Comparison of the Seismic Performance of Equivalent Straight and Curved Bridges due to Transverse Seismic Excitation

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ABSTRACT:

This study compares the transverse response of equivalent straight and curved bridges to investigate the hypothesis made by the AASHTO Guide Specification for LRFD Seismic Bridge Design that curved bridges may be analyzed as if they are straight, provided the bridge is regular. For this purpose curved bridges with subtended angles of 15, 30, 45, 60, 75, and 90 degrees, having the total arc length equal to the length of the equivalent straight bridge, are considered. Other parameters considered in this study are the number of spans (two, four and six), and abutment restraints (9 different conditions). The equivalent straight bridges are designed using the Direct Displacement Based Design (DDBD) procedure including these parameters. The resulting designs are then analyzed with Inelastic Time History Analysis using both straight and curved geometry. Each bridge was subjected to 7 spectrum compatible time histories. Individual as well as average results are tabulated.

It is observed that deviation in the response of the curved bridge from the equivalent straight bridge increases as the subtended angles become larger and the number of spans reduces. It was also found that the type and degree of abutment restraint is a rather critical parameter in controlling the response of the bridge, the most significant being longitudinal abutment restraint which had a profound impact on results.

Keywords: Direct Displacement Based Design; Seismic Design of horizontally Straight and Curved Bridge; Transverse Seismic Design of Curved Bridge

1. INTRODUCTION

Horizontally curved bridges make up a significant portion of the bridge population is United States. These bridges are often used to construct large and complex highway interchanges into densely populated areas to avoid traffic congestion and to increase the aesthetics of the structure. However, due to the curvature effect, the dynamic behavior of such bridges is more complicated than straight bridges, thus inherently creating challenges for engineers.

The AASHTO Guide Specification for LRFD Seismic Bridge Design defines irregularity based on geometry, namely: (1) Superstructure curvature as measured by the subtended angle along the entire bridge (see Fig. 2.2), (2) Relative lengths of adjacent spans, and (3) Relative stiffness of adjacent bents which is then used to define the level of analysis rigor. For example, Table 1.1 defines the AASHTO Guide Specification limits to the above irregularities. If a bridge satisfies these limits, AASHTO indicates that it may be designed and analyzed using the simplest analysis method, which is defined as an ‘equivalent static analysis’. In the event that one or more of the irregularities exceeds the limits, then an ‘elastic dynamic analysis’ is required. If P-Delta effects are significant or if the bridge is base isolated with a high degree of damping, then ‘nonlinear time history analysis’ is to be used. Furthermore, in the case of a curved bridge, AASHTO suggests that the analysis model can be that of a straight bridge if the subtended angle is less than 90 degrees. i.e., even if a bridge is considered irregular due to a subtended angle greater than 30 degrees as noted in Table 1, it may still be analyzed as if it were straight as long as the subtended angle is less than 90 degrees (albeit with elastic dynamic or inelastic time history analysis).

Table 1.1 Limits to irregularities that define required analysis method (AASHTO, 2009)

Number of Spans	2	3	4	5	6
Maximum subtended angle, degrees	30	30	30	30	30
Maximum span length ratio in adjacent spans	3	2	2	1.5	1.5
Maximum pier stiffness ratio in adjacent spans	NA	4	4	3	2

Akbari (2008), and Akbari and Maalek (2010) carried out research on a wider range of regular and irregular bridge configurations to investigate the adequacy of different analysis methods as well as the applicability of the simplified ones specified by the AASHTO Guide Specifications for the seismic analysis of straight bridges. They concluded that in cases where the flexibility of the columns of a single-column-bent viaduct was rather high, the effects of the higher modes diminish and as a consequence, the structure may be categorized as regular. In such cases, the results obtained from a simplified analysis method may be considered adequate for practical design purposes. On the other hand, for the analysis of irregular structures having rather short and stiff columns, the multi-mode method is to be employed as the minimum requirement for the attainment of meaningful results. They also confirmed that limiting the pier stiffness ratio in adjacent spans to 4 is an appropriate value as defined in the AASHTO code. However, none of the studies to date have been aimed to address the issue of analysis in regard to curved bridges. Thus, the purpose of this paper is to study the concept of curved bridge irregularity as defined in the AASHTO Guide Specification and to incorporate different abutment restraint conditions in the definition of curved bridge irregularity. In this regard an analytical study is performed to compare the seismic performance of regular curved bridges with that of equivalent straight bridges. To do so, the equivalent straight bridge is first designed using the Direct Displacement-Based Design (DDBD) procedure. This procedure is well established for the design of horizontally straight bridges outlined by Kowalsky (2002), and the textbook by Priestley et al. (2007) and is not described in this paper due to page limitations. Recently the DDBD procedure was established for the design of reinforced concrete deck arch bridges by Easa et al. (2011) using the basic idea of Kowalsky (2002). For the verification of the DDBD procedure and to compare the response of the equivalent straight and curved bridge model, inelastic time history analyses (ITHA) are carried out using the structural analysis package RUAUMOKO 3D by Carr (2009). The results obtained from the analysis are used to determine whether the curved bridge with different subtended angles can be modelled as an equivalent straight bridge. These results are summarize from 1323 ITHA which are produced for 2, 4, and 6 span bridges with 9 abutment restraint cases for straight and curved bridges. Each configuration was analyzed using seven spectrum compatible earthquake time histories.

