. 2019 Sep 1;194:334-43.
12. Wu S. Unseating mechanism of a skew bridge with seat-type abutments and a simplified method for estimating its support length requirement. Engineering Structures. 2019 Jul

15;191:194-205.
13. Yang CS, Werner SD, DesRoches R. Seismic fragility analysis of skewed bridges in the central southeastern United States. Engineering Structures. 2015 Jan 15;83:116-28.
14. [8] Watanabe, G., and Kawashima, K. Effectiveness of cable restrainer for mitigation rotation of a skewed bridge subjected to strong ground shaking. In: 13th world conference on earthquake engineering, Vancouver, Canada, 1–6 August 2004, Paper No. 789. Vancouver: University of British Columbia Press.
15. Wu S, Buckle IG, Itani AM, Istrati D. Experimental studies on seismic response of skew bridges with seat-type abutments. I: Shake table experiments. Journal of Bridge Engineering. 2019 Oct 1;24(10):04019096.
16. Wu S, Buckle IG, Itani AM, Istrati D. Experimental Studies on Seismic Response of Skew Bridges with Seat-Type Abutments. II: Results. Journal of Bridge Engineering. 2019 Oct 1;24(10):04019097.
17. Zakeri B, Padgett JE, Amiri GG. Fragility analysis of skewed single-frame concrete box-girder bridges. Journal of Performance of Constructed Facilities. 2014 Jun 1;28(3):571-82.
18. Ghotbi AR. Performance-based seismic assessment of skewed bridges with and without considering soil-foundation interaction effects for various site classes. Earthquake Engineering and Engineering Vibration. 2014 Sep 1;13(3):357-73.
19. Bhatnagar UR, Banerjee S. Fragility of skewed bridges under orthogonal seismic ground motions. Structure and Infrastructure Engineering. 2015 Sep 2;11(9):1113-30.
20. Bayat M, Daneshjoo F, Nisticò N. A novel proficient and sufficient intensity measure for probabilistic analysis of skewed highway bridges. Structural Engineering and Mechanics. 2015 Sep 1;55(6):1177-202.
21. Noori HZ, Amiri GG, Nekooei M, Zakeri B. Seismic fragility assessment of skewed MSSS-I girder concrete bridges with unequal height columns. Journal of Earthquake and Tsunami. 2016 Mar 16;10(01):1550013.
22. Mangalathu S, Heo G, Jeon JS. Artificial neural network based multi-dimensional fragility development of skewed concrete bridge classes. Engineering Structures. 2018 May 1;162:166-76.
23. Maragakis EA, Jennings PC. Analytical models for the rigid body motions of skew bridges. Earthquake engineering & structural dynamics. 1987 Nov;15(8):923-44.
24. Meng JY, Lui EM, Liu Y. Dynamic response of skew highway bridges. Journal of

earthquake engineering. 2001 Apr;5(02):205-23.
25. Maleki S. Free vibration of skewed bridges. Journal of Vibration and Control. 2001 Oct;7(7):935-52.
26. Amjadian M. Seismic behavior control of a skewed highway bridge using passive (seismic isolation) and semi-active methods (Doctoral dissertation, M. Sc. thesis, 2010 International Institute of Earthquake Engineering and Seismology, Tehran, Iran (in Farsi)).
27. Kalantari A, Amjadian M. An approximate method for dynamic analysis of highway skewed bridges with continuous deck. In9th US National and 10th Canadian Conference on Earthquake Engineering 2010, Including Papers from the 4th International Tsunami Symposium vol 2010 (Vol. 5).
28. Kalantari A, Amjadian M. An approximate method for dynamic analysis of skewed highway bridges with continuous rigid deck. Engineering Structures. 2010 Sep 1;32(9):2850-60.
29. Kalantari A, Amjadian M. Investigation of the seismic pounding effect on torsional response of highway bridges. In6th international conference of seismology and earthquake engineering 2011 May.
30. Dimitrakopoulos EG. Analysis of a frictional oblique impact observed in skew bridges. Nonlinear dynamics. 2010 Jun 1;60(4):575-95.
31. Dimitrakopoulos EG. Seismic response analysis of skew bridges with pounding deck–abutment joints. Engineering Structures. 2011 Mar 1;33(3):813-26.
32. Ghobarah AA, Tso WK. Seismic analysis of skewed highway bridges with intermediate supports. Earthquake Engineering & Structural Dynamics. 1973;2(3):235-48.
33. Özşahin E, Pekcan G. Effect of torsional ground motion on the seismic response of highway bridges. Bulletin of Earthquake Engineering. 2019 May 15;17(5):2603-25.
34. OpenSees. Open system for earthquake engineering simulation, Berkeley, CA, USA.
35. SAP 2000. Computers and Structures, Inc., Berkeley, California, USA.
36. Maleki S. Deck modeling for seismic analysis of skewed slab-girder bridges. Engineering Structures. 2002 Oct 1;24(10):1315-26.
37. Lou L, Zerva A. Effects of spatially variable ground motions on the seismic response of a skewed, multi-span, RC highway bridge. Soil Dynamics and Earthquake Engineering. 2005 Aug 1;25(7-10):729-40.
38. Pottatheere P, Renault P. Seismic vulnerability assessment of skew bridges.

