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Curvature Limitations In Bridge Codes

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CURVATURE LIMITATIONS IN BRIDGE CODES

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BY

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A Thesis
Presented to Ryerson University
In partial fulfillment of the
Requirement for the degree of
Master of Applied Science
In the program of
Civil Engineering
Toronto, Ontario, Canada, 2009

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“Curvature Limitations in Bridge Codes”

By Imad Eldin Ahmed Eisa Khalafalla

Ryerson University - Civil Engineering

Toronto, Ontario, Canada, 2009

ABSTRACT

In recent years, horizontally curved bridges have been widely used in congested urban areas, where multi-level interchange structures are necessary for modern highways. A series of horizontally curved bridges were analyzed in this study using a commercial finite-element program, ABAQUS. In each analysis, the behavior of bridges was investigated, and the major internal forces developed in the members were determined. Specifically, stresses, vertical deflections, vertical reactions and natural frequencies for different values of the horizontal angle of curvature. These values compared with the values of a straight bridge of similar span and cross-section configuration. Bridges taken into account were single and two-span horizontally curved concrete slab bridges, concrete T-beam bridges, concrete cellular bridges, concrete box girder bridges, slab-on-steel I-girder bridges, and composite steel box girder bridges. The design parameters considered were degree of curvature, span length, number of lanes, number of girders and/or boxes, and span-to-depth ratio. The stipulation made in bridge codes for treating a curved bridge as straight one is examined. Based on the data generated from the parametric study, sets of empirical expressions were developed to evaluate stress, deflection, reaction, and frequency distribution factors in a curved bridge system as related to a straight bridge system. Then these expressions were extended to establish more reliable expressions for curvature limitation to treat a curved bridge as straight one.

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TO MY FAMILY

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NOTATIONS

b	Half-width of the bridge
D	Depth of the bridge
DDF	Deflection distribution factor
$\mathbf{f}$	The nodal load vector
FDF	Frequency distribution factor
f_{sc}	The reaction on a single curved girder
f_{ss}	The reaction on a single straight girder
f_{csy}	The reaction on a system of curved girders
L	centreline curved span length
K_1	Amplification Factor
K_2	Distribution Factor
K_3	Reduction Factor
$\mathbf{K}$	The global stiffness matrix
N	Number of girders or boxes
R	Radius of curvature
RDF	Reaction distribution factor
(R_{curve})	Maximum vertical reaction forces for curved bridge
(R_{straight})	Maximum vertical reaction forces for straight bridge
(σ_{curve})	Maximum vertical stress forces for curved bridge
$(\sigma_{\text{straight}})$	Maximum vertical stress forces for straight bridge
(Δ_{curve})	Maximum vertical deflection forces for curved bridge

$(\Delta_{\text{straight}})$	Maximum vertical deflection forces for straight bridge
(ω_{curve})	Maximum frequency for curved bridge
$(\omega_{\text{straight}})$	Maximum frequency for straight bridge
S	Girder & Box spacing
SDF	Stress distribution factor
U	The nodal displacement vector
W	Width of the bridge

CHAPTER I

INTRODUCTION

1.1 General

In the past, highway bridges were placed by determining the most suitable crossing site, with slight regard to the general alignment of the roadway. After the bridge was located, the highway designer or surveyor laid out the highway to meet the bridge. In recent years, this situation has reversed and now bridges must fit the highway alignment that has been prearranged according to certain considerations. The growing demands on structures of curved alignment is presenting real challenges to engineers, especially in the design of congested urban areas where multi-level interchanges must be built within inflexible geometric restrictions. The use of horizontally curved bridges in a structure on curved alignment is a natural outcome of this trend toward aesthetic design. Beside the aesthetic considerations, horizontally curved bridges offer certain technical advantages where structures must be built to fit curved highway alignment, when compared with bridges composed of straight girders segments. In addition, horizontally curved bridges allow the designer to make use of continuous construction and its inherent advantages in situations which might otherwise be limited to simple spans. Continuous spans make more efficient use of materials and allow the elimination of many unwanted expansion details. A stiffer structure is obtained and in some cases more vertical clearance is available due to the use of shallower bridges. Horizontally curved girders also allow the designer increased flexibility, where possible locations of substructures are often limited because of required clearances. The use of straight bridges to span the same distance could mean a complicated framing system to

support the deck. When high substructures are involved, the use of longer spans may also result in savings.

Nowadays, horizontally curved bridges became an important component in highway bridges and the major advantages are structural efficiency, appearance, smooth traffic flow, and simplicity in detailing, and construction.

1.2 The Problem

In the early days of curved bridge design and construction, bridge superstructures supporting curved roadway alignment were comprised of short straight girders linked together at the supports. This resulted in inefficient use of very short spans between support piers. As the technology for designing and fabricating curved girders became available, it became possible to design curved bridges with much greater distances between supports.

Most recently, curved girders are widely used in bridge superstructures. However, due to the addition of curvature, the design and construction of bridges becomes greatly more complicated than that of straight bridges, and their structural behavior still not well understood. While in straight bridges, the girders, stringers, and floor beams can be designed by systematically isolating each member and applying standard loads, curved bridges must be designed with careful consideration to system-wide behavior. In essence, the addition of curvature adds torsion to the system that results in significant warping and distortional stresses within the member cross-sections. Furthermore, “secondary members” such as cross frames and diaphragms that provide stability in straight bridges become primary load carrying members in curved bridges.

Current codes pertaining to analysis and design of horizontally curved bridges are mostly based on experimental and analytical research conducted over 30 years ago as part of project CURT (Consortium of University Research Teams, 1975).

Treating the horizontally curved bridges as straight one with certain limitations is one of the methods to simplify the analysis and design procedure. Recently the CHBDC (2006), the AASHTO Guide Specifications for Horizontally Curved Bridges, (Guide, 2003), and AASHTO-LRFD (AASHTO, 2007) have specified certain limitations to treat horizontally curved bridges as straight one, but still more investigations are needed to examine these limitations for different bridges configurations, by considering new parameters, developing empirical expressions for stress, reaction, deflection, and frequency distribution factors to assist in filling the gaps found in the bridge codes.

CHBDC and the AASHTO Guide Specifications for Horizontally Curved Bridges have recommended the use of finite-element methods (FEA) as one of the methods for analysis for horizontally curved bridges, and it was used in this study. This study is an attempt to realize the abovementioned need. The results and the equations provided in this study will help bridge engineers in predicting new and more reliable limitations in treating the horizontally curved bridges as straight ones.

1.3 Objectives

The overall objectives of the research reported herein are:

1. Examine the applicability of the specified limitations of bridge curvature in North American Bridge Codes to treat a horizontally curved bridge as straight one in structural analysis and design.
2. Providing information that complements existing data and that will be practical for formulating complete design procedure for horizontally curved bridges.
3. Developing empirical expressions for stress, reaction, deflection, and frequency distribution factors to treat horizontally curved bridge as straight one.

1.4 Scope

The scope of this study includes the following:

1. A literature review on limitations in CHBDC and AASHTO codes related to the study.
2. Conducting a parametric study to examine bridge curvature limitations. The parameters to be considered in the study: degree of curvature, span length, numbers of lanes, and number of girders and/or boxes.
3. Constructing a finite element models using ABAQUS software to analyze these bridges under dead load to obtain bending stresses, reactions, vertical deflections, and natural frequencies for each studied bridge.
4. Analyzing the results, and make recommendations for modification of code equation, if applicable.

1.5 Contents and Arrangement of this study

Chapter **II** contains the literature review on types of bridges covered in this study, bridge curvature limitations in North American Codes (CHBDC, 2000), American bridge codes (AASHTO-LRFD, 2007; AASHTO, Guide, 1993, and 2003: ACI Manual of Concrete Practice Part 3, 2008), and previous studies related to distribution factors for straight and curved bridges. Chapter **III** describes the finite-element method, computer software “ABAQUS” used in the analysis, and modeling of concrete and steel bridges. Chapter **IV** presents the result of the parametric study performed in this study, and developed equations for bridge curvature limitations. Chapter **V** is the summary, conclusions, and recommendations for further future studies.

CHAPTER II

LITERATURE REVIEW

2.1 Horizontally Curved Concrete Bridge Types

In the bridge superstructures reinforced concrete sections are usually consist of slabs, T-beams, and box girders (Figure 2.1). Generally the controlling factors in the selection of the proper types of bridges are cost-effectiveness, and aesthetics. Occasionally, the selection is complicated by other considerations such as the deflection limits, life-cycle cost, traffic maintenance during construction stages, construction scheduling and worker safety, passage of flood debris, seismicity at the site, suitability for future widening, and commitments made to officials and individuals of the community. In some cases, a prestressed concrete or steel bridge may be a better choice.

2.1.1 Slab Bridges

The reinforced concrete slab bridges have the simplest superstructure configuration and the neatest appearance. They usually require more reinforcing steel and structural concrete than do girder-type bridges of the same span. However, the design details and formworks are easier and less expensive, and the construction time is shortest of any cast-in-place bridges. It has been found economical for simply supported span up to 9 m and for continuous spans up to 12 m. The maintenance of these types of bridges is very little except at transverse deck joints, when used, and bearing usually require little maintenance.

2.1.2 T-Beam Bridges

The T-Beam bridge consists of a transversely reinforced slab deck which spans across to the longitudinal support girders. These require a more complex formwork, particularly for skewed bridges, compared to the other superstructure forms. Generally the T-Beam bridges are more economical for spans of 12 to 18 m. The girder stem thickness usually varies from 35 to 55 cm and is controlled by the required horizontal spacing of the positive moment reinforcement. Best lateral spacing of longitudinal girders is typically between 1.8 to 3.0 m for a minimum cost of formwork and structural materials. However, where vertical supports for the formwork are difficult and expensive, girder spacing can be increased accordingly. Utilities, pipes, and conduit can be concealed between girders. Usually the construction time of these types of bridges is somewhat longer than required for slab bridges due to more complex forming. Their maintenance is low, except that bearing and transverse deck joint details may require attention. At stream crossing, with inadequate underclearance, floating may damage the girder stem.

2.1.3 Box-Girder Bridges

The Box-Girder Bridges have top deck, vertical web, bottom slab and are often used for spans of 15 to 36 m with girder spaced at 1.5 m times the structure depth. Outside this range, it is probably more economical to consider a different type of bridge, such as post-tensioned box girder or steel girder superstructure. This is because of the massive increase in volume and materials. The high torsional strength of the box girder makes it particularly suitable for sharp curve alignment, skewed piers and abutment, superelevation, and transitions such as interchange ramp structures. Utilities, pipes, and conduit can be concealed between boxes. It needs more construction time compared with slab or T-Beam bridges. Their maintenance is low, except that bearing and transverse deck joint details may cause some problems.

2.2 Horizontally Curved Steel Bridge Types

Horizontally curved steel bridges are used extensively in the construction of urban highways, and are continue to occupy a rising share of the bridge market. These structures, which constituted approximately a quarter of the steel bridges being constructed in the early 1990s [Structural Stability Research Council (SSRC) 1991], are often one of the few practical options at complicated interchanges or river crossings where limited site space or pier locations are available. Horizontally curved steel bridges also offer aesthetic and cost benefits over more traditional chorded structures that make their selection attractive even when site restrictions are not an issue. They are shallower than curved concrete bridges, which can often result in shorter approaches or fewer retaining walls when compared to structures containing deeper girders. Horizontally curved steel bridges can also be skewed to meet site demands. Given the benefits realized with the design and construction of horizontally curved steel bridges (e.g., reduced number of substructure units and length of deck overhangs; increased spans and traffic sight distances) and the continued decrease in available land space for new and replacement structures, the use of these bridge types is certain to increase. However, there is considerable additional complication associated with their analysis, design and construction compared to that for typical straight bridges. There are two general types of horizontally curved steel bridges, Steel-Concrete Composite I-Girder Bridges, and Steel-Concrete Composite Box Girder Bridges.

2.2.1 Steel-Concrete Composite I-Girder Bridges

Steel I-girders are perhaps more commonly used for horizontally curved bridges. These members have very little torsional stiffness and are stable only when connected to other girders using cross frames or diaphragms. Curvature of the superstructure leads to combined bending and torsion in the girders, significant forces in diaphragm and bracing members, and considerably more

interaction between components within the structural system than experienced in straight bridges. These effects must be considered in the analysis and design to ensure that the bridge components are proportioned properly.

Curved steel I-girder bridges are more attractive choice for most designers due to the following reasons: simplicity of fabrication and construction, less land is needed during erection, shallower sections can be designed, lighter weight of steel girders, and excellent serviceability performance.

Further more, curved I-girder bridges also provide a very appealing aesthetic shape than the chorded structure and thus are more attractive to conform to the existing terrain.

2.2.2 Steel-Concrete Composite Box Girder Bridges

Box girders are used extensively in the construction of urban highways, horizontally curved, and long-span bridges. Box girders have higher flexural capacity and torsional rigidity, and the closed shape reduces the exposed surface, making them less susceptible to corrosion. Box girders also provide smooth, aesthetically pleasing structures.

There are two types of steel box girders: steel-concrete composite box girders (i.e., steel box composite with concrete deck) and steel box girders with orthotropic decks. Composite box girders are generally used in moderate- to medium-span (30 to 60 m) bridges, and steel box girders with orthotropic decks are often used for longer-span bridges.

Composite box-girder bridges usually have single or multiple boxes. A single cell box is easy to analyze and relies on torsional stiffness to carry eccentric loads. The required flexural stiffness is independent of the torsional stiffness. A single box girder with multiple cells is economical for very long spans. Multiple webs reduce the flange shear lag and also share the shear forces. The bottom flange creates more equal deformations and better load distribution between adjacent

girders. The boxes in multiple box girders are relatively small and close together, making the flexural and torsional stiffness usually very high. The torsional stiffness of the individual boxes is generally less important than its relative flexural stiffness.

2.3 Limitations for Neglecting Curvature Effect in Horizontally Curved Bridges

Recently the Canadian Highway Bridge Design Code CHBDC (2000) and the AASHTO Guide Specifications for Horizontally Curved Bridges, (Guide 1993 & 2003) have specified certain limitations to treat horizontally curved bridges as straight one. These limitations can be summarized as follows:

2.3.1 Guide Specifications for Horizontally Curved Highway Bridges (AASHTO 1993)

For the Curved I-Girder bridges, the effects of curvature may be neglected in determining the primary bending moments in the longitudinal members, when the central angle subtended by each span is less the values given in Table 2.1.

Table 2.1 Limiting central angle for neglecting curvature in determining primary bending moment

Numbers of Girders	Angle for one Span	Angle for two or More Spans
2	2°	3°
3 or 4	3°	4°
5 or more	4°	5°

2.3.2 Guide Specifications for Horizontally Curved Steel Girder Highway Bridges (AASHTO 2003)

2.3.2.1 I-Girders

In the I-girder bridges, the effect of curvature may be ignored in the determination of vertical moment, when the following three conditions are met:

- Girders are concentric.
- Bearing lines are not skewed more than 10 degrees from radial, and
- The arc span divided by the girder radius is less than 0.06 radians.

2.3.2.2 Closed box and Tub Girders

In the box-girder bridges, the effect of curvature may be ignored in the determination of vertical moment, when the following three conditions are met:

- Girders are concentric.
- Bearing are not skewed, and
- The arc span divided by the girder radius is less than 0.3 radians and the girder depth is less than the width of the box at mid-depth.

2.3.3 AASHTO-LRFD Bridge Design Specifications (2004)

2.3.3.1 Concrete Box Girders

Except for cast-in-place multicell concrete box girders, segments of horizontally curved superstructures with torsionally stiff closed or portion thereof is less than 12 degrees may be analyzed as if the segment were straight. Horizontally cast-in-place multicell box girders may be designed as single-spine beams with straight segments, for central angle up to 34 degrees within one span, unless concerns about other force effects dictate otherwise.

The effect of curvature may be neglected on open cross-section, when the central angle subtended by each span is less than the values given in Table 2.1

2.3.4 Canadian Highway Bridge Design Code (CHBDC)

For bridges that are curved in plan and that are built with shored construction, the simplified method of analysis can be applied by treating the bridge as a straight provided that:

- There are at least two intermediate diaphragms per span.

- $\frac{L^2}{bR} \leq 1$

Where b = half-width of the bridge, L = centerline curved span length, and R = radius of curvature.

2.4 Review of Previous Study on Curved Bridges

2.4.1 General Review of Study

A few design and construction of horizontally curved steel bridges occurred, prior to 1960s. Curved steel girders were utilized only if using a chorded structure proved to be unworkable, and there were no any guidelines or specifications used to in designing these types of girders. Regardless of the lack of specifications, engineers began to identify the advantages related to the curved structures, and horizontally curved bridges were being designed with increasing regularity in the 1960s. The need to ensure uniform minimum standards of practice and safety for this structure type led directly to efforts to develop design guidelines that would put curved girder bridges on the same footing as more traditional highway bridges designed according to AASHTO Specifications. However, this need led to creation of the Consortium of University Research Teams (CURT) project, a large-scale research project funded by 25 states and managed by the Federal Highway Administration (FHWA), in 1969. The main goals of this project were:

- 1- Reviewing all existing publications on curved bridges;
- 2- Conducting experimental and analytical research to increase existing information related to curved girders;
- 3- Incorporating research results from ongoing state agency sponsored projects;
- 4- Develop simplified analysis and design methods with accompanying aids and computer programs; and
- 5- Correlated proposed analysis and design methods and procedures with existing analytical and experimental data.

A series of scale model laboratory tests accompanied by theoretical work and analytical studies, were created as a result from the CURT project.

(Mozer and Culver 1970; Mozer et al. 1971, 1973; Brennan 1970, 1971, 1974) conducted series of tests on I-girders to examine the behavior of single girders and girder pairs, and they studied the interaction between adjacent curved girders and the effect of bracing members in that interaction. Also one of the outputs of these studies, was a proposed three-dimensional analysis method and related computer code

As a result of the CURT project, a lot of theoretical and analytical works were completed, and developments of empirical models were conducted. These studies can be summarized as follows:

- (1) (McManus 1971), overall strength of doubly symmetric curved girder I sections in bending;
- (2) (Nasir 1970), local buckling behavior of curved girder flanges; and (3) (Brogan 1974; Culver et al. 1972, 1973), behavior of web panels in flexure.

From these experimental and mathematical studies, a tentative set of Specifications for allowable stress design (ASD) of curved girder bridges were developed (Culver 1972; CURT 1975). The proposed Specifications were reviewed by the Task Committee on Curved Girders of the ASCE—

AASHTO Committee on Flexural Members, and they also considered further curved bridge experimental and analytical studies. These studies were completed at the same time as the CURT project (Heins 1972; Mondkar and Powell 1974), and this work was combined with the CURT specifications and proposed by the Task Committee as guide specifications that were accepted by AASHTO in 1976 (Armstrong 1977). In the mid 1970s, the load factor design (LFD) criteria were added to the guide specifications through a research project sponsored by the American Iron and Steel Institute (AISI) (Stegmann and Galambos 1976), and this project changed the ASD criteria proposed by the CURT project team to an LFD format similar to that available in the 1973 *AASHTO Standard Specifications for Highway Bridges* (AASHTO 1973). The LFD criteria were developed directly from the proposed CURT specifications, and they were adopted by AASHTO and added to the ASD criteria to form the first edition of the *Guide Specs* (AASHTO 1980).

A second edition from the *Guide Specs* was published in 1993, after a number of revisions have been published, but the document issued in 1980 is largely unchanged in its fundamental content. The research in the behavior of horizontally curved steel bridges continued after initial publication of the *Guide Specs*. (e.g., Yoo and Carbine 1985). In the early 1990s an intensive efforts were initiated to improve these specifications. Specifically, after Task Group 14 of the Structural Stability Research Council on Horizontally Curved Girders published a report outlining problems associated with the specifications in their current form and proposed areas for research (SSRC 1991). However, this report provided the impulsion for a number of research projects aimed at developing updated and improved curved girder design specifications. In 1992 the Curved Steel Bridge Research Project (CSBRP), was initiated by FHWA. The objectives of this project were:

1- Collection and distribution of all curved bridge research completed in the U.S. and abroad; and

2- Experimentally and analytically address the behavior of curved I girders in bending, shear, and combined bending and shear.

This project has performed an extensive number of computer simulations using sophisticated finite element models, and a number of publications have been produced (Zurieck et al. 1994; Linzell 1999; Zureick et al. 2000; Jung and White 2001; Zureick et al. 2001).

Another project was initiated in 1993, sponsored by the National Cooperative Highway Research Program (NCHRP), to develop a set of improved specifications. The results of this project are published in NCHRP Report 424 (Hall et al. 1999). This report includes: a summary of past and ongoing curved bridge research, discussions of current U.S. curved bridge design and construction practices, an overview of the *Recommended Specs* (Hall and Yoo 1998) for LFD and construction of curved I and box girders, and future research recommendations.