2. BRIDGE CONFIGURATIONS AND MODELING

2.1. Typology of Straight and Curved Bridges

The three configurations of bridges considered in this study are shown in Fig. 2.1. The bridges consist of 2, 4 and 6 spans with equal span lengths of 28 m. The columns have a solid circular cross section with a radius of 2.5m and height equal to 15m. The local axes for the deck and piers along with global axes for the entire bridge structure are shown in Fig. 2.1. The local axes are used to provide the section properties of the elements and the global axes are used to show the displacements. In order to compare the results of the straight and curved bridges, the total arc lengths of the curved bridges are kept equal to the length of the straight bridge, as suggested by the AASHTO Guide Specification (2009). The plan views of the equivalent straight bridges, represented by ST, and curved bridges with six different subtended angles of 15, 30, 45, 60, 75, and 90 degrees are represented by C15, C30, C45, C60, C75, and C90 respectively as shown in Fig. 2.2. For the straight bridges the abutment local axes are the same as the global axes as shown in Fig. 2.1 while for the curved bridges the abutment local axes make an angle with the global X-axis as shown in Fig. 2.2. Depending upon the curvature of the superstructure this angle varies i.e. smaller for C15 and larger for C90.

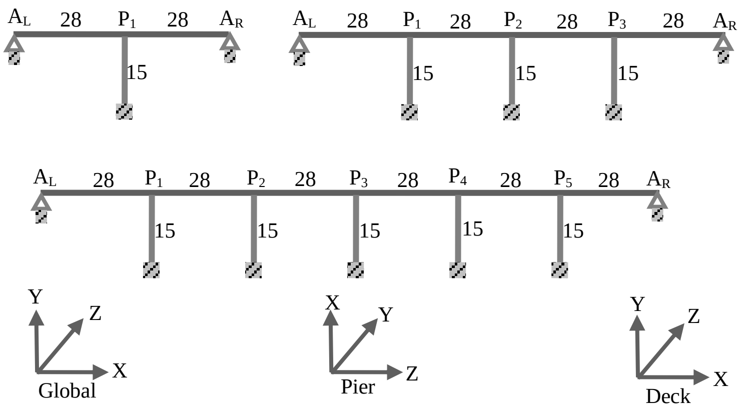


Figure 2.1 Typical configurations of 2, 4, and 6 span equivalent straight bridges

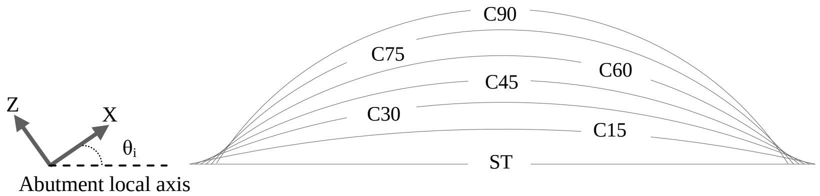


Figure 2.2 Plane view of straight and curved bridge with different subtended angles

2.2. Abutment Restraint Cases

During the course of this study it was noted that abutment restraint conditions will likely impact the seismic response of curved bridges, perhaps more than any other parameter. To understand the difference in response of equivalent straight and curved bridges, nine abutment restraint cases are defined as shown in Table 2.1. Several other parameters will affect the seismic response of bridges, such as the number of spans, adjacent span length ratio, movement joints, adjacent bent stiffness ratio, and torsional stiffness of the superstructure, among others. Some of these issues have been previously studied with regard to straight bridges, and will likely impact curved bridges as well. However, this study is focused on parameters that are likely to uniquely impact curved bridge response.

Table 2.1 Abutment restraint cases for straight and curved bridges (U- unrestrained, R- restrained, P.R- partial restraint (finite stiffness))

Case. No	Abutment translational D.O.F (local)			Abutment rotational D.O.F (local)		
	X-axis	Y-axis	Z-axis	X-axis	Y-axis	Z-axis
1	R	R	R	U	U	U
2	P.R	R	R	U	U	U
3	R	R	P.R	U	U	U
4	P.R	R	P.R	U	U	U
5	U	R	R	U	U	U
6	R	R	U	U	U	U
7	U	R	U	U	U	U
8	U	R	P.R	U	U	U
9	P.R	R	U	U	U	U

2.3. Analytical Model of the Bridge

A number of researchers have been developed and employed various types of frame element models for the seismic analysis of bridges. Wakefield et al. (1991) employed beam elements to model the box girder bridge deck, supporting columns, and cap beams of a reinforced concrete bridge. McCallen and

Romstad (1994) simulated the bridge deck and cap beams by a flexible beam and a series of rigid bars, respectively. Meng and Lui (2002) proposed a dual beam model capable of capturing the skewness of the bridge deck. Sourabh and Ashok (2009) compare their proposed frame model and finite element model for an S curved viaduct and concluded that the frame element model can capture the first 10 modes with reasonable accuracy. Despite the simplicity and ease of application, frame elements can provide reasonably good approximations to response if the major structural characteristics of the actual structure are modeled properly.