InProceedings of Fourteenth World Conference on Earthquake Engineering. Beijing, China 2008 Oct.

39. Reddy EP, Dasgupta K. Estimation of Seismic Capacity of Reinforced Concrete Skew Bridge by Nonlinear Static Analysis. InAdvances in Structural Engineering 2015 (pp. 1391-1401). Springer, New Delhi.
40. PEER NGA Database. Retrieved from<http://peer.berkeley.edu/nga/>[accessed in July, 2016].
41. Imbsen RA, Lea J, Kaliakin V, Perano KJ, Gates J, Perano S. SEISAB-I, Seismic Analysis of Bridges, User Manual. Report to National Science Foundation by Engineering Computer Corporation. 1984 Oct.
42. Wakefield RR, Nazmy AS, Billington DP. Analysis of seismic failure in skew RC bridge. Journal of Structural Engineering. 1991 Mar;117(3):972-86.
43. Meng JY, Lui EM. Seismic analysis and assessment of a skew highway bridge. Engineering Structures. 2000 Nov 1;22(11):1433-52.
44. Federal Highway Administration (FHWA). Seismic Design of Bridges, Design Example No. 4 — Three-span Continuous CIP Concrete Bridge. *Publication No. FHWA-SA-97-009*, October 1996.
45. Abdel-Mohti A, Pekcan G. Seismic response of skewed RC box-girder bridges. Earthquake Engineering and Engineering Vibration. 2008 Dec 1;7(4):415-26.
46. Kaviani P. Performance-based Seismic Assessment of Skewed Bridges. University of California, Irvine; 2011.
47. Kaviani P, Zareian F, Taciroglu E. Seismic behavior of reinforced concrete bridges with skew-angled seat-type abutments. Engineering Structures. 2012 Dec 1;45:137-50.
48. Kwon OS, Jeong SH. Seismic displacement demands on skewed bridge decks supported on elastomeric bearings. Journal of Earthquake Engineering. 2013 Oct 3;17(7):998-1022.
49. Han Q, Chen JY, Du XL, Huang C. Nonlinear seismic response of skewed highway bridges subjected to bidirectional near-fault ground motions. Journal of Bridge Engineering. 2017 Jul 1;22(7):04017032.
50. Omranian E, Abdelnaby AE, Abdollahzadeh G. Seismic vulnerability assessment of RC skew bridges subjected to mainshock-aftershock sequences. Soil Dynamics and Earthquake Engineering. 2018 Nov 1;114:186-97.
51. Maleki S, Bisadi V. Orthogonal effects in seismic analysis of skewed bridges. Journal