In 1999, a new project was initiated jointly by AISI and FHWA to extend the results of experimental tests conducted under the CURT project and the CSBRP through refined nonlinear finite element analysis, and to develop equations for load and resistance factor design of curved and straight steel bridge girders. The findings of this project contain: a general review of curved I-girder maximum strength equations that have been proposed within the literature, a recommended set of modifications to the *AASHTO LRFD Bridge Design Specifications* (AASHTO 2001), and correlation of the recommended design equations with prior experimental results and analytical results from the parametric study.

Another project research was initiated by NCHRP Project 12-52. The main objective of this project was to revise and recalibrate the *2003 Guide Specs* so that LRFD can be applied to curved steel bridges.

2.4.2 Other Research Studies

In 1970, Heins and Siminou initiated a research to study a simplified method for evaluating the internal forces and deformations in radial curved girder system. They developed equations, and distribution factors that will help in determination of required cross-sectional properties in a single, two, and three spans curved girder system. The factors developed in this study were as follows:

$$\text{Amplification Factor, } K_1 = \frac{f_{sc}}{f_{ss}}, \quad (2-1)$$

$$\text{Distribution Factor, } K_2 = \frac{f_{csy}}{f_{sc}}, \quad (2-2)$$

$$\text{Reduction Factor, } K_3 = \frac{f_{csy}}{f_{sc}} \quad (2-3)$$

Where f_{sc} is the reaction on a single curved girder, f_{ss} is the reaction on a single straight girder, and f_{csy} is the reaction on a system of curved girders.

The developed design equations in this study, have the following limitations: (1) girder spacing between 2 to 3 m; (2) girder span lengths varied from 15 to 30 m; (3) girders of the system must have a constant curvature limited to radii between 30 to 180 m; (4) number of girders in the system may be 4, 6 or 8; (5) only two and three spans bridges were examined, with all interior end spans of equal length.

In their study, Heins and Siminou's introduced design charts for modification factors of moment, shear, deflection, rotation, and warping torsion.

In 1984 Heins and Jin studied the effect of cross bracing spacing on curved bridge distribution factors. This study covered both single-girder and multi-girder system. They developed a space model frame idealization and used grid analysis for obtaining their results. They produced number of graphs and equations that correlate the effect of the cross bracing and distribution factor.

In 1985, Yoo and Littrell used 3-D finite-element method (SAP), to study the response of a system of 5 girders horizontally curved, connected by a slab and cross bracing under dead load and live load. The parameters considered in this study were: radius of curvature, length of girders and number of braced intervals. They developed empirical design equations to predict the ratio of: (a) Maximum bending stress; (b) maximum warping stress; and (c) maximum deck deflection. They concluded that: (1) maximum bending stresses and maximum deck deflections stabilized with minimal bracing; (2) warping stresses were sensitive to the number of braced intervals. They also observed that partially loaded lanes; 2 trucks out of 3 trucks (deck width capacity) located near the outside edge of the bridge produced higher stresses and deflection in the curved bridges due to the tilting of the bridge deck created by the nonsymmetrical load distribution.

In 1986, Brockenbrough used a 3-D finite-element model to study the effect of various parameters on the load distribution for 4-girder curved bridge. A two-span bridge comprised of composite concrete deck with steel I-girder and intermediate transverse cross frames between girders was investigated in this study. The conclusions of this study were: (1) the central angle per span, which includes the combined effect of curvature and span length had larger effects, (2)

the girder spacing, had larger effects identified; (3) variation in girder stiffness and cross-frame spacing had relatively small effects on live-load distribution factors. In this research Brockenbrough developed charts showing the variation of the distribution factors with the variation of these parameters.

In 1989, Schelling and Namini presented the results of a comprehensive research to study the response of simple and continuous span horizontally curved steel I-girder bridges with and without cross bracing, during construction phase due to self own weight.

Based on 3-D space frame model, Schelling and Namini developed empirical equations of moment distribution factors for different numbers of girders (2, 4, & 6) to determine the effect of the lateral bracing on curved bridges during construction. In their research, they concluded that the results from the simple-span can be applied conservatively to the continuous span bridges provided that the supports and radial span length ratios do not differ greatly from unity. Their developed empirical equation had a drawback because it can be used in conjunction with the results given by the 2-dimentional grid analysis method. In addition to that the range of the bridges spans considered in their models were (36m to 90m) which are impractical for slab on steel I-girder bridges.

Davidson et al. (1996) performed a research to study certain design parameters affecting the behavior of horizontally curved steel I-girder bridges. A finite-element, ABAQUS software was used in this study to construct a 3-girder Bridge model. The parameters considered in this study were: cross-frame spacing, span length, girder depth, number of girders, flange width, girder spacing. This study concluded that the span length, radius of curvature, flange width and cross frame spacing have the greatest effect on the warping-to-bending stress ratio. Based on this information, a regression analysis was performed to predict the effect of these parameters on the

warping-to-bending stress ratio. Consequently, an equation was developed from this regression and proposed for the preliminary cross-frame spacing design:

$$S_{\max} = L - \ln \left[\frac{R b_f}{2000 L^2} \right]^{-1.52} \quad (2.4)$$

Where $S_{\max}$ is the maximum bracing spacing in meters, L is the span length in meters, R is the radius of curvature in meters, and b_f is the flange width in millimeters.

In 2002, Zhang conducted a finite-element analysis to investigate the load distribution factors for curved I-girder bridges, in which 111 bridge models with radius of curvature less than 450m were analyzed. The parameters considered in the study were: radius of curvature (45 to 450 m), girder spacing (1.8 to 5.0 m), span length (15 to 70 m), slab thickness (170 to 300 mm), longitudinal stiffness (32122 to 72226 cm⁴), number of girders (3 to 7), and cross frame spacing (2 to 7 m). In this study, Zhang concluded that radius of curvature, girder spacing, and number of girders had significant effect on the load distribution, and span length, slab thickness, and longitudinal stiffness had slight effect. Also he showed that the effect of cross frame spacing and girder torsional inertia could be neglected, and the shear distribution factors have similar trend as that of moment distribution factors. The difference is that the shear distribution factor of the outside exterior girder and the inside exterior girder are close. A number of simplified equations were developed in this study for moment (+ ve & - ve) and shear distribution factors for exterior and interior girders, and it was found that the distribution factors of the outside exterior girder positive moment obtained from AASHTO Guide Commentary method (1993) for multiple-lane loading were less conservative compared with the results of FEM analysis. Also AASHTO-LRFD formulas for straight bridges led to either larger or smaller results when curved used for bridges, and Heins and Jin's formula was too conservative for all cases.

In 2004, Wassef performed an extensive research to study the structural response of composite steel I-girder bridge. He used finite-element computer software SAP2000 to model 192 simply supported straight and curved I-girder bridges. The parameters considered in this study were: span length, girder spacing, number of girders, and span-to-radius ratio L/R . In his study, Wassef examined the influence of these parameters on the moment, deflection, and warping stress distribution, and he concluded that: (1) curvature is the most critical parameter that influence the design of curved bridges; (2) span length, number of girders, and girder spacing affect the values of the moment and deflection distribution factors in general; (3) Full bridge live loading does not necessary produce the extreme design values of the moment or deflection distribution factors; (4) warping-to-bending stress ratio values were acceptable and within the limits, except for bridge with L/R ratio 0.7 and span length 35m; (5) CHBDC moment and deflection distribution factors overestimate the structural response of straight bridges.

In 2004, Nasr studied the live load distribution on the curved steel I-girder bridges. He performed an extensive parametric study, using the finite-element method, to determine the lateral load distribution factors based on AASHTO live loads. The parameters considered in this study were: radius of curvature, girder spacing, span length, slab thickness, number of girders, cross frame spacing, overhang width and girder longitudinal and torsional stiffness. The study findings were: (1) The distribution factors of outside exterior girder positive moment obtained from AASHTO (1993) Guide Commentary were un-conservative in some cases and conservative in other cases; (2) The outside exterior girder has always the most maximum value of moment and two-lane loading would generally produce the maximum girder response; and (3) For different bridge width the following parameters, has a significant effect on the distribution

factors: radius of curvature, span length, girder spacing and distance from the centre of exterior girder to the inside edge of traffic barrier.

In 2005, Al-Hashimy initiated an extensive parametric study on different simply supported straight and curved slab-on-steel I-girder bridges to study their structural behaviour and response. He used a finite-element SAP200, software to model and analyse 320 prototype straight and curved bridges. The parameters considered in this study were: Span length, Girder spacing, Number of girders, and Span-to-radius ratio (L/R). The bridge prototype models were subjected to the Canadian Highway Bridge Design Code (CHBDC) CL-625 truck, lane loading and dead loading, to examine the influence of these parameters on moment, shear, deflection and warping stress distribution. Based on this study Al-Hashimy concluded that:

1. Curvature is the most critical parameter in determining the lateral distribution factors and warping-to-bending stress ratio.
2. In general, the increase in the number of girders, as well as in girders spacing results in an increase in the shear distribution factor, moment distribution factor, and deflection distribution factor.
3. Span length has slightly effect on shear distribution factors;
4. There is a small effect on the shear distribution factors when The number of cross-bracing intervals are over 3,
5. The CHBDC significantly underestimates the structural response of curved bridges by treating them as straight bridges when, $\frac{L^2}{bR} \leq 1$.

In 2008, Ihsan-ul Haq conducted an extensive parametric study, using the finite-element computer software SAP2000, in which 614 simply supported curved I-steel Girder Bridge prototypes were analyzed to examine the key parameters affecting warping stresses in curved I-girder bridges under construction loads. The parameters considered in this study were: Span length, Girder spacing, Number of girders, number of cross bracing intervals between support lines, and Span-to-radius of curvature ratio (L/R). In this study, the previously available empirical equations for minimum number of cross-bracing intervals to limit warping stresses in curved I-girders were examined. Ihsan-ul Haq also investigated the moment and shear distribution factors of each girder under construction loads. Based on this study empirical expressions for moment and shear distribution factors for the curved girder were developed. The study findings were: (1) The increase of number of girders for the same girder spacing decreases the warping effects; (2) Warping-to-bending stress ratio in girder flanges increases with increase in bridge curvature, and decreases with increase in flange warping constant; (3) Utilizing “Torsion Box” in the form of added horizontal bracing members joining girders’ top and bottom flanges enhances the load distribution characteristics of the curved system but it has insignificant effect on the flange warping-to-bending stress ratio; and (4) Span length, radius of curvature, number of girders, and girder spacing have significant effect on the longitudinal bending moments, deflection, axial force in bracing members, and shear forces.

CHAPTER III

FINITE-ELEMENT ANALYSIS

3.1 General

Preceding to the construction of any structural system, an extensive engineering design and analysis process must be undertaken. During this process, many engineering assumptions are routinely used in the application of engineering principles and theories to practice. A subset of these assumptions is used in a multitude of analytical methods available to structural analyst. In the modern engineering office, with the increased power of personal computers, increasing numbers of engineers depend on structural analysis computer software to solve their engineering problems. This modernization of the engineering design office, couples with an increased demand placed on the accuracy and efficiency of structural design, require a more-detailed understanding of the basic principles and assumptions associated with the use of modern structural analysis computer programs. The most popular of these programs are GT STRUDL, STAADIII, SAP2000, as well as some more powerful and complex tools such as ADINA, ANSYS, NASTRAN, and ABAQUS.

Typically during the analytical stage of any bridge design, finite-element-based structural analysis programs are used to evaluate the structural integrity of the bridges system. Most structural analysis programs employ sound, well-established finite-element methodologies and algorithms to solve the analytical problem. It is of greatest importance for the users of these programs to understand the theories, assumptions, and limitations of numerical modeling using the finite-element method, as well as the limitations on the accuracy of computer systems used to execute these programs. The finite element method is one of the methods recognized by the

Canadian Highway Bridge Design Code (CHBDC 2000), section 5.9, for short and medium span bridges, and it is considered to be the most powerful, and multipurpose method. The most important advantages of the finite element method are:

- 1- Eliminate the differential equation completely from the solution.
- 2- Possibility to analyze structures having irregular shape with any material variations thereof.
- 3- Allow multiple loading conditions to be applied to the system.
- 4- Capability to use multiple structural elements such as plates, beams, and shells,
- 5- Ability to use multiple materials within the structure such as isotropic, orthotropic, and general anisotropic.
- 6- Possibility to increase the prediction accuracy in important region and reduce it in other region (thus reducing cost of the simulation).

This chapter presents a brief description of finite-element approach, description of modeling methodology, description of the structural geometry, and description of the boundary conditions and loads acting on the structure. The available commercial finite-element program, ABAQUS 6.6, was used to investigate the most probable responses of a modeled bridge structure. A general description of this software is presented later in this chapter. The procedure to perform an extensive parametric study on selected straight and curved bridge prototypes, and different bridge configurations, to evaluate the stresses, vertical deflections, vertical reactions and natural frequencies for different values of degree of curvature.

3.2 Finite-Element Approach

Finite Element Analysis (FEA) is a numerical method which provides solutions to problems that would otherwise be difficult to obtain. The method has wide application and enjoys extensive

utilization in the structural, thermal and fluid analysis areas. The finite element method is comprised of three major steps:

(1) **Pre-processing:** The user constructs a model of the part to be analyzed in which the geometry is divided into a number of discrete subregions, or "elements," connected at discrete points called "nodes." Certain of these nodes will have fixed displacements, and others will have prescribed loads. For a two-dimensional (2D) analysis, or a three-dimensional (3D) thin shell analysis, the elements are essentially 2D, but may be "warped" slightly to conform to a 3D surface. For a 3D solid analysis, the elements have physical thickness in all three dimensions. In addition, there are many special elements, such as axisymmetric elements for situations in which the geometry, material and boundary conditions are all symmetric about an axis. The model's degrees of freedom (dof) are assigned at the nodes. These models can be extremely time consuming to prepare, and commercial codes vie with one another to have the most user-friendly graphical "preprocessor" to assist in this rather tedious job. Some of these preprocessors can overlay a mesh on a preexisting CAD file, so that finite element analysis can be done conveniently as part of the computerized drafting-and-design process.

(2) **Analysis:** In this step the dataset prepared by the preprocessor is used as input to the finite element code itself, which constructs and solves a system of linear or nonlinear algebraic equations

$$\mathbf{K}_{ij}\mathbf{u}_j = \mathbf{f}_i \quad (3.1)$$

Where:

- $\mathbf{f}$ = the nodal load vector;
- $\mathbf{K}$ = the global stiffness matrix;
- $\mathbf{U}$ = the nodal displacement vector;

The formation of the **K** matrix is dependent on the type of problem being attacked. Commercial codes may have very large element libraries, with elements appropriate to a wide range of problem types. One of FEA's principal advantages is that many problem types can be addressed with the same code, simply by specifying the appropriate element types from the library.

(3) **Post-processing:** In the earlier days of finite element analysis, the user would pore through reams of numbers generated by the code, listing displacements and stresses at discrete positions within the model. It is easy to miss important trends and hot spots this way, and recent codes use graphical displays to assist in visualizing the results. A typical postprocessor display overlay colored contours representing stress levels on the model, showing a full-field picture.

3.3 The Finite Element Program ABAQUS

ABAQUS is a high-performance software package developed by Hibbitt, Karlsson & Sorensen, Inc. for the numerical modeling of structural response. It enables you to do linear or nonlinear, and static or dynamic types of analysis for a large spectrum of engineering problems. The ABAQUS suite of engineering analysis software packages are used throughout the world to simulate the physical response of structures and solid bodies to load, temperature, contact, impact, and other environmental conditions. Some of the specific capabilities of ABAQUS include: stress analysis (both static and dynamic responses), dynamic studies (linear and nonlinear problems), ability to model very large shape changes in solids (both two and three dimensions), heat transfer problems, coupled heat transfer and stress analysis, coupled pore fluid diffusion and stress analysis problems, eigenvalue buckling prediction, natural frequency

extraction, geostatic stress state, dynamic analysis of linear systems by modal methods, and element removal and replacement.

Furthermore, ABAQUS has a very extensive element library, including a full set of continuum elements, beam elements, shell and plate elements, among others. Also this software has an advanced material library, including the usual elastic and elastic – plastic solids; models for foams, concrete, soils, piezoelectric materials, and many others.

A data deck for ABAQUS contains model data and history data. The model data define a finite element model (geometry, materials definition, element properties, etc.). The history data define the sequence of events or loadings. History data is divided into steps, each step being a period of response of a particular type. All data definitions in ABAQUS are accomplished with option blocks. Each option is introduced by a keyword card. Within certain restrictions, you can use user subroutines as powerful and flexible tools for analysis. Post processing options include time history plots, variable-variable plots, and printed tables showing values as functions of time, output in a neutral plot format that you can read with the post-processing routine of your choice. There are also options that allow additional output (printed tables, contour or deformed configurations plots, FILE output) to be created at specified increments from an ABAQUS restart file.

3.4 Concrete Bridge Configurations

3.4.1 Concrete Solid Slab Bridge

216 (single & double spans), straight and curved concrete solid slab bridge prototypes were considered for finite-element analysis in the parametric study. Several major parameters were considered as follows:

- Span length (**L**): 10, 15, 20, and 25 m;
- Span-to-radius of curvature ratio (**L/R**): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, & 0.8
- Depth-to-span ratios (**D/L**): For simple span 1/15, and continuous span 1/22.
- Width of the bridge (**W**): 8 m, 12 m, & 16 m.

3.4.2 Concrete T-Beam Bridge

126 (single & double spans), straight and curved concrete T-beam bridge prototypes were considered for finite-element analysis in the parametric study. Several major parameters were considered as follows:

- Span length (**L**): 15, 25, and 35 m;
- Span-to-radius of curvature ratio (**L/R**): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, & 0.6
- Depth-to-span ratios (**D/L**): For simple span 1/15, and continuous span 1/20.
- Width of the bridge (**W**): 8 m, 12 m, & 16 m.
- Girder spacing (**S**): 2m
- Number of girders (**N**): 4 for 8 m width; 6 for 12 m width; & 8 for 16 m width;
- Number of solid end & intermediate diaphragms: 3 for 15 m span length; 4 for 25 m span length; & 5 for 35 m span length;

3.4.3 Concrete Box Girder Bridge

448 (single & double spans), straight and curved concrete box girder bridge prototypes were considered for finite-element analysis in the parametric study, including 168 concrete cellular

box girder, 168 multi-box girder, and 112 single box girder bridge. Several major parameters were considered as follows:

- Span length (**L**): 25, 35, 45, and 55 m;
- Span-to-radius of curvature ratio (**L/R**): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, & 0.6
- Depth-to-span ratios (**D/L**):
 - Cellular & multi-box girder: 1/14 for single span, and 1/18 for two spans;
 - Single box girder: 1/20 for single span, and 1/25 for two spans.
- Width of the bridge (**W**):
 - Cellular & multi-box girder: 8 m, 12 m, & 16 m;
 - Single box girder: 8 m, & 12 m.
- Box spacing (**S**): 4m for multi-box girder.
- Number of boxes (**N**):
 - Cellular box girder: 3 for 8 m width; 5 for 12 m width; 7 for 16 m width;
 - Multi-box girder: 2 for 8 m width; 3 for 12 m width; 4 for 16 m width;
- Number of solid end & intermediate diaphragms: 3 for 25 m span length; 4 for 35 m span length; 5 for 45 m span length; & 7 for 55 m span length;

Other concrete bridge configurations are listed below:

- The deck slab thickness of was taken as 200 mm,
- The girder web thickness was considered equal to 200 mm,
- The over-hanged slab length was considered equal to half the girder spacing,

- The bottom concrete flange, and solid end & intermediate diaphragm thickness were considered equal to 200 mm,
- The slope of the web for concrete single box girder was taken 1:4,
- Concrete solid end & intermediate diaphragms were spaced at equal intervals between the support lines.

Figure 3.1 visualizes the details of the typical concrete bridges cross-section used in this study.

3.5 Composite Bridge Configurations

3.5.1 Slab-On-Steel I-Girder Bridge

126 (single & double spans), straight and curved concrete slab-on-steel I-girder bridge prototypes were considered for finite-element analysis in the parametric study. Several major parameters were considered as follows:

- Span length (**L**): 15, 25, and 35 m;
- Girder spacing (**S**): 2 m;
- Depth-to-span ratios (**D/L**): 1/25 for single span, and 1/30 for two spans;
- Number of girders (**N**): 4 for 8 m width; 6 for 12 m width; 8 for 16 m with;
- Span-to-radius of curvature ratio (**L/R**): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, & 0.6;
- Number of X-bracing with top and bottom chord: 3 for 15 m span length; 5 for 25 m span length; and 7 for 35 m span length;
- The deck slab thickness of was taken as 200 mm;

- The girder web thickness was considered equal to 16 mm;
- The over-hanged slab length was considered equal to half the girder spacing;
- The bottom and top steel flanges width and thickness were maintained 300 mm, and 16 mm, respectively;

3.5.2 Steel Box Girder Bridge

280 (single & double spans), straight and curved steel box girder bridge prototypes were considered for finite-element analysis in the parametric study, including 168 steel multi-box girders, and 112 steel single girders. Several major parameters were considered as follows:

- Span length (**L**): 25, 35, 45, and 55 m;
- Box girder spacing (**S**): 4 m;
- Depth-to-span ratios (**D/L**): 1/30 for single span, and 1/35 for two spans;
- Width of the bridge (**W**):
 - Multi-box girder: 8 m, 12 m, & 16 m;
 - Single box girder: 8 m, & 12 m;
- Number of box girders (**N**):
 - Multi-box girder: 2 for 8 m width; 3 for 12 m width; 4 for 16 m width;
- Span-to-radius of curvature ratio (**L/R**): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, & 0.6;
- Number of X-bracing with top chord: 5 for 25 m span length; 7 for 35 & 45 m span length; and 10 for 55 m span length;
- The deck slab thickness of was taken as 200 mm,

- The bottom steel flange, girder web, and solid diaphragm thickness were considered equal to 16 mm,
- The over-hanged slab length was considered equal to half the girder spacing,
- The top steel flanges width and thickness were maintained 300 mm, and 16 mm, respectively.