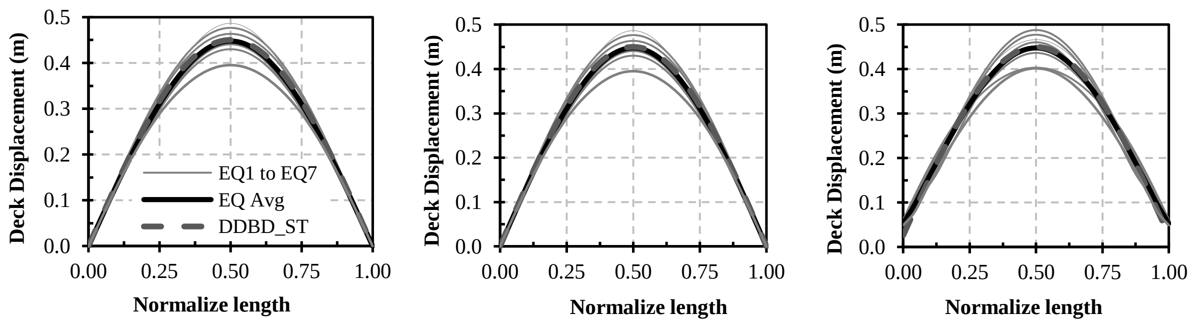
In this study frame element models are employed. The superstructures are modeled as linear-elastic beam-column (line) elements with material properties corresponding to cracked reinforced concrete. Depending upon the restraint case, springs are employed to model the abutment. The total superstructure weight is 180kN/m. In addition, 1/3rd of the column weight is lumped at the superstructure height as suggested by Priestley et al. (2007). Based on tributary area, these masses are distributed to the nodes of the superstructure by dividing each span of the superstructure into four elements. For the curved bridges, four linear elements are used to form the curved superstructure between two supports. The base of the pier is considered to be rigidly connected to the foundation and pinned supported with the superstructure. For the straight bridges the abutment restraints are provided in global axes as shown in Fig. 2.1 while for the curved bridge local axes which make an angle with the global X-axis as shown in Fig. 2.2 are used.

3. ANALYSIS RESULTS OF DDBD AND ITHA

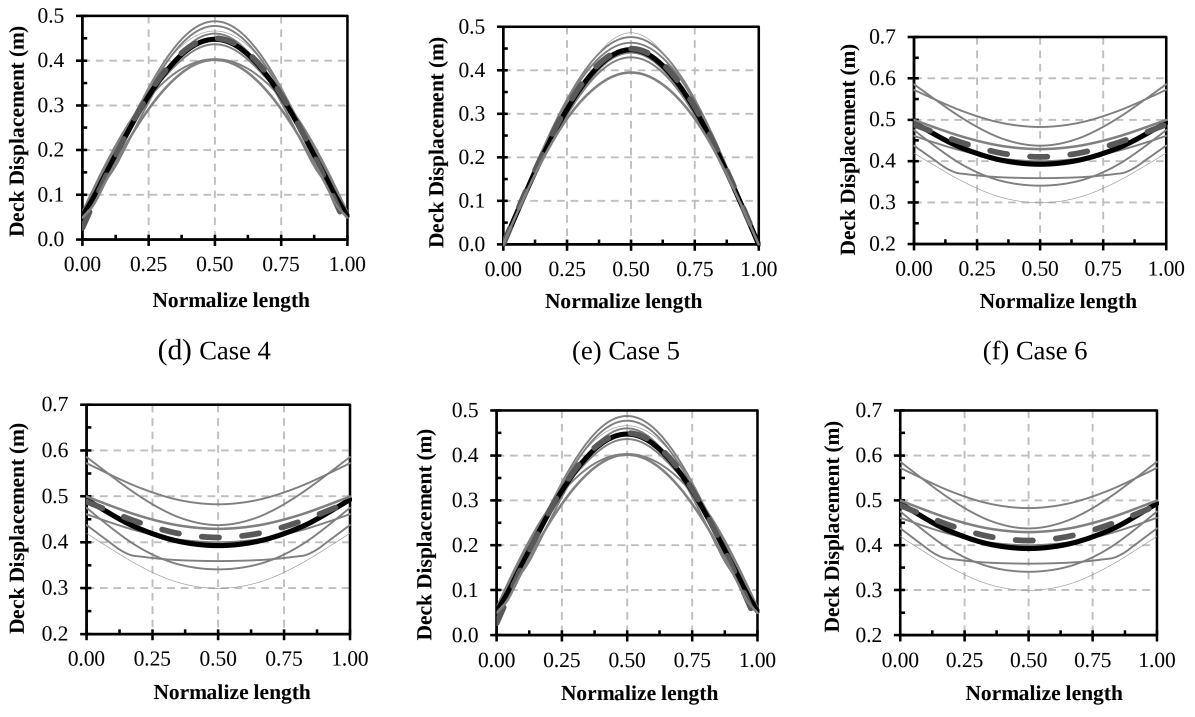
Having established the basic parameters for the study, the first step is to design each straight bridge in Fig. 2.1 using the DDBD procedure for the 9 abutment restraint conditions of Table 2.1. The design is based on the columns reaching a 3 percent drift limit with the abutments limited to 50 mm of displacement (for the partially restrained cases in Table 2.1). The resulting designs are analyzed using dynamic inelastic time history analysis (ITHA). Analysis is conducted with the program RUAUMOKO 3D by Carr (2009) utilizing the modified Takeda degrading stiffness model (Otani, 1981) to characterize non-linear response at the pier base. The analyses of the structures are performed using seven real acceleration time histories obtained from the PEER NGA database. These time histories are made compatible with the spectra used for design.