of Bridge Engineering. 2006 Jan;11(1):122-30.
52. Bayat M, Daneshjoo F, Nisticò N. The effect of different intensity measures and earthquake directions on the seismic assessment of skewed highway bridges. Earthquake Engineering and Engineering Vibration. 2017 Jan 1;16(1):165-79.
53. Nielson BG. Analytical fragility curves for highway bridges in moderate seismic zones (Doctoral dissertation, Georgia Institute of Technology), 2005.
54. Noori HR, Memarpour MM, Yakhchalian M, Soltanieh S. Effects of ground motion directionality on seismic behavior of skewed bridges considering SSI. Soil Dynamics and Earthquake Engineering. 2019 Dec 1;127:105820.
55. Kun C, Jiang L, Chouw N. Influence of pounding and skew angle on seismic response of bridges. Engineering Structures. 2017 Oct 1;148:890-906.
56. Kun C, Yang Z, Chouw N. Seismic performance of skewed bridges with simultaneous effects of pounding and supporting soil. Engineering Structures. 2018 Nov 1;174:26-38.
57. Yen WP, Chen G, Yashinski M, Hashash Y, Holub C, Wang K, Guo X. Lessons in bridge damage learned from the Wenchuan earthquake. Earthquake Engineering and Engineering Vibration. 2009 Jun 1;8(2):275-85.
58. Kawashima K, Takahashi Y, Ge H, Wu Z, Zhang J. Reconnaissance report on damage of bridges in 2008 Wenchuan, China, earthquake. Journal of Earthquake Engineering. 2009 Sep 30;13(7):965-96.
59. Han Q, Du X, Liu J, Li Z, Li L, Zhao J. Seismic damage of highway bridges during the 2008 Wenchuan earthquake. Earthquake Engineering and Engineering Vibration. 2009 Jun 1;8(2):263-73.
60. Guo J, Zhong J, Dang X, Yuan W. Influence of Multidirectional Cable Restrainer on Seismic Fragility of a Curved Bridge. Journal of Bridge Engineering. 2019 Mar 1;24(3):04018126.
61. Sarraf Shirazi R, Pekcan G, Itani A. Analytical fragility curves for a class of horizontally curved box-girder bridges. Journal of Earthquake Engineering. 2018 May 28;22(5):881-901.
62. Wang Z, Lee GC. A comparative study of bridge damage due to the Wenchuan, Northridge, Loma Prieta and San Fernando earthquakes. Earthquake Engineering and Engineering Vibration. 2009 Jun 1;8(2):251-61.
63. Sun Z, Wang D, Guo X, Si B, Huo Y. Lessons learned from the damaged Huilan

interchange in the 2008 Wenchuan earthquake. Journal of bridge engineering. 2012 Jan 1;17(1):15-24.

64. Amjadian M, Agrawal AK. Rigid-body motion of horizontally curved bridges subjected to earthquake-induced pounding. Journal of Bridge Engineering. 2016 Dec 1;21(12):04016090.
65. Tondini N, Stojadinovic B. Probabilistic seismic demand model for curved reinforced concrete bridges. Bulletin of earthquake engineering. 2012 Oct 1;10(5):1455-79.
66. Lai LY. Seismic Analysis of Horizontally Curved Girder Bridges. In7th. Canadian Conference on Earthquake Engineering, Montreal, Quebec 1995 (pp. 747-754).
67. Pahlavan H, Zakeri B, Amiri GG, Shaianfar M. Probabilistic vulnerability assessment of horizontally curved multiframe RC box-girder highway bridges. Journal of Performance of Constructed Facilities. 2016 Jun 1;30(3):04015038.
68. Abbasi M, Abedini MJ, Zakeri B, Ghodrati Amiri G. Seismic vulnerability assessment of a Californian multi-frame curved concrete box girder viaduct using fragility curves. Structure and Infrastructure Engineering. 2016 Dec 1;12(12):1585-601.
69. Li X, Zhang DY, Yan WM, Chen YJ, Xie WC. Shake-table test for a typical curved bridge: Wave passage and local site effects. Journal of Bridge Engineering. 2015 Feb 1;20(2):04014061.
70. Ni Y, Chen J, Teng H, Jiang H. Influence of earthquake input angle on seismic response of curved girder bridge. Journal of traffic and transportation engineering (English edition). 2015 Aug 1;2(4):233-41.
71. Rogers LP, Seo J. Vulnerability sensitivity of curved precast-concrete I-girder bridges with various configurations subjected to multiple ground motions. Journal of Bridge Engineering. 2017 Feb 1;22(2):04016118.
72. Kou CH, Benzley SE, Huang JY, Firmage DA. Free vibration analysis of curved thin-walled girder bridges. Journal of Structural Engineering. 1992 Oct;118(10):2890-910.
73. Serdar N, Folić R. Comparative analysis of modal responses for reinforced concrete (RC) straight and curved bridges. Procedia engineering. 2016 Jan 1;156:403-10.
74. Akbari R, Maadani S, Maalek S. Dynamic Assessment of Horizontally Curved Reinforced Concrete Box-Girder Bridges. Practice Periodical on Structural Design and Construction. 2019 Nov 1;24(4):04019024.
75. Jeon JS, DesRoches R, Kim T, Choi E. Geometric parameters affecting seismic fragilities of curved multi-frame concrete box-girder bridges with integral abutments.