Figure 3.2 visualizes the details of the typical composite steel girder bridges cross-section used in this study.

X-type cross-bracings with top chords inside and between boxes for steel box girder bridges, and with bottom chord for steel I-girder bridges, were utilized in this study as shown in Figure 3.2. These bracings were spaced at equal intervals between the support lines and were made of single steel angles dimensioned (L102xL102x9.5mm) and of 0.0018 m² cross sectional area. Steel solid diaphragms were located at each support for steel box girder bridges (single & multi-box girder).

Typical plan of straight and curved girders with the distribution of the transverse bracings are shown in Figure 3.6.

3.6 Research Assumptions

This study was based on the following assumptions:

- (1) All the bridges were single, and two spans,
- (2) All materials were elastic and homogenous,
- (3) The effect of road superelevation, and curbs were ignored;
- (4) Bridges had constant radii of curvature between support lines.

(5) The modulus of elasticity of concrete material was taken **25 GPa** with Poisson's ratio of **0.20**, while these design values for steel material were taken; **200 GPa** and **0.30**, respectively.

3.7 Finite-Element Bridges modeling

For more complex structures with complicated geometric configurations, such as curved girder bridges, or bridges with highly skewed supports, more-detailed finite-element models should be considered. In this study the modeling was performed using 3-D finite-element method with the ABAQUS 6.6 software to obtain, stresses, vertical deflections, vertical reactions and natural frequencies for the above mentioned concrete, and steel composite bridges and to determine their structural response. To simplify the analysis, the structure was divided into a number of components as follows: For concrete structures, the bridges were divided into a concrete deck slab, concrete webs, concrete bottom flange, and concrete solid end & intermediate diaphragms. For the steel composite structures, the bridges were divided into a concrete deck slab, steel webs, steel bottom flange, steel top flanges, steel solid end-diaphragm, cross bracing and top chords.

3.7.1 Aspect Ratio

An important issue to be considered in finite-element modeling is to improve accuracy, which in turn results in more efficient and cost-effective design. The aspect ratio is defined as the ratio of the longest dimension to the shortest dimension of a quadrilateral element. In many cases, as the aspect ratio increases, the inaccuracy of the solution increases (Logan, 2002). Logan presented a graph showing that as the aspect ratio rises above 4, the percentage of error from the exact solution increases greater than 15%. Accordingly, in this study, the aspect ratio is kept in acceptable ranges, by considering 72 elements in the longitudinal direction for single-span

bridges, and 36 elements for two-span bridges, whereas 6 elements were considered in the vertical direction for the concrete bridge webs, and 4 elements for the composite bridge webs.

3.7.2 Geometric Modeling

3.7.2.1 Concrete Bridges Modeling

From the element available in the ABAQUS library, a four-node shell element, type S4R, with six degrees of freedom at each node was selected to model the concrete deck slab, concrete webs, concrete bottom flange, and concrete solid end & intermediate diaphragms. A detailed diagram of the shell element S4R is shown in Figure 3.3.

3.7.2.2 Composite Bridges Modeling

A four-node shell element, type S4R, with six degrees of freedom at each node was selected to model the concrete deck slab, steel webs, steel bottom flange, and steel solid end diaphragms. A three-dimensional two-node beam element, type B31H, was chosen to model the top steel flanges, cross-bracing, and top chord.

3.7.3 Boundary Conditions

One of the most important factors for the success of the structural analysis is the proper characterization of the boundary conditions of the structural system. Condition of the columns or abutments at the support point must be examined and properly implemented into the structural analysis model. This can be accomplished via several means based on different engineering assumptions. For the static analysis, it is common to use a simple representation of support (e.g., fixed, pinned, roller) without characterizations of the soil/foundation stiffness. In modeling the

bridge supports in this study, the lower nodes of the web ends were restrained against translation in such way to simulate temperature-free bridge superstructure.

For single span bridge: at the right end of the bridge, one of the middle supports was restrained against all possible translations (vertical, lateral, and longitudinal), and at the other end of the bridge (left end), one of the middle supports was restrained against vertical and lateral translations. However, the rest of supports at both ends were restrained only against vertical translations. For double spans bridge: at both right and left ends, one of the middle supports was restrained against vertical and lateral translations, and at the inner supports, one of the middle supports was restrained against all possible translations (vertical, lateral, and longitudinal). However, the rest of the bridge supports were restrained only against vertical translations. Figures 3.5 and 3.6 show typical boundary conditions for single and double-span bridges respectively.

The multi-point constraint option in the ABAQUS software, type BEAM, which allows constraint between different degrees of freedom, was used between the shell nodes of the concrete deck slab and the beam element nodes of the steel top flanges. This multi-point constraint option insures full interaction between the concrete deck slab and steel I-girder or box girder, thus modeling the presence of the shear connectors. A detailed diagram of the beam element B31H is shown in Figure 3.4. Appendices A & B show samples of ABAQUS input files used in this study.

3.7.4 Loads

During the bridge design process, computer models are used to evaluate bridge structures for various service loads, such as traffic, wind, thermal, construction, and other service loads. These service loads can be represented by a series of static load cases applied to the structural

model. For the purpose of comparing the results of straight bridge with curved one, a uniformly distributed load of 10 kN/m^2 was applied to the bridge models analyzed in this study.

3.8 Calculation of the Reaction Distribution Factors

In evaluating the reaction distribution factor (RDF) for curved bridge, the maximum reaction forces, (R_{straight}) , and (R_{curve}) were determined from the finite-element modeling for straight and curved bridges due to a uniformly distributed load of 10 kN/m^2 , respectively. Consequently, the reaction distribution factors (RDF) was calculated as follows:

$$(\text{RDF}) = (R_{\text{curve}}) / (R_{\text{straight}}) \quad (3.2)$$

Where (RDF) is the reaction distribution factor for curved bridge. (R_{curve}) , and (R_{straight}) are the maximum vertical reaction forces found at supports from the finite-element analysis due to the uniformly distributed load.

3.9 Calculation of the Stress Distribution Factors

The stress distribution factor (SDF) for curved bridge was determined. From the finite-element modeling, the maximum vertical stresses $(\sigma_{\text{straight}})$, and (σ_{curve}) were determined for straight and curved bridges due to a uniformly distributed load of 10 kN/m^2 , respectively. Accordingly, the stress distribution factors (SDF) were calculated as follows:

$$(\text{SDF}) = (\sigma_{\text{curve}}) / (\sigma_{\text{straight}}) \quad (3.3)$$

Where (SDF) is the stress distribution factor for curved bridge. (σ_{curve}) , and $(\sigma_{\text{straight}})$ are the maximum vertical stresses found from the finite-element analysis due to the uniformly distributed load.

3.10 Calculation of the Deflection Distribution Factors

Similar to above process, the deflection distribution factor (DDF) for curved bridge was determined. From the finite-element modeling, the mid-span deflection values at the middle of the bottom flange, $(\Delta_{\text{straight}})$, and (Δ_{curve}) , were determined for a straight and curved bridges due to a uniformly distributed load of 10 kN/m^2 , respectively. Consequently, the deflection distribution factors (DDF), were calculated from the following equation:

$$(\text{DDF}) = (\Delta_{\text{curve}}) / (\Delta_{\text{straight}}) \quad (3.4)$$

Where (DDF) is the deflection distribution factor for curved bridge. (Δ_{curve}) , and $(\Delta_{\text{straight}})$ the maximum vertical deflections found from the finite-element analysis due to the uniformly distributed load.

3.11 Calculation of the Frequency Distribution Factors

In the same way as above, the frequency distribution factor (FDF) for curved bridge was determined. From the finite-element modeling, the frequency values $(\omega_{\text{straight}})$, and (ω_{curve}) , were determined for straight and curved bridges due to a uniformly distributed load of 10 kN/m^2 respectively. Accordingly, the frequency distribution factors (FDF), were calculated from the following equation:

$$(\text{FDF}) = (\omega_{\text{curve}}) / (\omega_{\text{straight}}) \quad (3.5)$$

Where (FDF) is the frequency distribution factor for curved bridge. (ω_{curve}) , and $(\omega_{\text{straight}})$ are the maximum frequencies found from the finite-element analysis due to the uniformly distributed load.

CHAPTER IV

RESULTS FROM THE PARAMETRIC STUDY

4.1 General

This chapter presents an extensive parametric study, using the finite-element method, in which 1196 (single & double spans), straight and curved (concrete, & composite) bridge prototypes were considered for finite-element analysis in this study. The parametric study conducted herein presents the: (1) stress distribution factor; (2) deflection distribution factor; (3) reaction distribution factor; and (4) frequency distribution factor. In order to precisely determine the parameters affecting the above distribution factors, a sensitivity study was first undertaken to determine the influence of the different parameters that may affect these distribution factors, and from previous studies (Wassef, 2004 & Al-Hashimy, 2005) the following key parameters were considered:

- (i). Span-to-radius of curvature ratio (**L/R**),
- (ii). Bridge span length (**L**),
- (iii). Bridge width (**W**),
- (iv). Number of spans (**single & double**),

A data base was generated from the parametric study, to develop empirical expressions for evaluating the distribution factors for stress, deflection, reaction, and frequency. Due to a large numbers of different bridges considered in this study, it will not be possible to demonstrate each observation for all different prototypes, and thus selection of different choices of bridge

configurations will be used to illustrate different comparison and observations in the parametric study.

4.2 Effect of Curvature on Distribution Factors

Curvature is considered one of the major factors that influencing the structural behavior of curved bridges. The data base generated from the parametric study was used to investigate the effect of curvature on stress, deflection, reaction, and frequency distribution factors. In this study, 240 graphs were drawn for different single & double span curved concrete & composite bridges (Box-girder, T-beam, Solid Slab, and slab on steel I-girder bridge), to study the effect of curvature on distribution factor. In these graphs, the X-axis represented the span-to-radius of curvature (L/R), the Y-axis represented the type of distribution factor, and the results of this investigation can be summarized as follows:

4.2.1 Stress Distribution in Simply Supported and Continuous Curved Bridges

The effect of curvature on the stress distribution was investigated for different bridge configurations. Figure 4.77 to 4.114 and Figure 4.197 to 218 show the stress distribution factor for different single & double span curved concrete & composite bridges (Box-girder, T-beam, Solid Slab, and slab on steel I-girder bridge), with different span length (10 m to 55m), different widths (8 m, 12 m, & 16 m), and different span-to-radius of curvature ratio L/R (0.1 to 0.6), when subjected to a uniformly distributed dead load. It can be observed that as L/R ratio increases, the stress distribution factor increases. For example in Figure 4.199, as the L/R ratio increased from 0.1 to 0.6 for simply supported slab on steel I-girder bridge with 35 m span length, and 8 m width , the stress distribution factor increased from 1.63 to 5.1.

4.2.2 Deflection Distributions in Simply Supported and Continuous Curved Bridges

The effect of degree of curvature on deflection was examined. Figure 4.115 to 4.152 and Figure 4.219 to 4.240 present the deflection distribution factor for the same bridge configurations stated above in the stress distribution factor. It can be seen that the deflection distribution factor increases with the increase in L/R ratio. For example in Figure 4.221, as the L/R ratio increased from 0.1 to 0.6 for simply supported slab on steel I-girder bridge with 35 m span length, and 8 m width, the stress distribution factor increased from 1.28 to 7.2. Moreover, it can be observed that the concrete and composite box-girder bridges have better resistance to deflection than the steel I-girder and concrete T-beam bridges.

4.2.3 Reaction Distributions in Simply Supported and Continuous Curved Bridges

The effect of degree of curvature on reaction was examined in this parametric study. Figure 4.39 to 4.76 and Figure 4.175 to 4.196 show the reaction distribution factor (RDF) for the bridge configurations mentioned above in stress distribution factor. It can be observed that the (RDF) increases with the increase in L/R ratio. For example in Figure 4.181, as the L/R ratio increased from 0.1 to 0.6 for simply supported composite box girder bridge with 55 m span length, and 8 m width, the (RDF) increased from 1.39 to 3.42.

4.2.4 Frequency Distributions in Simply Supported and Continuous Curved Bridges

The effect of degree of curvature on Frequency was investigated. Figure 4.1 to 4.38 and Figure 4.153 to 4.174 show the frequency distribution factor (FDF) for the bridge configurations stated above in stress distribution factor. It can be seen that the (FDF) decreases with the increase in L/R ratio. For example in Figure 4.155, as the L/R ratio increased from 0.1 to 0.6 for simply

supported composite slab on steel I-girder bridge with 35 m span length, and 16 m width , the (FDF) decreased from 0.92 to 0.42.

4.3 Development of New Distribution Factor Equations for Curved Bridges

As stated earlier in chapter I, one of the objectives of this study was to develop empirical expressions to evaluate the stress, deflection, reaction, and frequency distribution factor. From the result of the parametric study, new empirical equations were developed for different single & double span curved concrete & composite bridges (Box-girder, T-beam, Solid Slab, and slab on steel I-girder bridge curved bridges) to evaluate these parameters. The general equation for the distribution factor takes the following form:

$$DF = a \left(\frac{L}{R} \right)^b \times (L)^c \times (B)^d + e$$

Where

DF: is the distribution factor (stress, deflection, reaction, and frequency)

L : is the bridge span length in meters,

R : is the radius of curvature,

B : is the bridge width in meters,

a , b , c , d , and e are equation variables.

The least square method was used to develop the above equation, by minimizing the square of the difference between the distribution factors obtained from the FEA and those from the proposed equations. The Excel solver was then used to obtain the optimal solution and consequently the equation variables a , b , c , d , and e were determined. The developed expressions were extended to establish more reliable expressions for curvature limitations to treat a horizontally curved bridge as a straight one. The limiting values of (L/R) , to ignore curvature

effect were determined with 5% & 10% underestimation, and these limitations were compared with those recommended by North American Bridge Codes. Tables 4.1 to 4.4 show the list of developed expressions.

4.7 Comparison between Curvature Limitations in North American Bridge Codes and those obtained from Current Finite Element Analysis

As mentioned in chapter I, the main objective of this study was to examine the applicability of the specified limitations of bridge curvature in North American Bridge Codes to treat a horizontally curved bridge as straight one in structural analysis and design. The limitations recommended by the CHBDC, AASHTO guide specifications (1993, & 2003), and AASHTO LRFD 2004, were examined in this study. The results of this comparison are as follows:

4.7.1 Canadian Highway Bridge Design Code (CHBDC 2006) Limitations

The Canadian Highway Bridge Design Code (CHBDC) considers curved bridge to be treated as a straight one if:

$$L^2/BR \leq 0.5$$

Where, **L** is the curved span length, **B** is the bridge width, and **R** is the radius of curvature.

From the developed distribution factors equations, the limiting values of span-to-radius of curvature ratio (**L/R**), to treat horizontally curved bridge as straight one were calculated with 5% & 10% underestimation. These values were compared with the corresponding values calculates from CHBDC equation above as shown in Table 4.5 and 4.6. The summery of this comparison is as follows:

4.7.1.1 Stress Distribution Factor (SDF)

The (SDF) for the curvature limitations in Tables 4.1 to 4.4 (considering single span with 5% underestimation) were compared with the recommended by CHBDC. It can be clearly observed that the CHBDC is:

- (i) Satisfactory with concrete box girder bridge, except for multi-box girder bridge with $\text{span} \leq 25 \text{ m}$ and $\text{width} \geq 12 \text{ m}$.
- (ii) Underestimating the T-beam, and for solid slab only bridges with $\text{spans} \leq 15 \text{ m}$ & $\text{width} \geq 8 \text{ m}$.
- (iii) Satisfactory with the steel single-box girder and underestimating the steel multi-box girder for $\text{spans } 55 \geq L \geq 20 \text{ m}$ & $\text{width} \geq 16 \text{ m}$.
- (iv) Underestimating the slab on steel I-girder bridge.

4.7.1.2 Deflection Distribution Factor (DDF)

In comparing the (DDF) for the curvature limitations in Tables 4.1 to 4.4 (considering single span & 5% underestimation) with the limitations recommended by CHBDC, it can be clearly seen that the CHBDC:

- (i) For concrete bridges satisfactory with concrete single-box girder, and underestimates the cellular and multi-box girder with $\text{spans} \leq 35 \text{ m}$ & $\text{width} \geq 9 \text{ m}$. Also under estimate the T-beam and slab bridges.
- (ii) For composite bridges satisfactory with the single-box girder, and under- estimate the multi-box girder with $\text{spans} \leq 35 \text{ m}$ & $\text{width} \geq 9 \text{ m}$. Also under estimate the slab on steel I-girder bridge.

4.7.1.3 Reaction Distribution Factor (RDF)

In comparing the (RDF) for the curvature limitations in Tables 4.1 to 4.4 (considering single span & 5% underestimation) with the recommended by CHBDC, it can be obvious that the CHBDC is underestimating the (RDF) for all concrete and composite bridges examined in this study.

4.7.1.4 Frequency Distribution Factor (FDF)

The curvature limitations for (FDF) in Tables 4.1 to 4.4 (considering single span & 5% underestimation) were compared with the recommended by CHBDC, it can be obvious that the CHBDC:

- (i) For concrete bridges satisfactory with concrete cellular, multi-box girder, and single box girder. Underestimating the T-beam with spans ≤ 35 m & width > 8 m, and concrete solid slab with spans ≤ 15 m & width ≥ 12 m.
- (ii) For composite bridges satisfactory with multi-box girder, single-box girder, and underestimating the slab on steel I-girder bridges.

4.7.2 AASHTO Guide Specifications 1993 Limitations

The limitations recommended by guide specifications for horizontally curved highway bridges (AASHTO 1993) for steel I-girder bridge, were compared with the limitations from the developed expression with 10% underestimation, as shown in Tables 4.1 to 4.4. It can be clear that the AASHTO guide underestimates the stress distribution factor (SDF) for curved slab on steel I-girder bridges, to treat them as straight one.

4.7.3 AASHTO Guide Specifications 2003 Limitations

Similar to above process the limitations recommended by AASHTO guide 2003 for determining the vertical stress, were compared with the limitations from the developed expression with 10% underestimation, as shown in Tables 4.1 to 4.4. It can be obvious that the AASHTO guide 2003 is:

- (i) Satisfactory with single-span composite single box girder bridges and underestimating the single-span curved steel multi-box girder bridges with spans ≥ 25 m & width ≥ 16 m.
- (ii) Conservative with the two-span composite box-girder bridges (single & multi-box).
- (iii) Underestimating both single and double span slab on steel I-girder bridges.

4.7.4 AASHTO-LRFD Guide Specifications 2007 Limitations

The limitations recommended by AASHTO-LRFD guide specifications 2007 for determining the vertical stress, were compared with the limitations from the developed expression with 10% under estimation, as shown in Tables 4.1 to 4.4. It can be clearly seen that the AASHTO-LRFD guide 2007 is:

- (i) Satisfactory with single-span concrete multi-box girder, single-box girder bridges, and underestimating the concrete cellular bridges with span ≤ 35 m, & width ≤ 11 m.
- (ii) Underestimating the single-span concrete T-beam bridges with spans ≥ 25 m,

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Summary

A series of horizontally curved bridge prototypes were analyzed in this study to examine the applicability of the specified limitations of bridge curvature in North American Bridge Codes to treat a horizontally curved bridge as straight one in structural analysis and design. Bridges taken into account are single & double-span horizontally curved concrete slab bridges, concrete girder bridges, concrete box girder bridges, slab on steel I-girder bridges, and composite steel box girder bridges. The design parameters considered in this study are degree of curvature, number of spans, span length, numbers of lanes, and span-to-depth ratio.

A data base was generated from the parametric study, to develop empirical expressions for evaluating the distribution factors for stress, deflection, reaction, and frequency of curved bridges.

5.2 Conclusions

Based on the results from the parametric study, the following conclusions are drawn:

- (1) Curvature is the most important parameter that affecting the structural behavior of horizontally curved bridges. Increase in the degree of curvature leads to significant increase in the stress, deflection, and reaction distribution factors, and decrease in the frequency distribution factor.
- (2) This study showed that the reaction distribution factor is absolutely the most critical factor for treating single-span curved concrete and steel box-girder bridges as straight

one, while the deflection distribution factor is the critical one for double-span concrete (cellular & multi) and steel multi-box girder bridges.