3.1. Evaluation of DDBD Performance for Straight Bridges

The results for all 9 abutment restraint conditions for the 6 span bridges are shown in Figs. 3.1 and 3.2. The 2 and 4 span bridges are not shown here, but will be summarized later. Fig. 3.1 presents the target displacement profile for the straight bridge along with the analysis results under the influence of the 7 different earthquakes and the average of the 7 analyses. Results are shown for each of the 9 abutment restraint conditions. The purpose of these figures is to demonstrate the accuracy of the DDBD approach in capturing the response of straight bridges.



(a)Case 1 (b) Case 2 (c) Case 3



(d) Case 4 (e) Case 5 (f) Case 6

(g) Case 7 (h) Case 8 (i) Case 9

Figure 3.1 Comparison of ITHA to design target displacements for straight bridges

In cases where there is either partial or full translational restraint (Cases 1, 2, 3, 4, 5, and 8), the agreement between the target displacement patterns and inelastic time history analysis is very good on average, with little scatter among individual analysis results. In cases 6, 7, and 9 where there is no abutment translational restraint (global Z-axis as shown in Fig. 2.1), the average results are still very good, albeit with more scatter from the individual inelastic time history analysis results.

3.2. Comparison of ITHA Results for Straight and Curved Bridges

3.2.1. Comparison of the displacement response

In-order to compare the seismic performance of the equivalent straight bridge with the curved bridges having different subtended angles, ITHA of the curved bridges is carried out using the design capacities of the equivalent straight bridge. The results obtained are shown in Fig. 3.2 for all 9 abutment restraint conditions. The heavy dashed line in each figure represents the average of the seven analysis results for the equivalent straight bridge (identical to the solid line in Fig. 3.1) while the remaining lines are the average of the seven results for the curved bridges with different subtended angles. From this data, the following observations can be made: (1) For bridges that contain some degree of restraint at the abutment along the bridge longitudinal direction (local X-axis, cases 1, 2, 3, 4, 6, and 9), significant errors are introduced if a curved bridge is analyzed as if it were straight. In many cases, actual deformations (which represent the displacement profile of the deck in global Z-axis relative to the un-deformed position) are smaller than those obtained from analysis of a straight bridge. This is a consequence of the stiffening effect caused by the longitudinal restraint and superstructure curvature where arch action develops as high axial loads are generated in the superstructure. This effect increases as the subtended angle increases since more arching action takes place. While such a result is conservative for deformations, the net result is that the bridge would respond, in some cases, essentially elastic at the columns, while sustaining very high forces at the abutments as tabulated in section 3.2.2. If the bridges are analyzed as curved, the abutment force demands would be severely underestimated, resulting in potential failure at that location. (2) In the remaining cases (5, 7, and 8) where there is no abutment longitudinal restraint (local X-axis), the impact of superstructure curvature is minimal, although slightly increasing as the subtended angle increases. Bridges of 2 and 4 spans were also designed and analyzed and a similar result was obtained which are presented in section 3.3.