Engineering Structures. 2016 Sep 1;122:121-43.
76. Banerjee A, Chanda A, Das R. Seismic analysis of a curved bridge considering deck-abutment pounding interaction: an analytical investigation on the post-impact response. Earthquake Engineering & Structural Dynamics. 2017 Feb;46(2):267-90.
77. Abbasi M, Moustafa MA. Effect of shear keys on seismic response of irregular bridge configurations. Transportation Research Record. 2017;2642(1):155-65.
78. Hou G, Chen S. Bent Connection Options for Curved and Skewed SMC Bridges in Low-to-Moderate Seismic Regions. Practice Periodical on Structural Design and Construction. 2017 Nov 1;22(4):04017011.
79. Serdar N, Folić R. Vulnerability and optimal probabilistic seismic demand model for curved and skewed RC bridges. Engineering Structures. 2018 Dec 1;176:411-25.
80. Wilson T. Seismic performance of skewed and curved RC bridges (Doctoral dissertation, Colorado State University), 2013.
81. Wilson T, Chen S, Mahmoud H. Analytical case study on the seismic performance of a curved and skewed reinforced concrete bridge under vertical ground motion. Engineering Structures. 2015 Oct 1;100:128-36.
82. Li Q, Cheng M, Yin J, Zhou C. Study on seismic disaster mechanism of irregular C-shaped curved bridge with high piers. KSCE Journal of Civil Engineering. 2016 May 1;20(4):1429-36.
83. Williams D, Godden W. Seismic response of long curved bridge structures: experimental model studies. Earthquake Engineering & Structural Dynamics. 1979 Mar;7(2):107-28.
84. Kawashima K, Penzien J. Theoretical and experimental dynamic behaviour of a curved model bridge structure. Earthquake Engineering & Structural Dynamics. 1979 Mar;7(2):129-45.
85. Li N, Xu W, Chen Y, Yan W. Experimental research on adjacent pounding effect of midspan curved bridge with longitudinal slope. Engineering Structures. 2019 Oct 1;196:109320.
86. Tirasit P, Kawashima K. Seismic torsion response of skewed bridge piers. InProceedings of the JSCE Earthquake Engineering Symposium 2005 (Vol. 28, pp. 116-116). Japan Society of Civil Engineers.
87. Ghotbi AR. Performance-based seismic assessment of skewed bridges with and without considering soil-foundation interaction effects for various site classes. Earthquake

Engineering and Engineering Vibration. 2014 Sep 1;13(3):357-73.

88. Kawashima K, Tirasit P. Effect of nonlinear seismic torsion on the performance of skewed bridge piers. Journal of Earthquake Engineering. 2008 Aug 6;12(6):980-98.
89. Amjadian M, Agrawal AK. Torsional response of horizontally curved bridges subjected to earthquake-induced pounding. In16th World Conference on Earthquake Engineering 2017 Jan.
90. Deepu SP, Prajapat K, Ray-Chaudhuri S. Seismic vulnerability of skew bridges under bi-directional ground motions. Engineering Structures. 2014 Jul 15;71:150-60.
91. Maleki S. Seismic modeling of skewed bridges with elastomeric bearings and side retainers. Journal of bridge Engineering. 2005 Jul;10(4):442-9.
92. Huo Y, Zhang J. Effects of pounding and skewness on seismic responses of typical multispan highway bridges using the fragility function method. Journal of Bridge Engineering. 2013 Jun 1;18(6):499-515.
93. Federal Highway Administration (FHWA). Seismic Design of Bridges, Design Example No. 6 — Three-span Continuous CIP Concrete Bridge. *Publication No. FHWA-SA-97-011*, October 1996.
94. Birhane, T.H. Seismic behaviour of skewed and curved bridges. M. Tech. dissertation, Department of earthquake engineering, Indian institute of technology, Roorkee; 2008.

PUBLICATIONS

JOURNAL

1. Sandhu D, Gupta T. Free vibration analysis of bridges having combined skewness and curvature. Test Engineering and Management. 2020 March 12; Volume 83 Page Number: 610 – 619.
2. Sandhu D, Gupta T. State of the art literature review upon seismic response of skew and curved bridges. Communicated to Frontiers of Civil Engineering

CONFERENCE

1. Sandhu D, Gupta T. Modal analysis of Reinforced Concrete Skew-Curve Box-Girder Bridges. 8th International Conference on Advancements in Engineering and Technology. 20th and 21st March 2020. Bhai Gurdas Institute of Engineering, Sangrur, Punjab, India.

   Conference is postponed due to COVID-19.

2. Gupta T, Sandhu D. Seismic Analysis of Skew-Curved Bridges under Longitudinal Excitations. 3rd International Conference on Trends and Recent Advances in Civil Engineering. 20th and 21st August 2020. Amity University Uttar Pradesh, Noida, India.

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