(3) The stress distribution factor is the governing factor for both single and double-span curved slab on steel I-girder bridges to treat them as straight one.

(4) The CHBDC significantly underestimates the following distribution factors for curved bridges to treat them as straight one:

(i) The reaction distribution factor (RDF) for all concrete and steel bridges covered in this study.

(ii) The stress distribution factor (SDF) for Steel I-girder, concrete T-beam, concrete multi-box girder with spans ≤ 25 m & width ≥ 12 m, concrete solid slab with spans ≤ 15 m & width ≥ 8 m, and steel multi-box girder with spans $55 \geq L \geq 20$ m & width ≥ 16 m.

(iii) The deflection distribution factor (DDF) for concrete T-beam, solid slab, and steel I-girder. Also for (concrete & steel) multi-box girder, with spans ≤ 35 m & width ≥ 9 m.

(iv) The frequency distribution factor (FDF) for concrete T-beam with spans ≤ 35 m & width > 8 m, and concrete solid slab with spans ≤ 15 m & width ≥ 12 m.

(5) The AASHTO guide specifications (1993, 2003) underestimate the stress distribution factor (SDF) for curved slab on steel I-girder bridges to treat them as straight one. Also the 2003 guide specifications underestimate (SDF) for single-span curved steel multi-box

girder bridges with spans ≥ 25 m & width ≥ 16 m, and conservative with the curved two-span steel box-girder bridges (single & multi-box).

- (6) The AASHTO-LRFD guide specifications 2007 underestimate the stress distribution factor (SDF) for curved single-span concrete T-beam bridges with span ≥ 25 m, and also concrete cellular bridges with span ≤ 35 m & width ≤ 11 m.
- (7) Sets of empirical expressions for stress, deflection, reaction, and frequency distribution factors were developed for both single and double-span curved concrete and steel bridges.

5.3 Recommendations for Future Research

Further research is recommended in the following areas:

- 1- The study of stress, deflection, reaction, and frequency distribution factors for curved bridges to treat them as straight one, for more than two-span.
- 2- The effect of skew supports in stress, deflection, reaction, and frequency distribution factors for curved bridge system.
- 3- The effect of CHBDC truck loading conditions on the curvature limitations established in this thesis for dead loading.
- 4- Study of curvature limitations for non-composite steel I-girder and box girder bridges at construction state.
- 5- Study of curvature limitations in two-span bridges with central interior column support.
- 6- Investigate the CHBDC limitations for skew bridges to be treated as straight ones.

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Table 4.1 Distribution Factor Equations for Concrete Bridges with 5% underestimation

Bridge Type	Distribution Factor Type	Proposed Equation with 5% underestimation			
		Single-span	Eq. No.	Double-span	Eq. No.
Cellular Bridge	Stress	$(L/R)^{1.32} \times (L)^{-0.5} \times (B)^{-0.56} \leq 0.011$	4.1	$(L/R)^{1.64} \times (L)^{-1.55} \times (B)^{1.46} \leq 0.083$	4.21
	Deflection	$(L/R)^{1.11} \times (L)^{-0.46} \times (B)^{0.5} \leq 0.053$	4.2	$(L/R)^{1.09} \times (L)^{-1.04} \times (B)^{1.26} \leq 0.075$	4.22
	Reaction	$(L/R)^{0.98} \times (L)^{0.07} \times (B)^{-0.28} \leq 0.028$	4.3	$(L/R)^{1.07} \times (L)^{-0.5} \times (B)^{0.81} \leq 0.833$	4.23
	Frequency	$(L/R)^{1.93} \times (L)^{-0.26} \times (B)^{0.21} \leq 0.161$	4.4	$(L/R)^2 \times (L)^{-0.39} \times (B)^{0.38} \leq 0.455$	4.24
Governing Equation		The one for Reaction		The one for Deflection	
Multi-Box Girder Bridge	Stress	$(L/R)^{1.17} \times (L)^{-0.25} \times (B)^{0.62} \leq 0.217$	4.5	$(L/R)^{1.46} \times (L)^{-0.88} \times (B)^{1.3} \leq 0.385$	4.25
	Deflection	$(L/R)^{1.27} \times (L)^{-0.34} \times (B)^{0.71} \leq 0.078$	4.6	$(L/R)^{1.12} \times (L)^{-0.8} \times (B)^{1.34} \leq 0.167$	4.26
	Reaction	$(L/R)^{1.09} \times (L)^{-0.17} \times (B)^{-0.02} \leq 0.013$	4.7	$(L/R)^{1.92} \times (L)^{-0.8} \times (B)^{-0.33} \leq 0.01$	4.27
	Frequency	$(L/R)^{1.86} \times (L)^{-0.11} \times (B)^{0.46} \leq 0.357$	4.8	$(L/R)^2 \times (L)^{-0.49} \times (B)^{0.8} \leq 0.556$	4.28
Governing Equation		The one for Reaction		The one for Deflection	
Single Box Girder Bridge	Stress	$(L/R)^{1.24} \times (L)^{-0.56} \times (B)^{-0.25} \leq 0.014$	4.9	$(L/R)^{1.32} \times (L)^{-0.4} \times (B)^{0.18} \leq 0.417$	4.29
	Deflection	$(L/R)^{1.61} \times (L)^{-0.23} \times (B)^{0.21} \leq 0.068$	4.10	$(L/R)^{1.19} \times (L)^{-0.78} \times (B)^{0.77} \leq 0.111$	4.30
	Reaction	$(L/R)^{1.03} \times (L)^{1.18} \times (B)^{-1.19} \leq 0.135$	4.11	$(L/R)^{1.02} \times (L)^{-0.16} \times (B)^{0.22} \leq 0.556$	4.31
	Frequency	$(L/R)^{1.94} \times (L)^{0.1} \times (B)^{-0.16} \leq 0.263$	4.12	$(L/R)^2 \times (L)^{-0.03} \times (B)^{-0.01} \leq 1$	4.32
Governing Equation		The one for Reaction		The one for Deflection	
T-Beam Bridge	Stress	$(L/R)^{0.92} \times (L)^{0.84} \times (B)^{-0.07} \leq 0.333$	4.13	$(L/R)^{0.67} \times (L)^{0.39} \times (B)^{0.14} \leq 0.833$	4.33
	Deflection	$(L/R)^{1.14} \times (L)^{0.06} \times (B)^{0.27} \leq 0.037$	4.14	$(L/R)^{0.88} \times (L)^{-0.35} \times (B)^{0.61} \leq 0.082$	4.34
	Reaction	$(L/R)^{1.16} \times (L)^{-0.35} \times (B)^{-0.16} \leq 0.011$	4.15	$(L/R)^{1.12} \times (L)^{-0.2} \times (B)^{0.29} \leq 0.208$	4.35
	Frequency	$(L/R)^{1.14} \times (L)^{0.21} \times (B)^{0.06} \leq 0.192$	4.16	$(L/R)^{1.47} \times (L)^{0.17} \times (B)^{0.49} \leq 1.25$	4.36
Governing Equation		The Stress & deflection		The Stress & deflection	
Solid Slab Bridge	Stress	$(L/R)^{0.72} \times (L)^{-1.13} \times (B)^{1.03} \leq 0.139$	4.17	$(L/R)^{1.04} \times (L)^{-1.75} \times (B)^{1.75} \leq 0.061$	4.37
	Deflection	$(L/R)^{1.38} \times (L)^{-1.23} \times (B)^{1.15} \leq 0.015$	4.18	$(L/R)^{1.16} \times (L)^{-1.46} \times (B)^{1.47} \leq 0.02$	4.38
	Reaction	$(L/R)^{0.71} \times (L)^{0.002} \times (B)^{0.14} \leq 0.069$	4.19	$(L/R)^{0.79} \times (L)^{-1.18} \times (B)^{1.2} \leq 0.172$	4.39
	Frequency	$(L/R)^{1.3} \times (L)^{-1.24} \times (B)^{1.19} \leq 0.111$	4.20	$(L/R)^{1.52} \times (L)^{-1.83} \times (B)^{1.79} \leq 0.083$	4.40
Governing Equation		The one for Reaction		The one for Deflection	

Table 4.2 Distribution Factor Equations for Concrete Bridges with 10% underestimation

Bridge Type	Distribution Factor Type	Proposed Equation with 10% underestimation			
		Single-span	Eq. No.	Double-span	Eq. No.
Cellular Bridge	Stress	$(L/R)^{1.32} \times (L)^{-0.5} \times (B)^{-0.56} \leq 0.022$	4.41	$(L/R)^{1.64} \times (L)^{-1.55} \times (B)^{1.46} \leq 0.166$	4.61
	Deflection	$(L/R)^{1.11} \times (L)^{-0.46} \times (B)^{0.5} \leq 0.106$	4.42	$(L/R)^{1.09} \times (L)^{-1.04} \times (B)^{1.26} \leq 0.15$	4.62
	Reaction	$(L/R)^{0.98} \times (L)^{0.07} \times (B)^{-0.28} \leq 0.056$	4.43	$(L/R)^{1.07} \times (L)^{-0.5} \times (B)^{0.81} \leq 1.666$	4.63
	Frequency	$(L/R)^{1.93} \times (L)^{-0.26} \times (B)^{0.21} \leq 0.322$	4.44	$(L/R)^2 \times (L)^{-0.39} \times (B)^{0.38} \leq 0.91$	4.64
Governing Equation		The one for Reaction		The one for Deflection	
Multi-Box Girder Bridge	Stress	$(L/R)^{1.17} \times (L)^{-0.25} \times (B)^{0.62} \leq 0.434$	4.45	$(L/R)^{1.46} \times (L)^{-0.88} \times (B)^{1.3} \leq 0.77$	4.65
	Deflection	$(L/R)^{1.27} \times (L)^{-0.34} \times (B)^{0.71} \leq 0.156$	4.46	$(L/R)^{1.12} \times (L)^{-0.8} \times (B)^{1.34} \leq 0.334$	4.66
	Reaction	$(L/R)^{1.09} \times (L)^{-0.17} \times (B)^{-0.02} \leq 0.026$	4.47	$(L/R)^{1.92} \times (L)^{-0.8} \times (B)^{-0.33} \leq 0.02$	4.67
	Frequency	$(L/R)^{1.86} \times (L)^{-0.11} \times (B)^{0.46} \leq 0.714$	4.48	$(L/R)^2 \times (L)^{-0.49} \times (B)^{0.8} \leq 1.112$	4.68
Governing Equation		The one for Reaction		The one for Deflection	
Single Box Girder Bridge	Stress	$(L/R)^{1.24} \times (L)^{-0.56} \times (B)^{-0.25} \leq 0.028$	4.49	$(L/R)^{1.32} \times (L)^{-0.4} \times (B)^{0.18} \leq 0.834$	4.69
	Deflection	$(L/R)^{1.61} \times (L)^{-0.23} \times (B)^{0.21} \leq 0.136$	4.50	$(L/R)^{1.19} \times (L)^{-0.78} \times (B)^{0.77} \leq 0.222$	4.70
	Reaction	$(L/R)^{1.03} \times (L)^{1.18} \times (B)^{-1.19} \leq 0.27$	4.51	$(L/R)^{1.02} \times (L)^{-0.16} \times (B)^{0.22} \leq 1.112$	4.71
	Frequency	$(L/R)^{1.94} \times (L)^{0.1} \times (B)^{-0.16} \leq 0.526$	4.52	$(L/R)^2 \times (L)^{-0.03} \times (B)^{-0.01} \leq 2$	4.72
Governing Equation		The one for Reaction		The one for Deflection	
T-Beam Bridge	Stress	$(L/R)^{0.92} \times (L)^{0.84} \times (B)^{-0.07} \leq 0.666$	4.53	$(L/R)^{0.67} \times (L)^{0.39} \times (B)^{0.14} \leq 1.666$	4.73
	Deflection	$(L/R)^{1.14} \times (L)^{0.06} \times (B)^{0.27} \leq 0.074$	4.54	$(L/R)^{0.88} \times (L)^{-0.35} \times (B)^{0.61} \leq 0.164$	4.74
	Reaction	$(L/R)^{1.16} \times (L)^{-0.35} \times (B)^{-0.16} \leq 0.022$	4.55	$(L/R)^{1.12} \times (L)^{-0.2} \times (B)^{0.29} \leq 0.416$	4.75
	Frequency	$(L/R)^{1.14} \times (L)^{0.21} \times (B)^{0.06} \leq 0.384$	4.56	$(L/R)^{1.47} \times (L)^{0.17} \times (B)^{0.49} \leq 2.5$	4.76
Governing Equation		The Stress & deflection		The Stress & deflection	
Solid Slab Bridge	Stress	$(L/R)^{0.72} \times (L)^{-1.13} \times (B)^{1.03} \leq 0.278$	4.57	$(L/R)^{1.04} \times (L)^{-1.75} \times (B)^{1.75} \leq 0.122$	4.77
	Deflection	$(L/R)^{1.38} \times (L)^{-1.23} \times (B)^{1.15} \leq 0.03$	4.58	$(L/R)^{1.16} \times (L)^{-1.46} \times (B)^{1.47} \leq 0.04$	4.78
	Reaction	$(L/R)^{0.71} \times (L)^{0.002} \times (B)^{0.14} \leq 0.138$	4.59	$(L/R)^{0.79} \times (L)^{-1.18} \times (B)^{1.2} \leq 0.344$	4.79
	Frequency	$(L/R)^{1.3} \times (L)^{-1.24} \times (B)^{1.19} \leq 0.222$	4.60	$(L/R)^{1.52} \times (L)^{-1.83} \times (B)^{1.79} \leq 0.166$	4.80
Governing Equation		The one for Reaction		The one for Deflection	

Table 4.3 Distribution Factor Equations for Composite Bridges with 5% underestimation

Bridge Type	Distribution Factor Type	Proposed Equation with 5% underestimation			
		Single-span	Eq. No.	Double-span	Eq. No.
Multi-Box Girder Bridge	Stress	$(L/R)^{0.97} \times (L)^{0.14} \times (B)^{0.55} \leq 1$	4.81	$(L/R)^{1.63} \times (L)^{-1.1} \times (B)^{1.03} \leq 0.068$	4.93
	Deflection	$(L/R)^{1.24} \times (L)^{-0.45} \times (B)^{0.91} \leq 0.102$	4.82	$(L/R)^{1.11} \times (L)^{-0.84} \times (B)^{1.34} \leq 0.156$	4.94
	Reaction	$(L/R)^{0.98} \times (L)^{0.68} \times (B)^{-0.04} \leq 0.185$	4.83	$(L/R)^{1.28} \times (L)^{-1.47} \times (B)^{1.4} \leq 0.03$	4.95
	Frequency	$(L/R)^{1.84} \times (L)^{-0.28} \times (B)^{0.61} \leq 0.294$	4.84	$(L/R)^{1.99} \times (L)^{-0.46} \times (B)^{0.67} \leq 0.5$	4.96
Governing Equation		The one for Reaction		The one for Deflection	
Single Box Girder Bridge	Stress	$(L/R)^{0.97} \times (L)^{0.09} \times (B)^{0.38} \leq 0.833$	4.85	$(L/R)^{0.75} \times (L)^{-0.55} \times (B)^{2.03} \leq 10$	4.97
	Deflection	$(L/R)^{1.84} \times (L)^{0.1} \times (B)^{-0.1} \leq 0.102$	4.86	$(L/R)^{1.56} \times (L)^{0.04} \times (B)^{-0.64} \leq 0.185$	4.98
	Reaction	$(L/R)^{0.99} \times (L)^{0.97} \times (B)^{-1.01} \leq 0.102$	4.87	$(L/R)^{1.11} \times (L)^{-0.31} \times (B)^{0.16} \leq 0.238$	4.99
	Frequency	$(L/R)^{1.95} \times (L)^{0.6} \times (B)^{-0.74} \leq 0.455$	4.88	$(L/R)^2 \times (L)^{0.52} \times (B)^{-0.63} \leq 2.5$	4.100
Governing Equation		The one for Reaction		The one for Deflection	
Slab on I-Girder Bridge	Stress	$(L/R)^{0.92} \times (L)^{0.5} \times (B)^{0.04} \leq 0.054$	4.89	$(L/R)^{0.81} \times (L)^{-0.06} \times (B)^{0.08} \leq 0.039$	4.101
	Deflection	$(L/R)^{1.65} \times (L)^{0.18} \times (B)^{0.27} \leq 0.014$	4.90	$(L/R)^{1.28} \times (L)^{-0.2} \times (B)^{0.34} \leq 0.031$	4.102
	Reaction	$(L/R)^{0.87} \times (L)^{0.24} \times (B)^{-0.22} \leq 0.049$	4.91	$(L/R)^{1.08} \times (L)^{0.38} \times (B)^{0.52} \leq 5$	4.103
	Frequency	$(L/R)^{0.99} \times (L)^{0.1} \times (B)^{0.08} \leq 0.088$	4.92	$(L/R)^{1.38} \times (L)^{-0.13} \times (B)^{0.2} \leq 0.088$	4.104
Governing Equation		The one for Stress		The one for Stress	

Table 4.4 Distribution Factor Equations for Composite Bridges with 10% underestimation

Bridge Type	Distribution Factor Type	Proposed Equation with 10% underestimation			
		Single-span	Eq. No.	Double-span	Eq. No.
Multi-Box Girder Bridge	Stress	$(L/R)^{0.97} \times (L)^{0.14} \times (B)^{0.55} \leq 2$	4.105	$(L/R)^{1.63} \times (L)^{-1.1} \times (B)^{1.03} \leq 0.136$	4.117
	Deflection	$(L/R)^{1.24} \times (L)^{-0.45} \times (B)^{0.91} \leq 0.204$	4.106	$(L/R)^{1.11} \times (L)^{-0.84} \times (B)^{1.34} \leq 0.312$	4.118
	Reaction	$(L/R)^{0.98} \times (L)^{0.68} \times (B)^{-0.04} \leq 0.37$	4.107	$(L/R)^{1.28} \times (L)^{-1.47} \times (B)^{1.4} \leq 0.06$	4.119
	Frequency	$(L/R)^{1.84} \times (L)^{-0.28} \times (B)^{0.61} \leq 0.588$	4.108	$(L/R)^{1.99} \times (L)^{-0.46} \times (B)^{0.67} \leq 1$	4.120
Governing Equation		The one for Reaction		The one for Deflection	
Single Box Girder Bridge	Stress	$(L/R)^{0.97} \times (L)^{0.09} \times (B)^{0.38} \leq 1.666$	4.109	$(L/R)^{0.75} \times (L)^{-0.55} \times (B)^{2.03} \leq 20$	4.121
	Deflection	$(L/R)^{1.84} \times (L)^{0.1} \times (B)^{-0.1} \leq 0.204$	4.110	$(L/R)^{1.56} \times (L)^{0.04} \times (B)^{-0.64} \leq 0.37$	4.122
	Reaction	$(L/R)^{0.99} \times (L)^{0.97} \times (B)^{-1.01} \leq 0.204$	4.111	$(L/R)^{1.11} \times (L)^{-0.31} \times (B)^{0.16} \leq 0.476$	4.123
	Frequency	$(L/R)^{1.95} \times (L)^{0.6} \times (B)^{-0.74} \leq 0.91$	4.112	$(L/R)^2 \times (L)^{0.52} \times (B)^{-0.63} \leq 5$	4.124
Governing Equation		The one for Reaction		The one for Deflection	
Slab on I-Girder Bridge	Stress	$(L/R)^{0.92} \times (L)^{0.5} \times (B)^{0.04} \leq 0.108$	4.113	$(L/R)^{0.81} \times (L)^{-0.06} \times (B)^{0.08} \leq 0.078$	4.125
	Deflection	$(L/R)^{1.65} \times (L)^{0.18} \times (B)^{0.27} \leq 0.028$	4.114	$(L/R)^{1.28} \times (L)^{-0.2} \times (B)^{0.34} \leq 0.062$	4.126
	Reaction	$(L/R)^{0.87} \times (L)^{0.24} \times (B)^{-0.22} \leq 0.098$	4.115	$(L/R)^{1.08} \times (L)^{0.38} \times (B)^{0.52} \leq 10$	4.127
	Frequency	$(L/R)^{0.99} \times (L)^{0.1} \times (B)^{0.08} \leq 0.176$	4.116	$(L/R)^{1.38} \times (L)^{-0.13} \times (B)^{0.2} \leq 0.176$	4.128
Governing Equation		The one for Stress		The one for Stress	

Table 4.5.a Limitations of (L/R) Comparison between North American Bridge Codes and those obtained from Finite Element Analysis for Concrete Bridges