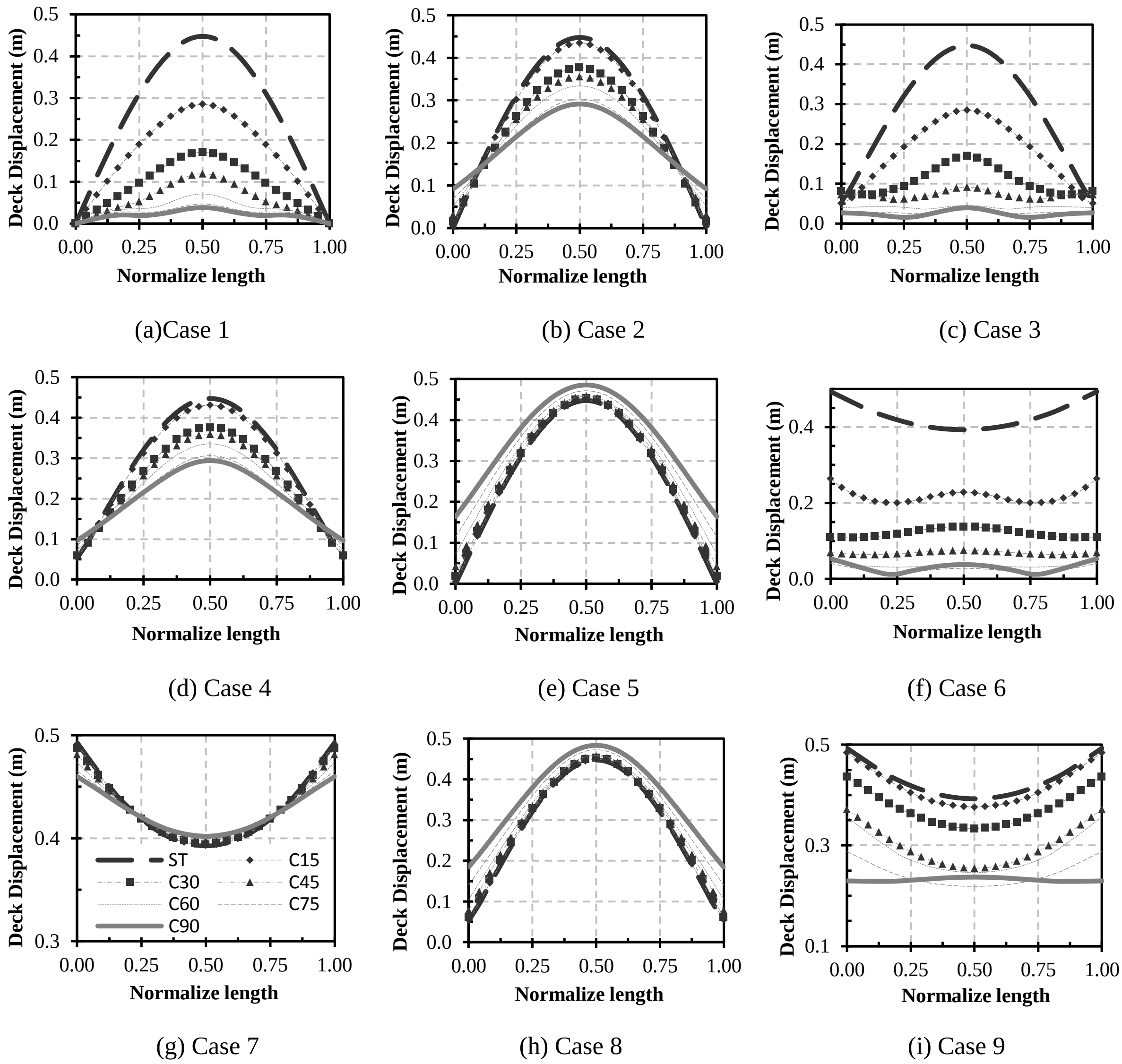


Figure 3.2 Comparison of the ITHA average results of equivalent straight and curved bridges

3.2.2. Comparison of the abutment shear force demand

In Fig. 3.3 results of 9 abutment restraint cases for 2, 4, and 6 span straight and curved bridges are compared. Each bar in the figure represents the average value of seven time history analysis. The first 3 figures (a, b, and c) compare the abutment transverse shear force demand for straight and curved bridges while the last three (d, e, and f) longitudinal shear force. The abutment longitudinal and transverse direction for the straight and curved bridges is along their respective local X and Z-axis as shown in Fig. 2.1 and 2.2. It is clear from the first three figures that the transverse shear force is conservative in almost all cases for 2, 4, and 6 span bridges however the longitudinal shear force is extremely un-conservative for the abutment restraint cases which have translational restraint in the local X-axis (Case 1, 2, 3, 4, 6, and 9) as depicted from the last three figures.

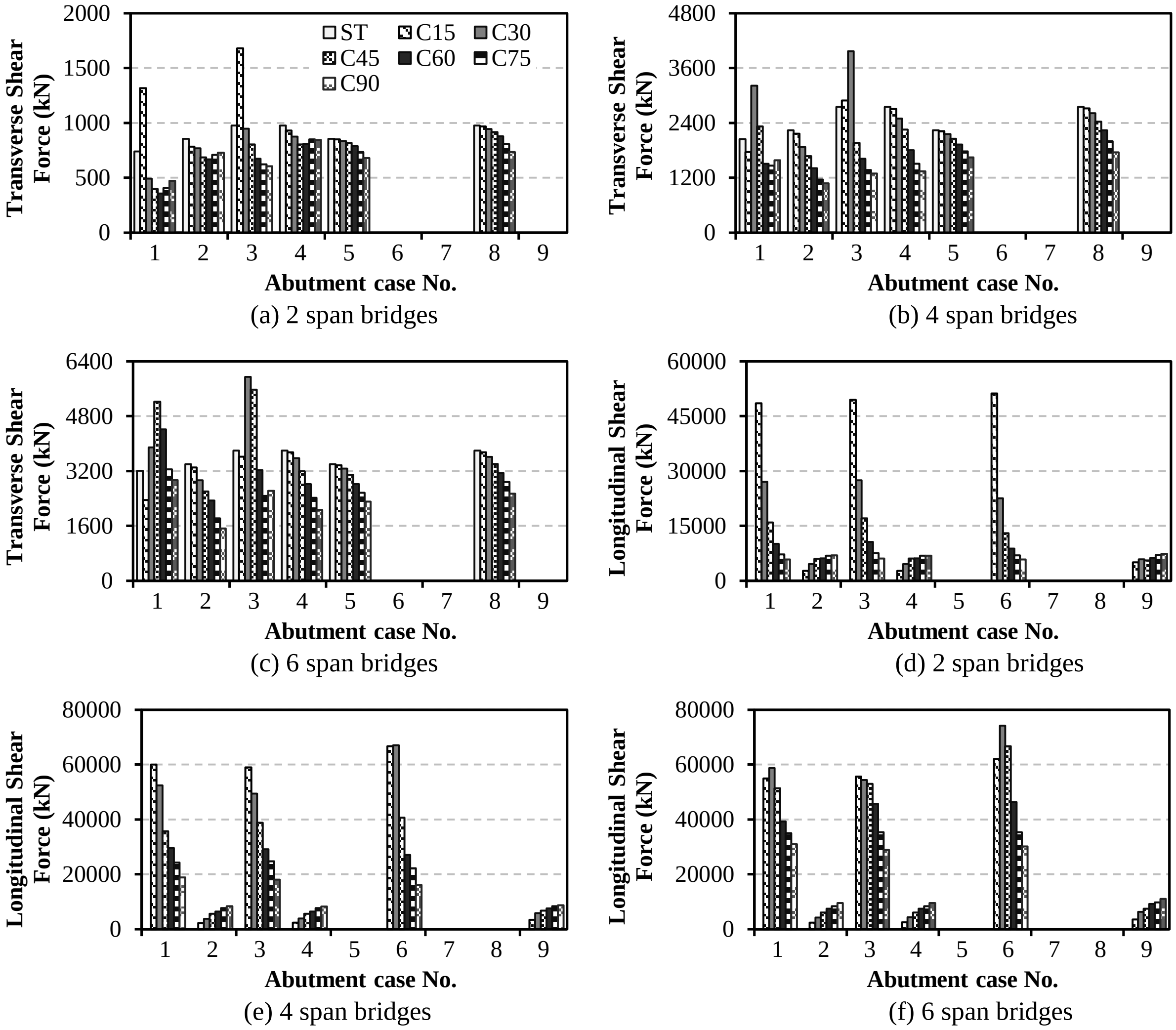


Figure 3.3 Comparison of the ITHA average results of equivalent straight and curved bridges

3.3. Displacement Index

As a means to present the results for all bridges, a displacement index is defined. This index is calculated by dividing the deck displacement of the straight bridge by that of the curved at each DOF and then calculating the maximum and minimum values as given by Eqn. 3.1

$$\Delta_{max\_Ratio} = max\left|\frac{\Delta_{ST,i}}{\Delta_{C\theta,i}}\right| \quad \Delta_{min\_Ratio} = min\left|\frac{\Delta_{ST,i}}{\Delta_{C\theta,i}}\right| \quad \text{for all } \Delta_{ST,i} \text{ and } \Delta_{C\theta,i} > 0 \tag{3.1}$$

where $\Delta_{ST,i}$ is the displacement of the deck at i^{th} DOF for the equivalent straight bridge and $\Delta_{C\theta,i}$ is the displacement of the deck at the corresponding DOF for the curved bridge at subtended angle θ. If the values from Eqn. 3.1 are close to 1 then the analysis results of the curved bridge matches that from the straight bridge. Values greater than 1 imply that the displacement of the curved bridge is less than the equivalent straight bridge and is conservative, with the opposite result for values less than 1.

3.3.1. Effect of curvature irregularity

Results are presented in Fig. 3.4 for the maximum and minimum displacement ratio. The first three figures (a, b, & c) show the maximum displacement ratio while the last three figures (d, e, & f) show the minimum displacement ratio for 2, 4, and 6 span bridges. From this data, it is evident that significant deviation occurs from a value of 1, especially for bridges with some degree of longitudinal abutment restraint. It is also easy to see the impact of subtended angle which is generally more pronounced as the angle becomes larger. Note that abutment case 1, 3 and 6 often has data off-scale as noted by the numbers in the boxes, which are the values from left to right for that case.