Limitations of (L/R) Comparison between North American Bridge Codes and those obtained from Finite Element Analysis for Concrete Bridges																										
Bridge Type	Bridge Parameters		Value of (L/R) according to Proposed Equation with 5% under estimation								Value of (L/R) according to Proposed Equation with 10% under estimation								Value of (L/R) according to CHBDC $L^2/BR \leq 0.5$	Value of (L/R) according to ASHTO-LRFD						
	Span Length (L) in m.	Width (B) in m.	Single-span				Double-span				Single-span				Double-span					Box Girder Types	Single-Span			Two or more spans		
			S	D	R	F	S	D	R	F	S	D	R	F	S	D	R	F			2 Beams	3 or 4 Beams	5 or more Beams	2 Beams	3-4 Beams	5 or more Beams
Cellular Bridge	25	8	0.27	0.11	0.04	0.48	1.39	0.35	1.09	0.97	0.45	0.20	0.08	0.68	2.12	0.66	2.08	1.38	0.16	0.6	-	-	-	-	-	-
	25	12	0.32	0.09	0.04	0.46	0.97	0.22	0.80	0.90	0.54	0.16	0.09	0.65	1.48	0.41	1.53	1.28	0.24	0.6	-	-	-	-	-	-
	25	16	0.36	0.08	0.05	0.44	0.75	0.16	0.64	0.85	0.61	0.14	0.09	0.63	1.14	0.30	1.23	1.21	0.32	0.6	-	-	-	-	-	-
	35	8	0.30	0.12	0.04	0.50	1.91	0.48	1.27	1.04	0.52	0.23	0.07	0.72	2.91	0.91	2.43	1.47	0.11	0.6	-	-	-	-	-	-
	35	12	0.36	0.10	0.04	0.48	1.33	0.30	0.94	0.96	0.61	0.19	0.08	0.68	2.03	0.57	1.79	1.36	0.17	0.6	-	-	-	-	-	-
	35	16	0.41	0.09	0.04	0.46	1.03	0.22	0.75	0.91	0.69	0.17	0.09	0.66	1.57	0.41	1.44	1.29	0.23	0.6	-	-	-	-	-	-
	45	8	0.34	0.13	0.04	0.52	2.42	0.61	1.43	1.09	0.57	0.25	0.07	0.74	3.69	1.16	2.73	1.55	0.09	0.6	-	-	-	-	-	-
	45	12	0.40	0.11	0.04	0.49	1.69	0.38	1.05	1.01	0.67	0.21	0.08	0.71	2.57	0.73	2.01	1.43	0.13	0.6	-	-	-	-	-	-
	45	16	0.45	0.10	0.04	0.48	1.31	0.28	0.85	0.96	0.76	0.18	0.09	0.69	1.99	0.52	1.62	1.35	0.18	0.6	-	-	-	-	-	-
	55	8	0.36	0.15	0.04	0.53	2.93	0.74	1.57	1.14	0.61	0.27	0.07	0.76	4.47	1.41	3.00	1.61	0.07	0.6	-	-	-	-	-	-
55	12	0.43	0.12	0.04	0.51	2.04	0.47	1.16	1.05	0.73	0.23	0.08	0.73	3.11	0.88	2.21	1.49	0.11	0.6	-	-	-	-	-	-	
55	16	0.49	0.11	0.04	0.49	1.58	0.33	0.93	1.00	0.82	0.20	0.09	0.71	2.41	0.63	1.78	1.41	0.15	0.6	-	-	-	-	-	-	
Multi-Box Girder	25	8	0.18	0.10	0.03	0.42	0.86	0.27	0.66	0.85	0.32	0.17	0.06	0.60	1.39	0.51	0.95	1.20	0.16	0.2	-	-	-	-	-	-
	25	12	0.14	0.08	0.03	0.38	0.60	0.17	0.71	0.72	0.26	0.14	0.06	0.55	0.97	0.31	1.02	1.02	0.24	0.2	-	-	-	-	-	-
	25	16	0.12	0.07	0.03	0.35	0.47	0.12	0.75	0.64	0.22	0.12	0.06	0.51	0.75	0.22	1.07	0.91	0.32	0.2	-	-	-	-	-	-
	35	8	0.19	0.11	0.03	0.42	1.06	0.35	0.76	0.92	0.35	0.19	0.06	0.62	1.70	0.65	1.09	1.30	0.11	0.2	-	-	-	-	-	-
	35	12	0.16	0.09	0.03	0.38	0.74	0.22	0.82	0.78	0.28	0.15	0.06	0.56	1.18	0.40	1.17	1.11	0.17	0.2	-	-	-	-	-	-
	35	16	0.13	0.07	0.03	0.36	0.57	0.15	0.86	0.70	0.24	0.13	0.06	0.52	0.92	0.28	1.23	0.99	0.23	0.2	-	-	-	-	-	-
	45	8	0.20	0.12	0.04	0.43	1.23	0.42	0.85	0.98	0.37	0.20	0.07	0.62	1.98	0.78	1.22	1.38	0.09	0.2	-	-	-	-	-	-
	45	12	0.16	0.09	0.04	0.39	0.86	0.26	0.91	0.83	0.30	0.16	0.07	0.57	1.38	0.48	1.30	1.18	0.13	0.2	-	-	-	-	-	-
	45	16	0.14	0.08	0.04	0.36	0.66	0.18	0.95	0.74	0.25	0.14	0.07	0.53	1.07	0.34	1.37	1.05	0.18	0.2	-	-	-	-	-	-
	55	8	0.21	0.12	0.04	0.44	1.39	0.48	0.92	1.03	0.38	0.21	0.07	0.63	2.23	0.90	1.32	1.45	0.07	0.2	-	-	-	-	-	-
	55	12	0.17	0.10	0.04	0.39	0.97	0.30	0.99	0.87	0.31	0.17	0.07	0.57	1.56	0.55	1.42	1.23	0.11	0.2	-	-	-	-	-	-
	55	16	0.15	0.08	0.04	0.37	0.75	0.21	1.04	0.78	0.27	0.14	0.07	0.53	1.20	0.39	1.49	1.10	0.15	0.2	-	-	-	-	-	-

Notes: S, stress; D, deflection; R, reaction; F, frequency

Table 4.5.b Limitations of (L/R) Comparison between North American Bridge Codes and those obtained from Finite Element Analysis for Concrete Bridges

Limitations of (L/R) Comparison between North American Bridge Codes and those obtained from Finite Element Analysis for Concrete Bridges

Bridge Type	Bridge Parameters		Value of (L/R) according to Proposed Equation with under estimation 5%								Value of (L/R) according to Proposed Equation with under estimation 10%								Value of (L/R) according to CHBDC $L^3/BR \leq 0.5$	Value of (L/R) according to ASHTO-LRFD						
	Span Length (L) in m.	Width (B) in m.	Single-span				Double-span				Single-span				Double-span					Box Girder Types	Single-Span			Two or more spans		
			S	D	R	F	S	D	R	F	S	D	R	F	S	D	R	F			2 Beams	3 or 4 Beams	5 or more Beams	2 Beams	3-4 Beams	5 or more Beams
Single-Box Girder	25	8	0.21	0.23	0.04	0.51	1.27	0.53	0.66	1.07	0.36	0.35	0.08	0.72	2.15	0.95	1.31	1.52	0.16	0.2	-	-	-	-	-	-
	25	12	0.23	0.22	0.06	0.52	1.20	0.41	0.61	1.07	0.40	0.33	0.12	0.75	2.03	0.73	1.20	1.52	0.24	0.2	-	-	-	-	-	-
	35	8	0.24	0.24	0.03	0.50	1.41	0.66	0.70	1.08	0.42	0.37	0.05	0.71	2.38	1.19	1.38	1.52	0.11	0.2	-	-	-	-	-	-
	35	12	0.26	0.23	0.04	0.51	1.33	0.51	0.64	1.08	0.46	0.35	0.08	0.73	2.25	0.92	1.26	1.53	0.17	0.2	-	-	-	-	-	-
	45	8	0.27	0.25	0.02	0.49	1.52	0.78	0.73	1.08	0.47	0.38	0.04	0.70	2.57	1.40	1.44	1.53	0.09	0.2	-	-	-	-	-	-
	45	12	0.29	0.23	0.03	0.51	1.44	0.60	0.67	1.08	0.52	0.36	0.06	0.72	2.43	1.08	1.32	1.53	0.13	0.2	-	-	-	-	-	-
	55	8	0.30	0.25	0.02	0.49	1.61	0.89	0.75	1.08	0.52	0.39	0.03	0.69	2.73	1.60	1.48	1.53	0.07	0.2	-	-	-	-	-	-
	55	12	0.32	0.24	0.03	0.50	1.53	0.69	0.69	1.09	0.56	0.37	0.05	0.72	2.58	1.23	1.36	1.54	0.11	0.2	-	-	-	-	-	-
T-Beam Bridge	15	8	0.03	0.03	0.06	0.13	0.07	0.05	0.26	0.39	0.06	0.05	0.11	0.24	0.19	0.12	0.49	0.63	0.27	-	0.03	0.05	0.07	0.05	0.07	0.09
	15	12	0.03	0.03	0.07	0.13	0.06	0.04	0.24	0.34	0.07	0.05	0.12	0.23	0.18	0.09	0.44	0.55	0.40	-	0.03	0.05	0.07	0.05	0.07	0.09
	15	16	0.03	0.02	0.07	0.12	0.06	0.03	0.22	0.31	0.07	0.05	0.12	0.23	0.17	0.07	0.41	0.50	0.53	-	0.03	0.05	0.07	0.05	0.07	0.09
	25	8	0.02	0.03	0.07	0.12	0.05	0.07	0.29	0.37	0.04	0.05	0.13	0.21	0.14	0.14	0.54	0.59	0.16	-	0.03	0.05	0.07	0.05	0.07	0.09
	25	12	0.02	0.03	0.08	0.11	0.05	0.05	0.26	0.32	0.04	0.05	0.14	0.21	0.13	0.11	0.48	0.52	0.24	-	0.03	0.05	0.07	0.05	0.07	0.09
	25	16	0.02	0.02	0.08	0.11	0.04	0.04	0.24	0.29	0.04	0.04	0.14	0.21	0.12	0.09	0.45	0.47	0.32	-	0.03	0.05	0.07	0.05	0.07	0.09
	35	8	0.01	0.03	0.08	0.11	0.04	0.07	0.31	0.36	0.03	0.05	0.15	0.20	0.12	0.16	0.57	0.57	0.11	-	0.03	0.05	0.07	0.05	0.07	0.09
	35	12	0.01	0.03	0.08	0.11	0.04	0.06	0.28	0.31	0.03	0.05	0.15	0.20	0.11	0.12	0.51	0.50	0.17	-	0.03	0.05	0.07	0.05	0.07	0.09
	35	16	0.01	0.02	0.09	0.11	0.04	0.05	0.26	0.28	0.03	0.04	0.16	0.19	0.10	0.10	0.48	0.45	0.23	-	0.03	0.05	0.07	0.05	0.07	0.09
Slab Bridge	10	8	0.12	0.07	0.02	0.25	0.32	0.11	0.40	0.62	0.32	0.11	0.04	0.42	0.62	0.19	0.97	0.98	0.40	-	-	-	-	-	-	-
	10	12	0.07	0.05	0.01	0.17	0.16	0.06	0.22	0.38	0.18	0.08	0.04	0.29	0.31	0.12	0.52	0.61	0.60	-	-	-	-	-	-	-
	10	16	0.05	0.04	0.01	0.13	0.10	0.04	0.14	0.27	0.12	0.06	0.04	0.22	0.19	0.08	0.34	0.43	0.80	-	-	-	-	-	-	-
	15	8	0.23	0.09	0.02	0.36	0.63	0.18	0.74	1.01	0.60	0.16	0.04	0.62	1.22	0.32	1.77	1.59	0.27	-	-	-	-	-	-	-
	15	12	0.13	0.07	0.01	0.25	0.32	0.11	0.40	0.63	0.34	0.11	0.04	0.43	0.62	0.19	0.96	0.99	0.40	-	-	-	-	-	-	-
	15	16	0.09	0.05	0.01	0.19	0.20	0.07	0.26	0.45	0.22	0.09	0.04	0.33	0.38	0.13	0.62	0.70	0.53	-	-	-	-	-	-	-
	20	8	0.36	0.12	0.02	0.48	1.02	0.26	1.13	1.43	0.95	0.20	0.04	0.82	1.98	0.46	2.72	2.25	0.20	-	-	-	-	-	-	-
	20	12	0.20	0.09	0.01	0.33	0.52	0.15	0.61	0.88	0.53	0.14	0.04	0.56	1.00	0.28	1.47	1.40	0.30	-	-	-	-	-	-	-
	20	16	0.13	0.07	0.01	0.25	0.32	0.11	0.39	0.63	0.35	0.11	0.04	0.43	0.62	0.19	0.95	0.99	0.40	-	-	-	-	-	-	-
	25	8	0.52	0.15	0.02	0.59	1.48	0.34	1.58	1.87	1.35	0.25	0.04	1.01	2.89	0.61	3.80	2.94	0.16	-	-	-	-	-	-	-
	25	12	0.29	0.11	0.01	0.41	0.75	0.20	0.85	1.16	0.76	0.18	0.04	0.70	1.46	0.37	2.05	1.83	0.24	-	-	-	-	-	-	-
	25	16	0.19	0.08	0.01	0.31	0.46	0.14	0.55	0.82	0.50	0.14	0.04	0.54	0.90	0.26	1.32	1.30	0.32	-	-	-	-	-	-	-

Notes: S, stress; D, deflection; R, reaction; F, frequency

Table 4.6 Limitations of (L/R) Comparison between North American Bridge Codes and those obtained from Finite Element Analysis for Composite Bridges

Limitations of (L/R) Comparison between North American Bridge Codes and those obtained from Finite Element Analysis for Composite Bridges																										
Bridge Type	Bridge Parameters		Value of (L/R) according to Proposed Equation with under estimation								5% Value of (L/R) according to Proposed Equation with under estimation								Value of (L/R) according to CHBDC	Value of (L/R) according to ASHTO Guide specification 1993						Value of (L/R) according to ASHTO Guide specification 2003
	Span Length (L) in m.	Width (B) in m.	Single-span				Double-span				Single-span				Double-span					Single-Span			Two or more spans			
			S	D	R	F	S	D	R	F	S	D	R	F	S	D	R	F		2 girders	3 or 4 girders	5 or more girders	2 girders	3-4 girders	5 or more girders	
Multi-Box Girder	25	8	0.19	0.11	0.02	0.42	0.72	0.29	0.59	0.87	0.39	0.19	0.04	0.61	1.11	0.55	1.02	1.23	0.16	-	-	-	-	-	-	0.3
	25	12	0.15	0.08	0.02	0.37	0.56	0.18	0.38	0.76	0.31	0.14	0.04	0.54	0.86	0.34	0.65	1.07	0.24	-	-	-	-	-	-	0.3
	25	16	0.13	0.07	0.02	0.33	0.47	0.13	0.28	0.69	0.27	0.12	0.04	0.49	0.71	0.24	0.48	0.97	0.32	-	-	-	-	-	-	0.3
	35	8	0.18	0.13	0.02	0.44	0.91	0.38	0.87	0.94	0.38	0.22	0.03	0.65	1.39	0.71	1.50	1.33	0.11	-	-	-	-	-	-	0.3
	35	12	0.15	0.09	0.02	0.39	0.70	0.23	0.56	0.82	0.30	0.16	0.03	0.56	1.08	0.43	0.96	1.16	0.17	-	-	-	-	-	-	0.3
	35	16	0.12	0.08	0.02	0.35	0.59	0.16	0.41	0.74	0.25	0.13	0.03	0.51	0.90	0.31	0.70	1.05	0.23	-	-	-	-	-	-	0.3
	45	8	0.18	0.14	0.01	0.46	1.08	0.46	1.17	0.99	0.36	0.24	0.03	0.67	1.65	0.86	2.00	1.41	0.09	-	-	-	-	-	-	0.3
	45	12	0.14	0.10	0.01	0.40	0.83	0.28	0.75	0.87	0.29	0.18	0.03	0.59	1.27	0.53	1.29	1.23	0.13	-	-	-	-	-	-	0.3
	45	16	0.12	0.08	0.01	0.37	0.69	0.20	0.55	0.79	0.24	0.14	0.03	0.53	1.06	0.37	0.94	1.11	0.18	-	-	-	-	-	-	0.3
	55	8	0.17	0.15	0.01	0.47	1.23	0.53	1.47	1.04	0.35	0.26	0.02	0.69	1.89	1.00	2.52	1.47	0.07	-	-	-	-	-	-	0.3
	55	12	0.14	0.11	0.01	0.42	0.95	0.33	0.94	0.91	0.28	0.19	0.02	0.60	1.46	0.61	1.62	1.28	0.11	-	-	-	-	-	-	0.3
Single-Box Girder	55	16	0.12	0.09	0.01	0.38	0.80	0.23	0.69	0.82	0.24	0.16	0.03	0.55	1.22	0.43	1.18	1.17	0.15	-	-	-	-	-	-	0.3
	25	8	0.27	0.27	0.04	0.55	1.36	0.72	0.61	1.10	0.56	0.40	0.07	0.78	3.44	1.12	1.13	1.56	0.16	-	-	-	-	-	-	0.3
	25	12	0.23	0.28	0.05	0.64	0.46	0.85	0.57	1.25	0.47	0.41	0.11	0.91	1.15	1.33	1.07	1.77	0.24	-	-	-	-	-	-	0.3
	35	8	0.26	0.27	0.03	0.49	1.75	0.71	0.67	1.01	0.54	0.39	0.05	0.70	4.40	1.11	1.24	1.43	0.11	-	-	-	-	-	-	0.3
	35	12	0.22	0.27	0.04	0.57	0.58	0.84	0.63	1.15	0.46	0.40	0.08	0.82	1.47	1.31	1.17	1.62	0.17	-	-	-	-	-	-	0.3
	45	8	0.26	0.26	0.02	0.46	2.10	0.71	0.71	0.94	0.53	0.38	0.04	0.65	5.29	1.11	1.33	1.34	0.09	-	-	-	-	-	-	0.3
	45	12	0.22	0.27	0.03	0.53	0.70	0.84	0.67	1.07	0.45	0.39	0.06	0.76	1.77	1.31	1.26	1.52	0.13	-	-	-	-	-	-	0.3
	55	8	0.25	0.26	0.02	0.43	2.43	0.71	0.76	0.90	0.52	0.38	0.03	0.61	6.13	1.10	1.41	1.27	0.07	-	-	-	-	-	-	0.3
Slab on I-Girder Bridge	55	12	0.22	0.27	0.02	0.50	0.81	0.83	0.71	1.02	0.44	0.39	0.05	0.71	2.05	1.30	1.33	1.44	0.11	-	-	-	-	-	-	0.3
	15	8	0.01	0.04	0.03	0.06	0.02	0.06	0.49	0.18	0.02	0.06	0.06	0.11	0.04	0.11	0.94	0.29	0.27	0.03	0.05	0.07	0.05	0.07	0.09	0.06
	15	12	0.01	0.04	0.03	0.05	0.02	0.06	0.41	0.17	0.02	0.06	0.06	0.11	0.04	0.10	0.77	0.27	0.40	0.03	0.05	0.07	0.05	0.07	0.09	0.06
	15	16	0.01	0.04	0.03	0.05	0.02	0.05	0.35	0.16	0.02	0.05	0.07	0.11	0.04	0.09	0.67	0.26	0.53	0.03	0.05	0.07	0.05	0.07	0.09	0.06
	25	8	0.01	0.04	0.02	0.05	0.02	0.07	0.41	0.18	0.01	0.06	0.05	0.11	0.05	0.12	0.78	0.30	0.16	0.03	0.05	0.07	0.05	0.07	0.09	0.06
	25	12	0.01	0.04	0.02	0.05	0.02	0.06	0.34	0.17	0.01	0.05	0.05	0.10	0.04	0.11	0.64	0.29	0.24	0.03	0.05	0.07	0.05	0.07	0.09	0.06
	25	16	0.01	0.03	0.03	0.05	0.02	0.06	0.29	0.17	0.01	0.05	0.06	0.10	0.04	0.10	0.56	0.27	0.32	0.03	0.05	0.07	0.05	0.07	0.09	0.06
	35	8	0.01	0.04	0.02	0.05	0.02	0.07	0.37	0.19	0.01	0.06	0.04	0.10	0.05	0.13	0.69	0.31	0.11	0.03	0.05	0.07	0.05	0.07	0.09	0.06
	35	12	0.01	0.03	0.02	0.05	0.02	0.07	0.30	0.18	0.01	0.05	0.05	0.10	0.05	0.11	0.57	0.30	0.17	0.03	0.05	0.07	0.05	0.07	0.09	0.06
35	16	0.01	0.03	0.02	0.05	0.02	0.06	0.26	0.17	0.01	0.05	0.05	0.10	0.04	0.11	0.50	0.28	0.23	0.03	0.05	0.07	0.05	0.07	0.09	0.06	

Notes: S, stress; D, deflection; R, reaction; F, frequency

Figure 2.1 Typical concrete bridge sections

Figure 2.2 Typical composite bridge sections

Figure 3.1 Finite Element Representation of Concrete Bridge Cross section

Figure 3.2 Finite Element Representation of Composite Bridge Cross section

Figure 3.3 Boundary conditions for Single-span Bridge models

Figure 3.4 Boundary conditions for Double-span Bridge models

Figure 3.5 ABAQUS model view for composite multi-box girder bridge

Figure 3.6 ABAQUS model view for composite multi-box girder bridge X- bracing & solid Diaphragm

Figure 3.7 **ABAQUS model view for concrete multi-box girder bridge**

Figure 3.7 **ABAQUS model view for concrete single-box girder bridge**

Figure 4.1 Effect of Curvature on the (FDF) for Simply Supported Concrete T-Beam Bridges with span 15 m, and widths 8 m, 12 m, & 16 m.

Figure 4.2 Effect of Curvature on the (FDF) for Simply Supported Concrete T-Beam Bridges with span 25m, and widths 8 m, 12 m, & 16 m.

Figure 4.3 Effect of Curvature on the (FDF) for Simply Supported Concrete T-Beam Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.4 Effect of Curvature on the (FDF) for Simply Supported Concrete Cellular Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.5 Effect of Curvature on the (FDF) for Simply Supported Concrete Cellular Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.6 Effect of Curvature on the (FDF) for Simply Supported Concrete Cellular Bridges with span 45 m, and widths 8 m, 12 m, & 16 m.

Figure 4.7 Effect of Curvature on the (FDF) for Simply Supported Concrete Cellular Bridges with span 55 m, and widths 8 m, 12 m, & 16 m.

Figure 4.8 Effect of Curvature on the (FDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.9 Effect of Curvature on the (FDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.10 Effect of Curvature on the (FDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.11 Effect of Curvature on the (FDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.12 Effect of Curvature on the (FDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.13 Effect of Curvature on the (FDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.14 Effect of Curvature on the (FDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.15 Effect of Curvature on the (FDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.16 Effect of Curvature on the (FDF) for Simply Supported Concrete Slab Bridges with span (L) 10 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.17 Effect of Curvature on the (FDF) for Simply Supported Concrete Slab Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.18 Effect of Curvature on the (FDF) for Simply Supported Concrete Slab Bridges with span (L) 20 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.19 Effect of Curvature on the (FDF) for Simply Supported Concrete Slab Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.20 Effect of Curvature on the (FDF) for Two-Span Concrete T-Beam Bridges with span 15 m, and widths 8 m, 12 m, & 16 m.

Figure 4.21 Effect of Curvature on the (FDF) for Two-Span Concrete T-Beam Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.22 Effect of Curvature on the (FDF) for Two-Span Concrete T-Beam Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.23 Effect of Curvature on the (FDF) for Two-Span Concrete Cellular Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.24 Effect of Curvature on the (FDF) for Two-Span Concrete Cellular Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.25 Effect of Curvature on the (FDF) for Two-Span Concrete Cellular Bridges with span 45 m, and widths 8 m, 12 m, & 16 m.

Figure 4.26 Effect of Curvature on the (FDF) for Two-Span Concrete Cellular Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.27 Effect of Curvature on the (FDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.28 Effect of Curvature on the (FDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.29 Effect of Curvature on the (FDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.30 Effect of Curvature on the (FDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.31 Effect of Curvature on the (FDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.32 Effect of Curvature on the (FDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.33 Effect of Curvature on the (FDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.34 Effect of Curvature on the (FDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.35 Effect of Curvature on the (FDF) for Two-Span Concrete Slab Bridges with span (L) 10 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.36 Effect of Curvature on the (FDF) for Two-Span Concrete Slab Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.37 Effect of Curvature on the (FDF) for Two-Span Concrete Slab Bridges with span (L) 20 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.38 Effect of Curvature on the (FDF) for Two-Span Concrete Slab Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.39 Effect of Curvature on the (RDF) for Simply Supported Concrete T-Beam Bridges with span 15 m, and widths 8 m, 12 m, & 16 m.

Figure 4.40 Effect of Curvature on the (RDF) for Simply Supported Concrete T-Beam Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.41 Effect of Curvature on the (RDF) for Simply Supported Concrete T-Beam Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.42 Effect of Curvature on the (RDF) for Simply Supported Concrete Cellular Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.43 Effect of Curvature on the (RDF) for Simply Supported Concrete Cellular Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.44 Effect of Curvature on the (RDF) for Simply Supported Concrete Cellular Bridges with span 45 m, and widths 8 m, 12 m, & 16 m.

Figure 4.45 Effect of Curvature on the (RDF) for Simply Supported Concrete Cellular Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.46 Effect of Curvature on the (RDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.47 Effect of Curvature on the (RDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.48 Effect of Curvature on the (RDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.49 Effect of Curvature on the (RDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.50 Effect of Curvature on the (RDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.51 Effect of Curvature on the (RDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.52 Effect of Curvature on the (RDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.53 Effect of Curvature on the (RDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.54 Effect of Curvature on the (RDF) for Simply Supported Concrete Slab Bridges with span (L) 10 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.55 Effect of Curvature on the (RDF) for Simply Supported Concrete Slab Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m

Figure 4.56 Effect of Curvature on the (RDF) for Simply Supported Concrete Slab Bridges with span (L) 20 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.57 Effect of Curvature on the (RDF) for Simply Supported Concrete Slab Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.58 Effect of Curvature on the (RDF) for Two-Span Concrete T-Beam Bridges with span 15 m, and widths 8 m, 12 m, & 16 m.

Figure 4.59 Effect of Curvature on the (RDF) for Two-Span Concrete T-Beam Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.60 Effect of Curvature on the (RDF) for Two-Span Concrete T-Beam Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.61 Effect of Curvature on the (RDF) for Two-Span Concrete Cellular Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.62 Effect of Curvature on the (RDF) for Two-Span Concrete Cellular Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.63 Effect of Curvature on the (RDF) for Two-Span Concrete Cellular Bridges with span 45 m, and widths 8 m, 12 m, & 16 m.

Figure 4.64 Effect of Curvature on the (RDF) for Two-Span Concrete Cellular Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.65 Effect of Curvature on the (RDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.66 Effect of Curvature on the (RDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.67 Effect of Curvature on the (RDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.68 Effect of Curvature on the (RDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.69 Effect of Curvature on the (RDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.70 Effect of Curvature on the (RDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.71 Effect of Curvature on the (RDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.72 Effect of Curvature on the (RDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.73 Effect of Curvature on the (RDF) for Two-Span Concrete Slab Bridges with span (L) 10 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.74 Effect of Curvature on the (RDF) for Two-Span Concrete Slab Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.75 Effect of Curvature on the (RDF) for Two-Span Concrete Slab Bridges with span (L) 20 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.76 Effect of Curvature on the (RDF) for Two-Span Concrete Slab Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.77 Effect of Curvature on the (SDF) for Simply Supported Concrete T-Beam Bridges with span 15 m, and widths 8 m, 12 m, & 16 m.

Figure 4.78 Effect of Curvature on the (SDF) for Simply Supported Concrete T-Beam Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.79 Effect of Curvature on the (DDF) for Simply Supported Concrete T-Beam Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.80 Effect of Curvature on the (SDF) for Simply Supported Concrete Cellular Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.81 Effect of Curvature on the (SDF) for Simply Supported Concrete Cellular Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.82 Effect of Curvature on the (SDF) for Simply Supported Concrete Cellular Bridges with span 45 m, and widths 8 m, 12 m, & 16 m.

Figure 4.83 Effect of Curvature on the (SDF) for Simply Supported Concrete Cellular Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.84 Effect of Curvature on the (SDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.85 Effect of Curvature on the (SDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.86 Effect of Curvature on the (SDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.87 Effect of Curvature on the (SDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.88 Effect of Curvature on the (SDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.89 Effect of Curvature on the (SDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.90 Effect of Curvature on the (SDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.91 Effect of Curvature on the (SDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.92 Effect of Curvature on the (SDF) for Simply Supported Concrete Slab Bridges with span (L) 10 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.93 Effect of Curvature on the (SDF) for Simply Supported Concrete Slab Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.94 Effect of Curvature on the (SDF) for Simply Supported Concrete Slab Bridges with span (L) 20 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.95 Effect of Curvature on the (SDF) for Simply Supported Concrete Slab Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.96 Effect of Curvature on the (SDF) for Two-Span Concrete T-Beam Bridges with span 15 m, and widths 8 m, 12 m, & 16 m.

Figure 4.97 Effect of Curvature on the (SDF) for Two-Span Concrete T-Beam Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.98 Effect of Curvature on the (SDF) for Two-Span Concrete T-Beam Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.99 Effect of Curvature on the (SDF) for Two-Span Concrete Cellular Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.100 Effect of Curvature on the (SDF) for Two-Span Concrete Cellular Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.101 Effect of Curvature on the (SDF) for Two-Span Concrete Cellular Bridges with span 45 m, and widths 8 m, 12 m, & 16 m.

Figure 4.102 Effect of Curvature on the (SDF) for Two-Span Concrete Cellular Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.103 Effect of Curvature on the (SDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.104 Effect of Curvature on the (SDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.105 Effect of Curvature on the (SDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.106 Effect of Curvature on the (SDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.107 Effect of Curvature on the (SDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.108 Effect of Curvature on the (SDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.109 Effect of Curvature on the (SDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.110 Effect of Curvature on the (SDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.111 Effect of Curvature on the (SDF) for Two-Span Concrete Slab Bridges with span (L) 10 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.112 Effect of Curvature on the (SDF) for Two-Span Concrete Slab Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.113 Effect of Curvature on the (SDF) for Two-Span Concrete Slab Bridges with span (L) 20 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.114 Effect of Curvature on the (SDF) for Two-Span Concrete Slab Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.115 Effect of Curvature on the (DDF) for Simply Supported Concrete T-Beam Bridges with span 15 m, and widths 8 m, 12 m, & 16 m.

Figure 4.116 Effect of Curvature on the (DDF) for Simply Supported Concrete T-Beam Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.117 Effect of Curvature on the (DDF) for Simply Supported Concrete T-Beam Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.118 Effect of Curvature on the (DDF) for Simply Supported Concrete Cellular Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.119 Effect of Curvature on the (DDF) for Simply Supported Concrete Cellular Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.120 Effect of Curvature on the (DDF) for Simply Supported Concrete Cellular Bridges with span 45 m, and widths 8 m, 12 m, & 16 m.

Figure 4.121 Effect of Curvature on the (DDF) for Simply Supported Concrete Cellular Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.122 Effect of Curvature on the (DDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.123 Effect of Curvature on the (DDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.124 Effect of Curvature on the (DDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.125 Effect of Curvature on the (DDF) for Simply Supported Concrete multi-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.126 Effect of Curvature on the (DDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.127 Effect of Curvature on the (DDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.128 Effect of Curvature on the (DDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.129 Effect of Curvature on the (DDF) for Simply Supported Concrete Single-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.130 Effect of Curvature on the (DDF) for Simply Supported Concrete Slab Bridges with span (L) 10 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.131 Effect of Curvature on the (DDF) for Simply Supported Concrete Slab Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.132 Effect of Curvature on the (DDF) for Simply Supported Concrete Slab Bridges with span (L) 20 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.133 Effect of Curvature on the (DDF) for Simply Supported Concrete Slab Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.134 Effect of Curvature on the (DDF) for Two-Span Concrete T-Beam Bridges with span 15 m, and widths 8 m, 12 m, & 16 m.

Figure 4.135 Effect of Curvature on the (DDF) for Two-Span Concrete T-Beam Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.136 Effect of Curvature on the (DDF) for Two-Span Concrete T-Beam Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.137 Effect of Curvature on the (DDF) for Two-Span Concrete Cellular Bridges with span 25 m, and widths 8 m, 12 m, & 16 m.

Figure 4.138 Effect of Curvature on the (DDF) for Two-Span Concrete Cellular Bridges with span 35 m, and widths 8 m, 12 m, & 16 m.

Figure 4.139 Effect of Curvature on the (DDF) for Two-Span Concrete Cellular Bridges with span 45 m, and widths 8 m, 12 m, & 16 m.

Figure 4.140 Effect of Curvature on the (DDF) for Two-Span Concrete Cellular Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.141 Effect of Curvature on the (DDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.142 Effect of Curvature on the (DDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.143 Effect of Curvature on the (DDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.144 Effect of Curvature on the (DDF) for Two-Span Concrete Multi-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.145 Effect of Curvature on the (DDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.146 Effect of Curvature on the (DDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.147 Effect of Curvature on the (DDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.148 Effect of Curvature on the (DDF) for Two-Span Concrete Single-Box Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.149 Effect of Curvature on the (DDF) for Two-Span Concrete Slab Bridges with span (L) 10 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.150 Effect of Curvature on the (DDF) for Two-Span Concrete Slab Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.151 Effect of Curvature on the (DDF) for Two-Span Concrete Slab Bridges with span (L) 20 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.152 Effect of Curvature on the (DDF) for Two-Span Concrete Slab Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.153 Effect of Curvature on the (FDF) for Simply Supported Steel I-Girder Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.154 Effect of Curvature on the (FDF) for Simply Supported Steel I-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.155 Effect of Curvature on the (FDF) for Simply Supported Steel I-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.156 Effect of Curvature on the (FDF) for Simply Supported Steel Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.157 Effect of Curvature on the (FDF) for Simply Supported Steel Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.158 Effect of Curvature on the (FDF) for Simply Supported Steel Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.159 Effect of Curvature on the (FDF) for Simply Supported Steel Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.160 Effect of Curvature on the (FDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.161 Effect of Curvature on the (FDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.162 Effect of Curvature on the (FDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.163 Effect of Curvature on the (FDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.164 Effect of Curvature on the (FDF) for Two-Span Steel I-Girder Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.165 Effect of Curvature on the (FDF) for Two-Span Steel I-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.166 Effect of Curvature on the (FDF) for Two-Span Steel I-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.167 Effect of Curvature on the (FDF) for Two-Span Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.168 Effect of Curvature on the (FDF) for Two-Span Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.169 Effect of Curvature on the (FDF) for Two-Span Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.170 Effect of Curvature on the (FDF) for Two-Span Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.171 Effect of Curvature on the (FDF) for Two-Span Single Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.172 Effect of Curvature on the (FDF) for Two-Span Single Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.173 Effect of Curvature on the (FDF) for Two-Span Single Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.174 Effect of Curvature on the (FDF) for Two-Span Single Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.175 Effect of Curvature on the (RDF) for Simply Supported Steel I-Girder Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.176 Effect of Curvature on the (RDF) for Simply Supported Steel I-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.177 Effect of Curvature on the (RDF) for Simply Supported Steel I-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.178 Effect of Curvature on the (RDF) for Simply Supported Steel Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.179 Effect of Curvature on the (RDF) for Simply Supported Steel Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.180 Effect of Curvature on the (RDF) for Simply Supported Steel Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.181 Effect of Curvature on the (RDF) for Simply Supported Steel Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.182 Effect of Curvature on the (RDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.183 Effect of Curvature on the (RDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.184 Effect of Curvature on the (RDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.185 Effect of Curvature on the (RDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.186 Effect of Curvature on the (RDF) for Two-Span Steel I-Girder Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.187 Effect of Curvature on the (RDF) for Two-Span Steel I-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.188 Effect of Curvature on the (RDF) for Two-Span Steel I-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.189 Effect of Curvature on the (RDF) for Two-Span Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.190 Effect of Curvature on the (RDF) for Two-Span Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.191 Effect of Curvature on the (RDF) for Two-Span Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.192 Effect of Curvature on the (RDF) for Two-Span Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.193 Effect of Curvature on the (RDF) for Two-Span Single Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.194 Effect of Curvature on the (RDF) for Two-Span Single Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.195 Effect of Curvature on the (RDF) for Two-Span Single Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.196 Effect of Curvature on the (RDF) for Two-Span Single Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.197 Effect of Curvature on the (SDF) for Simply Supported Steel I-Girder Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.198 Effect of Curvature on the (SDF) for Simply Supported Steel I-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.199 Effect of Curvature on the (SDF) for Simply Supported Steel I-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.200 Effect of Curvature on the (SDF) for Simply Supported Steel Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.201 Effect of Curvature on the (SDF) for Simply Supported Steel Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.201 Effect of Curvature on the (SDF) for Simply Supported Steel Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.203 Effect of Curvature on the (SDF) for Simply Supported Steel Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.204 Effect of Curvature on the (SDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.205 Effect of Curvature on the (SDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.206 Effect of Curvature on the (SDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.207 Effect of Curvature on the (SDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.208 Effect of Curvature on the (SDF) for Two-Span Steel I-Girder Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.209 Effect of Curvature on the (SDF) for Two-Span Steel I-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.210 Effect of Curvature on the (SDF) for Two-Span Steel I-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.211 Effect of Curvature on the (SDF) for Two-Span Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.211 Effect of Curvature on the (SDF) for Two-Span Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.213 Effect of Curvature on the (SDF) for Two-Span Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.214 Effect of Curvature on the (SDF) for Two-Span Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.215 Effect of Curvature on the (SDF) for Two-Span Single Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.216 Effect of Curvature on the (SDF) for Two-Span Single Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.217 Effect of Curvature on the (SDF) for Two-Span Single Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.218 Effect of Curvature on the (SDF) for Two-Span Single Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.219 Effect of Curvature on the (DDF) for Simply Supported Steel I-Girder Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.220 Effect of Curvature on the (DDF) for Simply Supported Steel I-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.221 Effect of Curvature on the (DDF) for Simply Supported Steel I-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.222 Effect of Curvature on the (DDF) for Simply Supported Steel Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.223 Effect of Curvature on the (DDF) for Simply Supported Steel Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.224 Effect of Curvature on the (DDF) for Simply Supported Steel Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.225 Effect of Curvature on the (DDF) for Simply Supported Steel Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.226 Effect of Curvature on the (DDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.227 Effect of Curvature on the (DDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.228 Effect of Curvature on the (DDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.229 Effect of Curvature on the (DDF) for Simply Supported Steel Single Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

Figure 4.230 Effect of Curvature on the (DDF) for Two-Span Steel I-Girder Bridges with span (L) 15 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.231 Effect of Curvature on the (DDF) for Two-Span Steel I-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.232 Effect of Curvature on the (DDF) for Two-Span Steel I-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.233 Effect of Curvature on the (DDF) for Two-Span Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.234 Effect of Curvature on the (DDF) for Two-Span Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.235 Effect of Curvature on the (DDF) for Two-Span Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.236 Effect of Curvature on the (DDF) for Two-Span Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, 12 m, & 16 m.

Figure 4.237 Effect of Curvature on the (DDF) for Two-Span Single Box-Girder Bridges with span (L) 25 m, and width (W) 8 m, & 12 m.

Figure 4.238 Effect of Curvature on the (DDF) for Two-Span Single Box-Girder Bridges with span (L) 35 m, and width (W) 8 m, & 12 m.

Figure 4.239 Effect of Curvature on the (DDF) for Two-Span Single Box-Girder Bridges with span (L) 45 m, and width (W) 8 m, & 12 m.

Figure 4.240 Effect of Curvature on the (DDF) for Two-Span Single Box-Girder Bridges with span (L) 55 m, and width (W) 8 m, & 12 m.