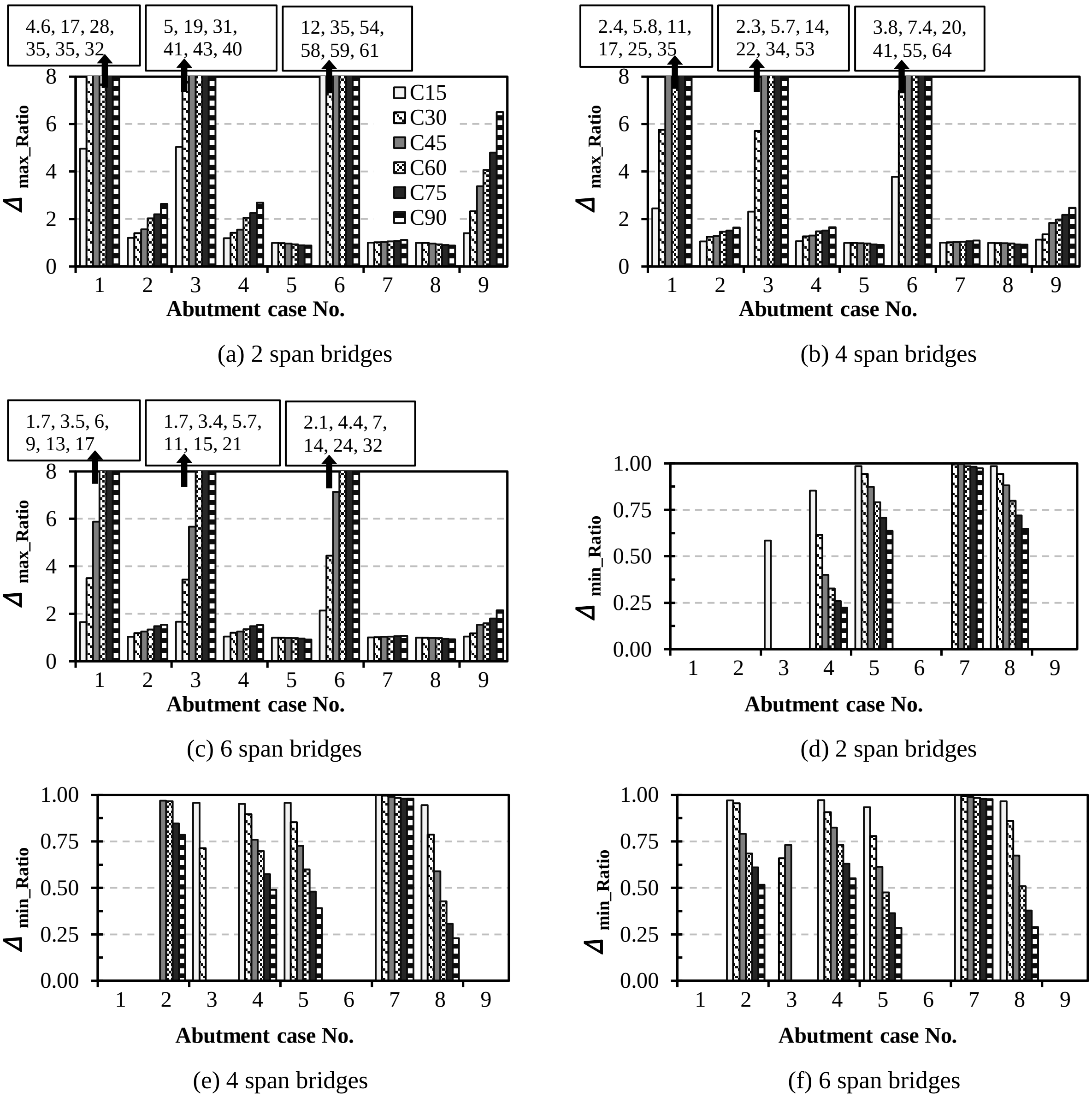
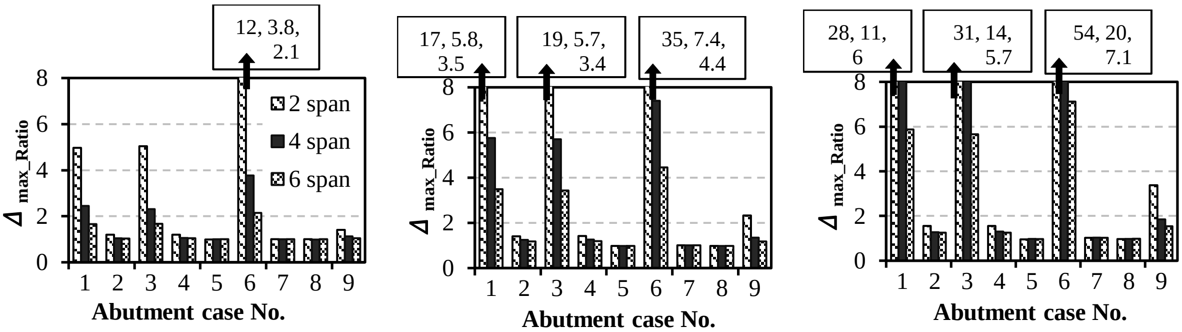


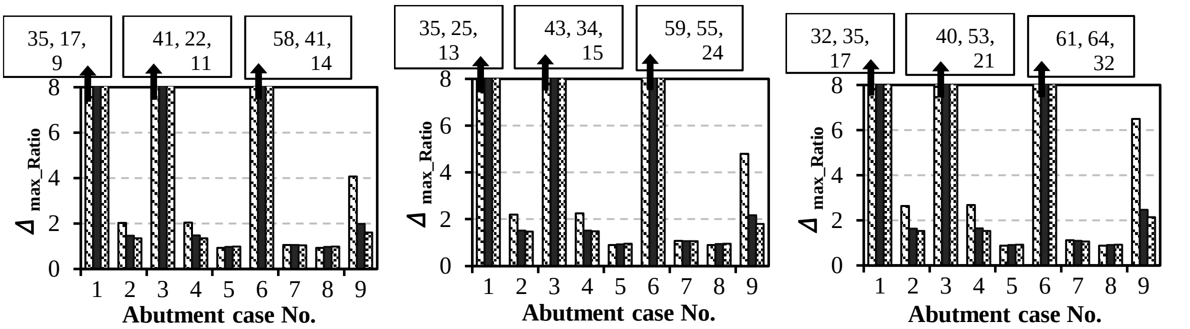
Figure 3.4 Maximum and minimum displacements ratio of the straight to curved bridges for all cases grouped by number of spans

3.3.2. Effect of number of spans

The data shown in Fig. 3.4 can also be grouped according to subtended angle, which allows comparison in each figure of the impact of span length as shown in Fig. 3.5 and 3.6 for the maximum and minimum displacement ratios respectively. The same legend shown in Fig. 3.5(a) is used for all figures (Figs. 3.5 and 3.6). It is evident from these figures that decrease in number of spans or span length increase the deviation of response from curved bridges i.e. largest error occurs for 2 span bridges than 4 and 6 span bridges, as expected, which is more pronounce from Fig. 3.5.

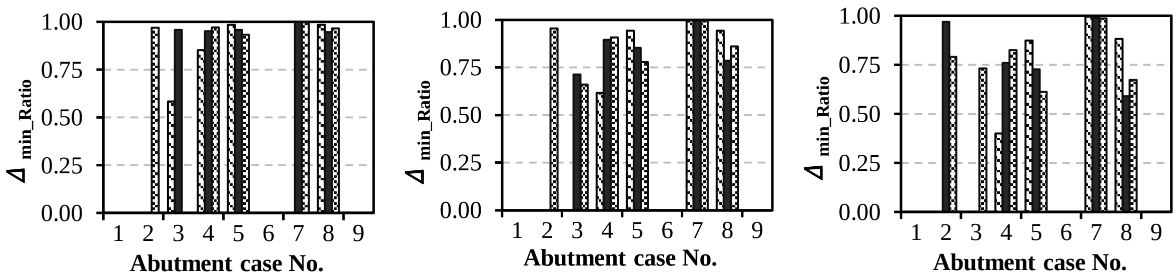


(a) 15 Degree subtended angle (b) 30 Degree subtended angle (c) 45 Degree subtended angle

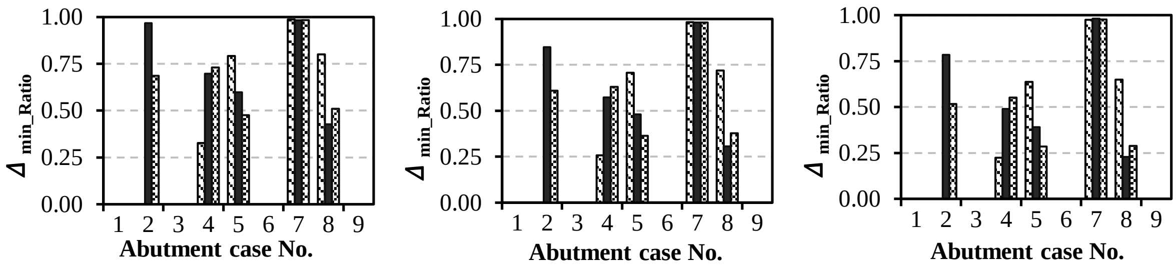


(d) 60 Degree subtended angle (e) 75 Degree subtended angle (f) 90 Degree subtended angle

Fig. 3.5 Maximum displacement ratios of the straight to curved bridges grouped by subtended angles



(a) 15 Degree subtended angle (b) 30 Degree subtended angle (c) 45 Degree subtended angle



(d) 60 Degree subtended angle (e) 75 Degree subtended angle (f) 90 Degree subtended angle

Fig. 3.6 Minimum displacement ratios of the straight to curved bridges grouped by subtended angles

4. CONCLUSION

The aim of this analytical investigation was to evaluate the AASHTO Guide Specification hypothesis that curved bridges can be analyze as if they are straight provided the bridge is regular. For this purpose curved bridges with subtended angles of 15, 30, 45, 60, 75, and 90 degrees, having the total arc length equal to the length of the equivalent straight bridge, were considered. It was observed that abutment restraint conditions are critical parameters for the variation of the response between equivalent straight and curved bridges. Thus an additional 9 abutment restraint cases with different numbers of spans (two, four and six) were also investigated. The equivalent straight bridges were first designed considering these parameters by using the Direct Displacement Based Design (DDBD) procedure. The resulting designs were then analyzed with Inelastic Time History Analysis using both straight and curved geometry for seven spectrum compatible time histories. The average results of seven time histories were compared for both straight and curved bridges for the two response quantities, (1) inelastic displacement profile of the superstructure and (2) shear forces at the abutments, and the following conclusions were drawn: (1) generally the deviation in the response (displacement demand) of the curved bridge from the equivalent straight bridge increases as the subtended angles become larger and the number of spans reduces (2) it was found that the type and degree of abutment restraint is a rather critical parameter in controlling the response of the bridge, the most significant being longitudinal abutment restraint which had a profound impact on results (3) For bridges that contain some degree of restraint at the abutment along the bridge longitudinal direction (local X-axis, cases 1, 2, 3, 4, 6, and 9), significant errors were introduced if a curved bridge is analyzed as if it is straight. In many cases, actual deformations were smaller than those obtained from analysis of a straight bridge. In the remaining cases (5, 7, and 8) where there is no abutment longitudinal restraint (local X-axis), the impact of superstructure curvature was minimal, although slightly increasing as the subtended angle increases (4) the longitudinal shear demand on the curved bridge is significant in comparison to the straight bridge and increases as the curvature of the superstructure increases.

This study was limited only to the transverse response of the bridge. Future research will work to develop the DDBD approach for the design of curved bridges as well as considering other irregularity parameters such as adjacent span length ratio, movement joints, adjacent bent stiffness ratio, and torsional stiffness of the superstructure, amongst others for both the longitudinal and transverse response of the bridge.

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