APPENDIX (A.1): ABAQUS input file for single-span curved concrete multi-box girder bridge

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*HEADING
CONCRETE MULTI BOX GIRDER-BRIDGE (CURVED) - SIMPLY SUPPORTED LINEAR, L=45, W= 8, L/R=0.1
**DATA CHECK
*PREPRINT,ECHO=YES,MODEL=NO,HISTORY=NO
*****REFERENCE NODE COORDINATES 2L2B45S3.3D*****
*NODE
1,0,0,0
48001,0,0,-3.1
*** SLAB COORDINATES ***
2,-22.2907,445.4426,0
34,-22.6905,453.4326,0
7202,22.2907,445.4426,0
7234,22.6905,453.4326,0
*** GIRDER COORDINATES ***
48006,-22.3407,446.4414,-3.1
55206,22.3407,446.4414,-3.1
48030,-22.6406,452.4339,-3.1
55230,22.6406,452.4339,-3.1
*****NODE GENERATION FOR END DIAPHRAMS*****
*NGEN,NSET=ORIGIN
1,48001,8000
*NGEN,NSET=NEND
***|left end****
2,34,2
6,48006,8000
30,48030,8000
8006,8030,2
16006,16030,2
24006,24030,2
32006,32030,2
40006,40030,2
48006,48030,2
***right end****
7202,7234,2
7206,55206,8000
7230,55230,8000
15206,15230,2
23206,23230,2
31206,31230,2
39206,39230,2
47206,47230,2
55206,55230,2
*****
*NSET,NSET=LEFT1
48014
*NSET,NSET=LEFT3
48006,48022,48030
*NSET,NSET=RIGHT1
55214
*NSET,NSET=RIGHT3
55206,55222,55230
*NSET,NSET=REACT
LEFT1,LEFT3,RIGHT1,RIGHT3
*****NODE GEN. FOR TOP SLAB *****
*NGEN,NSET=NPLATET,LINE=C
2,7202,100,1
4,7204,100,1
6,7206,100,1
8,7208,100,1
10,7210,100,1
12,7212,100,1
14,7214,100,1
16,7216,100,1
18,7218,100,1
20,7220,100,1
22,7222,100,1
24,7224,100,1
26,7226,100,1
28,7228,100,1
30,7230,100,1
32,7232,100,1
34,7234,100,1
*****NODE GEN. FOR WEBS *****

```


*NGEN,NSET=NWEB,LINE=C

8006,15206,100,8001
8014,15214,100,8001
8022,15222,100,8001
8030,15230,100,8001
16006,23206,100,16001
16014,23214,100,16001
16022,23222,100,16001
16030,23230,100,16001
24006,31206,100,24001
24014,31214,100,24001
24022,31222,100,24001
24030,31230,100,24001
32006,39206,100,32001
32014,39214,100,32001
32022,39222,100,32001
32030,39230,100,32001
40006,47206,100,40001
40014,47214,100,40001
40022,47222,100,40001
40030,47230,100,40001
48006,55206,100,48001
48014,55214,100,48001
48022,55222,100,48001
48030,55230,100,48001

*****NODE GEN FOR BOTTOM FLANGE *****

*NGEN,NSET=NPLATEB,LINE=C

48008,55208,100,48001
48010,55210,100,48001
48012,55212,100,48001
48016,55216,100,48001
48018,55218,100,48001
48020,55220,100,48001
48024,55224,100,48001
48026,55226,100,48001
48028,55228,100,48001

*****NODE GEN FOR MIDDLE DIAPHRAGMS *****

*NGEN,NSET=NMID

middle left

9806,9830,2
17806,17830,2
25806,25830,2
33806,33830,2
41806,41830,2

middle

11606,11630,2
19606,19630,2
27606,27630,2
35606,35630,2
43606,43630,2

middle right

13406,13430,2
21406,21430,2
29406,29430,2
37406,37430,2
45406,45430,2

*****ELEMENT GEN FOR TOP SLAB *****

*ELEMENT,TYPE=S4R

1,2,102,104,4

*ELGEN,ELSET=ESLABT

1,72,100,16,16,2,1

*ELSET,ELSET=LANE,GEN

1,1137,16
2,1138,16
3,1139,16
4,1140,16
5,1141,16
6,1142,16
7,1143,16
8,1144,16
9,1145,16
10,1146,16
11,1147,16

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12,1148,16
13,1149,16
14,1150,16
15,1151,16
16,1152,16
*****ELEMENT GEN FOR BOTTOM FLANGE *****
*ELEMENT,TYPE=S4R
1153,48006,48106,48108,48008
1441,48022,48122,48124,48024
*ELGEN,ELSET=ESLABB
1153,72,100,4,4,2,1
1441,72,100,4,4,2,1
*****ELEMENT GEN FOR WEBS *****
*ELEMENT,TYPE=S4R
1729,8006,8106,106,6
2161,8014,8114,114,14
2593,8022,8122,122,22
3025,8030,8130,130,30
*ELGEN,ELSET=WEB
1729,72,100,6,6,8000,1
2161,72,100,6,6,8000,1
2593,72,100,6,6,8000,1
3025,72,100,6,6,8000,1
*****ELEMENT GEN FOR END & MIDDLE DIAPHRAGMS *****
*ELEMENT,TYPE=S4R
3457,8006,8008,8,6
3529,9806,9808,1808,1806
3601,11606,11608,3608,3606
3673,13406,13408,5408,5406
3745,15206,15208,7208,7206
*ELGEN,ELSET=DIAPH
3457,12,2,6,6,8000,1
3529,12,2,6,6,8000,1
3601,12,2,6,6,8000,1
3673,12,2,6,6,8000,1
3745,12,2,6,6,8000,1
*****MATERIAL PROPERTIES *****
*SHELL SECTION,ELSET=WEB,MATERIAL=CON
.2,5
*SHELL SECTION,ELSET=DIAPH,MATERIAL=CON
.2,5
*SHELL SECTION,ELSET=ESLABB,MATERIAL=CON
.2,5
*SHELL SECTION,ELSET=ESLABT,MATERIAL=CON
.2,5
*MATERIAL,NAME=CON
*DENSITY
2400
*ELASTIC
25000E6,.2
*****
*BOUNDARY
LEFT1,1
LEFT1,2
LEFT1,3
LEFT3,3
RIGHT1,2
RIGHT1,3
RIGHT3,3
*****
*ELSET,ELSET=MIDSLAB,GEN
561,592
*ELSET,ELSET=MIDBOTFLANG,GEN
1293,1300
1581,1588
*ELSET,ELSET=MIDWEB,GEN
1939,1950
2371,2382
2803,2814
3235,3246
*NGEN,NSET=MID
51606,51630,8
*****
*STEP

```

```
*STATIC
*DLOAD
LANE,P,-10000
*****
*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDSLAB
S11
*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDBOTFLANG
S11
*NODEPRINT,NSET=MID
U3
*NODEPRINT,NSET=REACT
RF3
*****
*ENDSTEP
*STEP
*FREQUENCY
1
*ELPRINT,MODE=1
*ENDSTEP
```

APPENDIX (A.2): ABAQUS input file for two-span curved concrete multi-box girder bridge


```

*HEADING
CONCRETE MULTI BOX GIRDER-BRIDGE (CURVED) - CONTINUOUS LINEAR, L=45, W=12, L/R=0.5
**DATA CHECK
*PREPRINT,ECHO=YES,MODEL=NO,HISTORY=NO
*****REFERENCE NODE COORDINATES 3L3B45S2.5D*****
*NODE
1,0,0,0
48001,0,0,-2.3
*** SLAB COORDINATES ***
2,-43.0483,168.5908,0
50,-46.0171,180.2177,0
7202,43.0483,168.5908,0
7250,46.0171,180.2177,0
*** GIRDER COORDINATES ***
48006,-43.2957,169.5597,-2.3
55206,43.2957,169.5597,-2.3
48046,-45.7697,179.2488,-2.3
55246,45.7697,179.2488,-2.3
*****NODE GENERATION FOR END DIAPHRAGM*****
*NGEN,NSET=ORIGIN
1,48001,8000
*NGEN,NSET=NEND
***left end****
2,50,2
6,48006,8000
46,48046,8000
8006,8046,2
16006,16046,2
24006,24046,2
32006,32046,2
40006,40046,2
48006,48046,2
***right end****
7202,7250,2
7206,55206,8000
7246,55246,8000
15206,15246,2
23206,23246,2
31206,31246,2
39206,39246,2
47206,47246,2
55206,55246,2
*****
*NSET,NSET=LEFT1
48022
*NSET,NSET=LEFT3
48006,48014,48030,48038,48046
*NSET,NSET=MID1
51622
*NSET,NSET=MID3
51606,51614,51630,51638,51646
*NSET,NSET=RIGHT1
55222
*NSET,NSET=RIGHT3
55206,55214,55230,55238,55246
*NSET,NSET=REACT
LEFT1,LEFT3,MID1,MID3,RIGHT1,RIGHT3
*****NODE GEN. FOR TOP SLAB *****
*NGEN,NSET=NPLATET,LINE=C
2,7202,100,1
4,7204,100,1
6,7206,100,1
8,7208,100,1
10,7210,100,1
12,7212,100,1
14,7214,100,1
16,7216,100,1
18,7218,100,1
20,7220,100,1
22,7222,100,1
24,7224,100,1
26,7226,100,1
28,7228,100,1

```

30,7230,100,1
 32,7232,100,1
 34,7234,100,1
 36,7236,100,1
 38,7238,100,1
 40,7240,100,1
 42,7242,100,1
 44,7244,100,1
 46,7246,100,1
 48,7248,100,1
 50,7250,100,1

*****NODE GEN. FOR WEBS *****

*NGEN,NSET=NWEB,LINE=C

8006,15206,100,8001
 8014,15214,100,8001
 8022,15222,100,8001
 8030,15230,100,8001
 8038,15238,100,8001
 8046,15246,100,8001
 16006,23206,100,16001
 16014,23214,100,16001
 16022,23222,100,16001
 16030,23230,100,16001
 16038,23238,100,16001
 16046,23246,100,16001
 24006,31206,100,24001
 24014,31214,100,24001
 24022,31222,100,24001
 24030,31230,100,24001
 24038,31238,100,24001
 24046,31246,100,24001
 32006,39206,100,32001
 32014,39214,100,32001
 32022,39222,100,32001
 32030,39230,100,32001
 32038,39238,100,32001
 32046,39246,100,32001
 40006,47206,100,40001
 40014,47214,100,40001
 40022,47222,100,40001
 40030,47230,100,40001
 40038,47238,100,40001
 40046,47246,100,40001
 48006,55206,100,48001
 48014,55214,100,48001
 48022,55222,100,48001
 48030,55230,100,48001
 48038,55238,100,48001
 48046,55246,100,48001

*****NODE GEN FOR BOTTOM FLANGE *****

*NGEN,NSET=NPLATEB,LINE=C

48008,55208,100,48001
 48010,55210,100,48001
 48012,55212,100,48001
 48016,55216,100,48001
 48018,55218,100,48001
 48020,55220,100,48001
 48024,55224,100,48001
 48026,55226,100,48001
 48028,55228,100,48001
 48032,55232,100,48001
 48034,55234,100,48001
 48036,55236,100,48001
 48040,55240,100,48001
 48042,55242,100,48001
 48044,55244,100,48001

*****NODE GEN FOR MIDDLE DIAPHRAGM *****

*NGEN,NSET=NMID

middle left spanl

8906,8946,2
 16906,16946,2
 24906,24946,2
 32906,32946,2
 40906,40946,2

middle left span2

9806,9846,2
17806,17846,2
25806,25846,2
33806,33846,2
41806,41846,2

middle left span3

10706,10746,2
18706,18746,2
26706,26746,2
34706,34746,2
42706,42746,2

middle support

11606,11646,2
19606,19646,2
27606,27646,2
35606,35646,2
43606,43646,2

middle right span1

12506,12546,2
20506,20546,2
28506,28546,2
36506,36546,2
44506,44546,2

middle right span2

13406,13446,2
21406,21446,2
29406,29446,2
37406,37446,2
45406,45446,2

middle right span3

14306,14346,2
22306,22346,2
30306,30346,2
38306,38346,2
46306,46346,2

*****ELEMENT GEN FOR TOP SLAB *****

*ELEMENT,TYPE=S4R

1,2,102,104,4

*ELGEN,ELSET=ESLABT

1,72,100,24,24,2,1

*ELSET,ELSET=LANE,GEN

1,1705,24
2,1706,24
3,1707,24
4,1708,24
5,1709,24
6,1710,24
7,1711,24
8,1712,24
9,1713,24
10,1714,24
11,1715,24
12,1716,24
13,1717,24
14,1718,24
15,1719,24
16,1720,24
17,1721,24
18,1722,24
19,1723,24
20,1724,24
21,1725,24
22,1726,24
23,1727,24
24,1728,24

*****ELEMENT GEN FOR BOTTOM FLANGE *****

*ELEMENT,TYPE=S4R

1729,48006,48106,48108,48008
2017,48022,48122,48124,48024
2305,48038,48138,48140,48040
*ELGEN,ELSET=ESLABB
1729,72,100,4,4,2,1

```

2017,72,100,4,4,2,1
2305,72,100,4,4,2,1
*****ELEMENT GEN FOR WEBS *****
*ELEMENT,TYPE=S4R
2593,8006,8106,106,6
3025,8014,8114,114,14
3457,8022,8122,122,22
3889,8030,8130,130,30
4321,8038,8138,138,38
4753,8046,8146,146,46
*ELGEN,ELSET=WEB
2593,72,100,6,6,8000,1
3025,72,100,6,6,8000,1
3457,72,100,6,6,8000,1
3889,72,100,6,6,8000,1
4321,72,100,6,6,8000,1
4753,72,100,6,6,8000,1
*****ELEMENT GEN FOR END & MIDDLE DIAPHRAGMS *****
*ELEMENT,TYPE=S4R
5185,8006,8008,8,6
5305,8906,8908,908,906
5425,9806,9808,1808,1806
5545,10706,10708,2708,2706
5665,11606,11608,3608,3606
5785,12506,12508,4508,4506
5905,13406,13408,5408,5406
6025,14306,14308,6308,6306
6145,15206,15208,7208,7206
*ELGEN,ELSET=DIAPH
5185,20,2,6,6,8000,1
5305,20,2,6,6,8000,1
5425,20,2,6,6,8000,1
5545,20,2,6,6,8000,1
5665,20,2,6,6,8000,1
5785,20,2,6,6,8000,1
5905,20,2,6,6,8000,1
6025,20,2,6,6,8000,1
6145,20,2,6,6,8000,1
*****MATERIAL PROPERTIES *****
*SHELL SECTION,ELSET=WEB,MATERIAL=CON
.2,5
*SHELL SECTION,ELSET=DIAPH,MATERIAL=CON
.2,5
*SHELL SECTION,ELSET=ESLABB,MATERIAL=CON
.2,5
*SHELL SECTION,ELSET=ESLABT,MATERIAL=CON
.2,5
*MATERIAL,NAME=CON
*DENSITY
2400
*ELASTIC
25000E6,.2
*****
*BOUNDARY
LEFT1,2
LEFT1,3
LEFT3,3
MID1,1
MID1,2
MID1,3
MID3,3
RIGHT1,2
RIGHT1,3
RIGHT3,3
*****
*ELSET,ELSET=MIDSLAB,GEN
841,888
*ELSET,ELSET=MIDBOTFLANG,GEN
1797,1804
1941,1948
2085,2092
2229,2236
2373,2380
2517,2524

```



```

*ELSET,ELSET=MIDWEB,GEN
2803,2814
3235,3246
3667,3678
4099,4110
4531,4542
4963,4974
*NGEN,NSET=MID
49806,49846,8
53406,53446,8
*****
*STEP
*STATIC
*DLOAD
LANE,P,-10000
*****
*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDSLAB
S11
*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDBOTFLANG
S11
*NODEPRINT,NSET=MID
U3
*NODEPRINT,NSET=REACT
RF3
*****
*ENDSTEP
*STEP
*FREQUENCY
1
*ELPRINT,MODE=1
*ENDSTEP

```

APPENDIX (B.1): ABAQUS input file for single-span curved steel box-girder bridge

*HEADING
STEEL BOX GIRDER-BRIDGE (CURVED) - SIMPLY SUPPORTED LINEAR, L=55, W=16, L/R=0.1

**DATA CHECK

*PREPRINT,ECHO=YES,MODEL=NO,HISTORY=NO

*****REFERENCE NODE COORDINATES 4L4B55S1.9D*****

*NODE

1,0,0,0

8001,0,0,-0.108

40001,0,0,-1.992

*** SLAB COORDINATES ***

2,-27.0887,541.3226,0

66,-27.8884,557.3026,0

7202,27.0887,541.3226,0

7266,27.8884,557.3026,0

*** GIRDER COORDINATES ***

8006,-27.1387,542.3214,-0.108

40006,-27.1387,542.3214,-1.992

15206,27.1387,542.3214,-0.108

47206,27.1387,542.3214,-1.992

8062,-27.8384,556.3039,-0.108

40062,-27.8384,556.3039,-1.992

15262,27.8384,556.3039,-0.108

47262,27.8384,556.3039,-1.992

*****NODE GENERATION FOR END DIAPHRAGMS*****

*NGEN,NSET=ORIGIN

8001,40001,8000

*NGEN,NSET=NEND

left end

2,66,2

8006,40006,8000

8062,40062,8000

8006,8062,2

16006,16062,2

24006,24062,2

32006,32062,2

40006,40062,2

right end

7202,7266,2

15206,47206,8000

15262,47262,8000

15206,15262,2

23206,23262,2

31206,31262,2

39206,39262,2

47206,47262,2

*NSET,NSET=LEFT1

40030

*NSET,NSET=LEFT3

40006,40014,40022,40038,40046,40054,40062

*NSET,NSET=RIGHT1

47230

*NSET,NSET=RIGHT3

47206,47214,47222,47238,47246,47254,47262

*NSET,NSET=REACT

LEFT1,LEFT3,RIGHT1,RIGHT3

*****NODE GEN. FOR TOP SLAB*****

*NGEN,NSET=NPLATET,LINE=C

2,7202,100,1

4,7204,100,1

6,7206,100,1

8,7208,100,1

10,7210,100,1

12,7212,100,1

14,7214,100,1

16,7216,100,1

18,7218,100,1

20,7220,100,1

22,7222,100,1

24,7224,100,1

26,7226,100,1
28,7228,100,1
30,7230,100,1
32,7232,100,1
34,7234,100,1
36,7236,100,1
38,7238,100,1
40,7240,100,1
42,7242,100,1
44,7244,100,1
46,7246,100,1
48,7248,100,1
50,7250,100,1
52,7252,100,1
54,7254,100,1
56,7256,100,1
58,7258,100,1
60,7260,100,1
62,7262,100,1
64,7264,100,1
66,7266,100,1

*****NODE GEN FOR TOP FLANGE*****

*NGEN,NSET=NTOPFLNG,LINE=C

8006,15206,100,8001
8014,15214,100,8001
8022,15222,100,8001
8030,15230,100,8001
8038,15238,100,8001
8046,15246,100,8001
8054,15254,100,8001
8062,15262,100,8001

*****NODE GEN. FOR WEBS*****

*NGEN,NSET=NWEB,LINE=C

16006,23206,100,16001
16014,23214,100,16001
16022,23222,100,16001
16030,23230,100,16001
16038,23238,100,16001
16046,23246,100,16001
16054,23254,100,16001
16062,23262,100,16001
24006,31206,100,24001
24014,31214,100,24001
24022,31222,100,24001
24030,31230,100,24001
24038,31238,100,24001
24046,31246,100,24001
24054,31254,100,24001
24062,31262,100,24001
32006,39206,100,32001
32014,39214,100,32001
32022,39222,100,32001
32030,39230,100,32001
32038,39238,100,32001
32046,39246,100,32001
32054,39254,100,32001
32062,39262,100,32001
40006,47206,100,40001
40014,47214,100,40001
40022,47222,100,40001
40030,47230,100,40001
40038,47238,100,40001
40046,47246,100,40001
40054,47254,100,40001
40062,47262,100,40001

*****NODE GEN FOR BOTTOM FLANGE*****

*NGEN,NSET=NPLATEB,LINE=C

40008,47208,100,40001
40010,47210,100,40001
40012,47212,100,40001
40016,47216,100,40001
40018,47218,100,40001
40020,47220,100,40001
40024,47224,100,40001


```

40026,47226,100,40001
40028,47228,100,40001
40032,47232,100,40001
40034,47234,100,40001
40036,47236,100,40001
40040,47240,100,40001
40042,47242,100,40001
40044,47244,100,40001
40048,47248,100,40001
40050,47250,100,40001
40052,47252,100,40001
40056,47256,100,40001
40058,47258,100,40001
40060,47260,100,40001
*****ELEMENT GEN FOR TOP SLAB *****
*ELEMENT,TYPE=S4R
1,2,102,104,4
*ELGEN,ELSET=ESLABT
1,72,100,32,32,2,1
*****
*ELSET,ELSET=LANE,GEN
1,2273,32
2,2274,32
3,2275,32
4,2276,32
5,2277,32
6,2278,32
7,2279,32
8,2280,32
9,2281,32
10,2282,32
11,2283,32
12,2284,32
13,2285,32
14,2286,32
15,2287,32
16,2288,32
17,2289,32
18,2290,32
19,2291,32
20,2292,32
21,2293,32
22,2294,32
23,2295,32
24,2296,32
25,2297,32
26,2298,32
27,2299,32
28,2300,32
29,2301,32
30,2302,32
31,2303,32
32,2304,32
*****ELEMENT GEN FOR BOTTOM FLANGE *****
*ELEMENT,TYPE=S4R
2305,40006,40106,40108,40008
2593,40022,40122,40124,40024
2881,40038,40138,40140,40040
3169,40054,40154,40156,40056
*ELGEN,ELSET=ESLABB
2305,72,100,4,4,2,1
2593,72,100,4,4,2,1
2881,72,100,4,4,2,1
3169,72,100,4,4,2,1
*****ELEMENT GEN FOR TOP FLANGE *****
*ELEMENT,TYPE=B31H
3457,8006,8106
3529,8014,8114
3601,8022,8122
3673,8030,8130
3745,8038,8138
3817,8046,8146
3889,8054,8154
3961,8062,8162

```

```

*ELGEN,ELSET=TOPFL
3457,72,100,1
3529,72,100,1
3601,72,100,1
3673,72,100,1
3745,72,100,1
3817,72,100,1
3889,72,100,1
3961,72,100,1
*****ELEMENT GEN FOR WEBS *****
*ELEMENT,TYPE=S4R
4033,16006,16106,8106,8006
4321,16014,16114,8114,8014
4609,16022,16122,8122,8022
4897,16030,16130,8130,8030
5185,16038,16138,8138,8038
5473,16046,16146,8146,8046
5761,16054,16154,8154,8054
6049,16062,16162,8162,8062
*ELGEN,ELSET=WEB
4033,72,100,4,4,8000,1
4321,72,100,4,4,8000,1
4609,72,100,4,4,8000,1
4897,72,100,4,4,8000,1
5185,72,100,4,4,8000,1
5473,72,100,4,4,8000,1
5761,72,100,4,4,8000,1
6049,72,100,4,4,8000,1
*****ELEMENT GEN FOR END DIAPHRAGMS *****
*ELEMENT,TYPE=S4R
6337,16006,16008,8008,8006
6353,16022,16024,8024,8022
6369,16038,16040,8040,8038
6385,16054,16056,8056,8054
6401,23206,23208,15208,15206
6417,23222,23224,15224,15222
6433,23238,23240,15240,15238
6449,23254,23256,15256,15254
*ELGEN,ELSET=DIAPH
6337,4,2,4,4,8000,1
6353,4,2,4,4,8000,1
6369,4,2,4,4,8000,1
6385,4,2,4,4,8000,1
6401,4,2,4,4,8000,1
6417,4,2,4,4,8000,1
6433,4,2,4,4,8000,1
6449,4,2,4,4,8000,1
*****END FLANGE ELEMENTS *****
*ELEMENT,TYPE=B31H
6465,8006,8008
6469,8022,8024
6473,8038,8040
6477,8054,8056
6481,15206,15208
6485,15222,15224
6489,15238,15240
6493,15254,15256
*ELGEN,ELSET=ENDFL
6465,4,2,1,1,1,1
6469,4,2,1,1,1,1
6473,4,2,1,1,1,1
6477,4,2,1,1,1,1
6481,4,2,1,1,1,1
6485,4,2,1,1,1,1
6489,4,2,1,1,1,1
6493,4,2,1,1,1,1
*****ELEMENT GEN FOR TRUSS ELEMENTS *****
*NGEN,NSET=XBP,LINE=C
24010,31210,100,24001
24018,31218,100,24001
24026,31226,100,24001
24034,31234,100,24001
24042,31242,100,24001
24050,31250,100,24001

```

24058,31258,100,24001

*ELEMENT,TYPE=B31H

6497,8806,8814

6498,8806,24810

6499,24810,40814

6500,8814,24810

6501,24810,40806

*ELGEN,ELSET=XBRAC

6497,8,800,20,4,16,5

6498,8,800,20,4,16,5

6499,8,800,20,4,16,5

6500,8,800,20,4,16,5

6501,8,800,20,4,16,5

*****ELEMENT GEN FOR END & MIDDLE TRUSS ELEMENTS BETWEEN BOXES *****

*ELEMENT,TYPE=B31H

20001,8014,8022

20002,8014,24018

20003,24018,40022

20004,8022,24018

20005,24018,40014

*ELGEN,ELSET=XBRAC

20001,10,800,15,3,16,5

20002,10,800,15,3,16,5

20003,10,800,15,3,16,5

20004,10,800,15,3,16,5

20005,10,800,15,3,16,5

*****MATERIAL PROPERTIES *****

*BEAM SECTION,SECTION=CIRC,ELSET=XBRAC,MATERIAL=STEEL

.0244

5,5

*SHELL SECTION,ELSET=WEB,MATERIAL=STEEL

.016,5

*BEAM SECTION,SECTION=RECT,ELSET=TOPFL,MATERIAL=STEEL

.016,.3

5,5

*BEAM SECTION,SECTION=RECT,ELSET=ENDFL,MATERIAL=STEEL

.016,.3

5,5

*SHELL SECTION,ELSET=DIAPH,MATERIAL=STEEL

.016,5

*SHELL SECTION,ELSET=ESLABB,MATERIAL=STEEL

.016,5

*MATERIAL,NAME=STEEL

*DENSITY

7800

*ELASTIC

200000E6,.3

*SHELL SECTION,ELSET=ESLABT,MATERIAL=CON

.2,5

*MATERIAL,NAME=CON

*DENSITY

2400

*ELASTIC

25000E6,.2

*****MULTIPOINT CONSTRAINT *****

*NGEN,NSET=SLABN6,LINE=C

6,7206,100,1

*NGEN,NSET=FLANGEN6,LINE=C

8006,15206,100,8001

*NGEN,NSET=SLABN14,LINE=C

14,7214,100,1

*NGEN,NSET=FLANGEN14,LINE=C

8014,15214,100,8001

*NGEN,NSET=SLABN22,LINE=C

22,7222,100,1

*NGEN,NSET=FLANGEN22,LINE=C

8022,15222,100,8001

*NGEN,NSET=SLABN30,LINE=C

30,7230,100,1

*NGEN,NSET=FLANGEN30,LINE=C

8030,15230,100,8001

*NGEN,NSET=SLABN38,LINE=C

```

38,7238,100,1
*NGEN,NSET=FLANGEN38,LINE=C
8038,15238,100,8001
*NGEN,NSET=SLABN46,LINE=C
46,7246,100,1
*NGEN,NSET=FLANGEN46,LINE=C
8046,15246,100,8001
*NGEN,NSET=SLABN54,LINE=C
54,7254,100,1
*NGEN,NSET=FLANGEN54,LINE=C
8054,15254,100,8001
*NGEN,NSET=SLABN62,LINE=C
62,7262,300,1
*NGEN,NSET=FLANGEN62,LINE=C
8062,15262,300,8001
*NSET,NSET=T1
8,10,12,24,26,28,40,42,44,56,58,60
*NSET,NSET=B1
8008,8010,8012,8024,8026,8028,8040,8042,8044,8056,8058,8060
*NSET,NSET=T2
7208,7210,7212,7224,7226,7228,7240,7242,7244,7256,7258,7260
*NSET,NSET=B2
15208,15210,15212,15224,15226,15228,15240,15242,15244,15256,15258,15260
*MPG
BEAM,SLABN6,FLANGEN6
BEAM,SLABN14,FLANGEN14
BEAM,SLABN22,FLANGEN22
BEAM,SLABN30,FLANGEN30
BEAM,SLABN38,FLANGEN38
BEAM,SLABN46,FLANGEN46
BEAM,SLABN54,FLANGEN54
BEAM,SLABN62,FLANGEN62
BEAM,T1,B1
BEAM,T2,B2
*****
*BOUNDARY
LEFT1,1
LEFT1,2
LEFT1,3
LEFT3,3
RIGHT1,2
RIGHT1,3
RIGHT3,3
*****
*ELSET,ELSET=MIDSLAB,GEN
1121,1184
*ELSET,ELSET=MIDBOTFLANGE,GEN
2445,2452
2733,2740
3021,3028
3309,3316
*ELSET,ELSET=MIDWEB,GEN
4173,4180
4461,4468
4749,4756
5037,5044
5325,5332
5613,5620
5901,5908
6189,6196
*ELSET,ELSET=MIDTOPFLANGE
3996,3997,3924,3925,3852,3853,3780,3781,3708,3709,3636,3637,3564,3565,3492,3493
*NGEN,NSET=MID
43606,43662,8
*****
*STEP
*STATIC
*DLOAD
LANE,P,-10000
*****
*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDSLAB
S11
*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDBOTFLANGE
S11

```



```
*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDWEB
S11
*NODEPRINT,NSET=MID
U3
*NODEPRINT,NSET=REACT
RF3
*****
*ENDSTEP
*STEP
*FREQUENCY
1
*ELPRINT,MODE=1
*ENDSTEP
```

APPENDIX (B.2): ABAQUS input file for two-span curved steel box-girder bridge

```

*HEADING
STEEL BOX GIRDER-BRIDGE (CURVED) - CONTINUOUS LINEAR, L=55, W=12, L/R=0.4
**DATA CHECK
*PREPRINT,ECHO=YES,MODEL=NO,HISTORY=NO
*****REFERENCE NODE COORDINATES 3L3B55S*****
*NODE
1,0,0,0
8001,0,0,-0.108
40001,0,0,-1.692
*** SLAB COORDINATES ***
2,-53.4420,263.6379,0
50,-55.8261,275.3987,0
7202,53.4420,263.6379,0
7250,55.8261,275.3987,0
*** GIRDER COORDINATES ***
8006,-53.6407,264.6180,-0.108
40006,-53.6407,264.6180,-1.692
15206,53.6407,264.6180,-0.108
47206,53.6407,264.6180,-1.692
8046,-55.6274,274.4186,-0.108
40046,-55.6274,274.4186,-1.692
15246,55.6274,274.4186,-0.108
47246,55.6274,274.4186,-1.692
*****NODE GENERATION FOR END DIAPHRAGMS*****
*NGEN,NSET=ORIGIN
8001,40001,8000
*NGEN,NSET=NEND
***left end***
2,50,2
8006,40006,8000
8046,40046,8000
8006,8046,2
16006,16046,2
24006,24046,2
32006,32046,2
40006,40046,2
***right end***
7202,7250,2
15206,47206,8000
15246,47246,8000
15206,15246,2
23206,23246,2
31206,31246,2
39206,39246,2
47206,47246,2
*****
*NSET,NSET=LEFT1
40022
*NSET,NSET=LEFT3
40006,40014,40030,40038,40046
*NSET,NSET=MID1
43622
*NSET,NSET=MID3
43606,43614,43630,43638,43646
*NSET,NSET=RIGHT1
47222
*NSET,NSET=RIGHT3
47206,47214,47230,47238,47246
*NSET,NSET=REACT
LEFT1,LEFT3,MID1,MID3,RIGHT1,RIGHT3
*****NODE GEN. FOR TOP SLAB *****
*NGEN,NSET=NPLATET,LINE=C
2,7202,100,1
4,7204,100,1
6,7206,100,1
8,7208,100,1
10,7210,100,1
12,7212,100,1
14,7214,100,1
16,7216,100,1
18,7218,100,1
20,7220,100,1
22,7222,100,1

```

```

24,7224,100,1
26,7226,100,1
28,7228,100,1
30,7230,100,1
32,7232,100,1
34,7234,100,1
36,7236,100,1
38,7238,100,1
40,7240,100,1
42,7242,100,1
44,7244,100,1
46,7246,100,1
48,7248,100,1
50,7250,100,1
*****NODE GEN FOR TOP FLANGE *****
*NGEN,NSET=NTOPFLNG,LINE=C
8006,15206,100,8001
8014,15214,100,8001
8022,15222,100,8001
8030,15230,100,8001
8038,15238,100,8001
8046,15246,100,8001
*****NODE GEN. FOR WEBS *****
*NGEN,NSET=NWEB,LINE=C
16006,23206,100,16001
16014,23214,100,16001
16022,23222,100,16001
16030,23230,100,16001
16038,23238,100,16001
16046,23246,100,16001
24006,31206,100,24001
24014,31214,100,24001
24022,31222,100,24001
24030,31230,100,24001
24038,31238,100,24001
24046,31246,100,24001
32006,39206,100,32001
32014,39214,100,32001
32022,39222,100,32001
32030,39230,100,32001
32038,39238,100,32001
32046,39246,100,32001
40006,47206,100,40001
40014,47214,100,40001
40022,47222,100,40001
40030,47230,100,40001
40038,47238,100,40001
40046,47246,100,40001
*****NODE GEN FOR BOTTOM FLANGE *****
*NGEN,NSET=NPLATEB,LINE=C
40008,47208,100,40001
40010,47210,100,40001
40012,47212,100,40001
40016,47216,100,40001
40018,47218,100,40001
40020,47220,100,40001
40024,47224,100,40001
40026,47226,100,40001
40028,47228,100,40001
40032,47232,100,40001
40034,47234,100,40001
40036,47236,100,40001
40040,47240,100,40001
40042,47242,100,40001
40044,47244,100,40001
*****NODE GEN FOR MIDDLE DIAPHRAGM *****
*NGEN,NSET=NMID
***middle***
11606,11646,2
19606,19646,2
27606,27646,2
35606,35646,2
*****ELEMENT GEN FOR TOP SLAB *****
*ELEMENT,TYPE=S4R

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1,2,102,104,4
*ELGEN,ELSET=ESLABT
1,72,100,24,2,1
*****
*ELSET,ELSET=LANE,GEN
1,1705,24
2,1706,24
3,1707,24
4,1708,24
5,1709,24
6,1710,24
7,1711,24
8,1712,24
9,1713,24
10,1714,24
11,1715,24
12,1716,24
13,1717,24
14,1718,24
15,1719,24
16,1720,24
17,1721,24
18,1722,24
19,1723,24
20,1724,24
21,1725,24
22,1726,24
23,1727,24
24,1728,24
*****ELEMENT GEN FOR BOTTOM FLANGE *****
*ELEMENT,TYPE=S4R
1729,40006,40106,40108,40008
2017,40022,40122,40124,40024
2305,40038,40138,40140,40040
*ELGEN,ELSET=ESLABB
1729,72,100,4,4,2,1
2017,72,100,4,4,2,1
2305,72,100,4,4,2,1
*****ELEMENT GEN FOR TOP FLANGE *****
*ELEMENT,TYPE=B31H
2593,8006,8106
2665,8014,8114
2737,8022,8122
2809,8030,8130
2881,8038,8138
2953,8046,8146
*ELGEN,ELSET=TOPFL
2593,72,100,1
2665,72,100,1
2737,72,100,1
2809,72,100,1
2881,72,100,1
2953,72,100,1
*****ELEMENT GEN FOR WEBS *****
*ELEMENT,TYPE=S4R
3025,16006,16106,8106,8006
3313,16014,16114,8114,8014
3601,16022,16122,8122,8022
3889,16030,16130,8130,8030
4177,16038,16138,8138,8038
4465,16046,16146,8146,8046
*ELGEN,ELSET=WEB
3025,72,100,4,4,8000,1
3313,72,100,4,4,8000,1
3601,72,100,4,4,8000,1
3889,72,100,4,4,8000,1
4177,72,100,4,4,8000,1
4465,72,100,4,4,8000,1
*****ELEMENT GEN FOR END & MIDDLE DIAPHRAGMS *****
*ELEMENT,TYPE=S4R
4753,16006,16008,8008,8006
4769,16022,16024,8024,8022
4785,16038,16040,8040,8038
4801,19606,19608,11608,11606

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4817,19622,19624,11624,11622
4833,19638,19640,11640,11638
4849,23206,23208,15208,15206
4865,23222,23224,15224,15222
4881,23238,23240,15240,15238
*ELGEN,ELSET=DIAPH
4753,4,2,4,4,8000,1
4769,4,2,4,4,8000,1
4785,4,2,4,4,8000,1
4801,4,2,4,4,8000,1
4817,4,2,4,4,8000,1
4833,4,2,4,4,8000,1
4849,4,2,4,4,8000,1
4865,4,2,4,4,8000,1
4881,4,2,4,4,8000,1
*****END & MIDDLE FLANGE ELEMENTS *****
*ELEMENT,TYPE=B31H
4897,8006,8008
4901,8022,8024
4905,8038,8040
4909,11606,11608
4913,11622,11624
4917,11638,11640
4921,15206,15208
4925,15222,15224
4929,15238,15240
*ELGEN,ELSET=ENDFL
4897,4,2,1,1,1,1
4901,4,2,1,1,1,1
4905,4,2,1,1,1,1
4909,4,2,1,1,1,1
4913,4,2,1,1,1,1
4917,4,2,1,1,1,1
4921,4,2,1,1,1,1
4925,4,2,1,1,1,1
4929,4,2,1,1,1,1
*****ELEMENT GEN FOR TRUSS ELEMENTS *****
*NGEN,NSET=XBP,LINE=C
24010,31210,100,24001
24018,31218,100,24001
24026,31226,100,24001
24034,31234,100,24001
24042,31242,100,24001
*****
*ELEMENT,TYPE=B31H
4933,8406,8414
4934,8406,24410
4935,24410,40414
4936,8414,24410
4937,24410,40406
5053,12006,12014
5054,12006,28010
5055,28010,44014
5056,12014,28010
5057,28010,44006
*ELGEN,ELSET=XBRAC
4933,8,400,15,3,16,5
4934,8,400,15,3,16,5
4935,8,400,15,3,16,5
4936,8,400,15,3,16,5
4937,8,400,15,3,16,5
5053,8,400,15,3,16,5
5054,8,400,15,3,16,5
5055,8,400,15,3,16,5
5056,8,400,15,3,16,5
5057,8,400,15,3,16,5
*****ELEMENT GEN FOR END & MIDDLE TRUSS ELEMENTS BETWEEN BOXES *****
*ELEMENT,TYPE=B31H
20001,8014,8022
20002,8014,24018
20003,24018,40022
20004,8022,24018
20005,24018,40014
*ELGEN,ELSET=XBRAC

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20001,19,400,10,2,16,5
20002,19,400,10,2,16,5
20003,19,400,10,2,16,5
20004,19,400,10,2,16,5
20005,19,400,10,2,16,5
*****MATERIAL PROPERTIES *****
*BEAM SECTION,SECTION=CIRC,ELSET=XBRAC,MATERIAL=STEEL
.0244
5,5
*SHELL SECTION,ELSET=WEB,MATERIAL=STEEL
.016,5
*BEAM SECTION,SECTION=RECT,ELSET=TOPFL,MATERIAL=STEEL
.016,.3
5,5
*BEAM SECTION,SECTION=RECT,ELSET=ENDFL,MATERIAL=STEEL
.016,.3
5,5
*****
*SHELL SECTION,ELSET=DIAPH,MATERIAL=STEEL
.016,5
*SHELL SECTION,ELSET=ESLABB,MATERIAL=STEEL
.016,5
*MATERIAL,NAME=STEEL
*DENSITY
7800
*ELASTIC
200000E6,.3
*SHELL SECTION,ELSET=ESLABT,MATERIAL=CON
.2,5
*MATERIAL,NAME=CON
*DENSITY
2400
*ELASTIC
25000E6,.2
*****MULTIPOINT CONSTRAINT *****
*NGEN,NSET=SLABN6,LINE=C
6,7206,100,1
*NGEN,NSET=FLANGEN6,LINE=C
8006,15206,100,8001
*NGEN,NSET=SLABN14,LINE=C
14,7214,100,1
*NGEN,NSET=FLANGEN14,LINE=C
8014,15214,100,8001
*NGEN,NSET=SLABN22,LINE=C
22,7222,100,1
*NGEN,NSET=FLANGEN22,LINE=C
8022,15222,100,8001
*NGEN,NSET=SLABN30,LINE=C
30,7230,100,1
*NGEN,NSET=FLANGEN30,LINE=C
8030,15230,100,8001
*NGEN,NSET=SLABN38,LINE=C
38,7238,100,1
*NGEN,NSET=FLANGEN38,LINE=C
8038,15238,100,8001
*NGEN,NSET=SLABN46,LINE=C
46,7246,100,1
*NGEN,NSET=FLANGEN46,LINE=C
8046,15246,100,8001
*NSET,NSET=T1
8,10,12,24,26,28,40,42,44
*NSET,NSET=B1
8008,8010,8012,8024,8026,8028,8040,8042,8044
*NSET,NSET=T2
3608,3610,3612,3624,3626,3628,3640,3642,3644
*NSET,NSET=B2
11608,11610,11612,11624,11626,11628,11640,11642,11644
*NSET,NSET=T3
7208,7210,7212,7224,7226,7228,7240,7242,7244
*NSET,NSET=B3
15208,15210,15212,15224,15226,15228,15240,15242,15244
*MPC
BEAM,SLABN6,FLANGEN6
BEAM,SLABN14,FLANGEN14

```

BEAM,SLABN22,FLANGEN22
BEAM,SLABN30,FLANGEN30
BEAM,SLABN38,FLANGEN38
BEAM,SLABN46,FLANGEN46
BEAM,T1,B1
BEAM,T2,B2
BEAM,T3,B3

*BOUNDARY

LEFT1,2
LEFT1,3
LEFT3,3
MID1,1
MID1,2
MID1,3
MID3,3
RIGHT1,2
RIGHT1,3
RIGHT3,3

*ELSET,ELSET=MIDSLAB,GEN

841,888

*ELSET,ELSET=MIDBOTFLANGE,GEN

1797,1804
1941,1948
2085,2092
2229,2236
2373,2380
2517,2524

*ELSET,ELSET=MIDWEB,GEN

3093,3100
3237,3244
3381,3388
3525,3532
3669,3676
3813,3820
3957,3964
4101,4108
4245,4252
4389,4396
4533,4540
4677,4684

*ELSET,ELSET=MIDTOPFLANGE

2988,2989,2916,2917,2844,2845,2772,2773,2700,2701,2628,2629

*NGEN,NSET=MID

41806,41846,8
45406,45446,8

*STEP

*STATIC

*DLOAD

LANE,P,-10000

*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDSLAB

S11

*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDBOTFLANGE

S11

*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDTOPFLANGE

S11

*ELPRINT,POSITION=AVERAGED AT NODES,ELSET=MIDWEB

S11

*NODEPRINT,NSET=MID

U3

*NODEPRINT,NSET=REACT

RF3

*ENDSTEP

*STEP

*FREQUENCY

1

*ELPRINT,MODE=1

*ENDSTEP

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