Literature Review in Analysis of Horizontally Curved Box-Girder Bridges

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Abstract— This paper present a literature review related to Curved span PSC Box girder. The curvilinear nature of box girder bridges with their complex deformation patterns and stress fields have led designers adopt conservative methods for analysis & design. Recent literature on curved girder bridges to understand the complex behavior. In the present study an attempt has been made to study the Significance of PSC Box Girders & Type, Curvature effect of span, live load effect, wrapping stress in curved Box girder, Shear Lag & Torsion effect due to curvature. Comparative study of analysis & design of PSC T-girder with PSC Box girder using software Staad - pro, ANSYS, MIDAS and CSI Bridge. Normal & Skew Box Girder with different geometrical combination has been included.

Key words: Curved Bridges, Curved PSC Box, Structural Analysis & Design, Prestressing, Wrapping Stress, Torsion, Bridge Design, Shear Lag

I. Introduction

Bridge is life line of road network, both in urban and rural areas. With rapid technology growth the conventional bridge has been replaced by innovative cost effective structural system such as T-Beam Girder System and Box Girder Bridge System. In spite of difficult design procedure and complex form work requirement , box girders, have gained wide acceptance in freeway and bridge systems due to their structural efficiency, better stability, serviceability, economy of construction and aesthetic appearance. In bridge design procedure span length and live load are important and affect the conceptualization stage of design. Various live loads that are defined by IRC 6:2016 and experienced by bridge deck system are Class A, Class B, Class AA and Class 70R. These are the combinations of wheel load and track loads. Wheel loads are one which are transferred by the wheels of trucks and track loads are one which are transferred by pair of wheels and axels connected by belts. The effect of these loads varies from span to span. For example, on shorter spans track load governs whereas on larger span wheel load govern. Designs considering combinations of these loads on bridge deck system provide scope for research. However, the bridge deck structural system adopted is influence by factor like economy and complexity in construction.

The construction of curved span girder bridges in interchanges of modern highway system has become increasingly popular for economic and aesthetic reasons in many countries over the world. Particularly in India especially in growing cities such bridges of curved alignment have been used in the design of crowded urban areas where the multilevel interchanges must be built with inflexible geometric restrictions. The curve alignment box girder bridges are very complicated to analysis and design due to their complex behavior compared to straight span bridges. Treating the horizontally curve bridges as straight is one of the recommended method to simplify their analysis and design procedures as per some foreign codes but such recommendations are not mentioned in IRC codes. The recommendations given in the foreign codes (CHBDC & AASHTO-LFRD) are underestimates the actual structural behavior of curved span box girders. Curved bridges may be entirely constructed of reinforced concrete, prestressed concrete, steel, or composite concrete deck on steel I- or box girders. Concrete box girders are usually cast in situ or precast in segments erected on false work or launching frame and then prestressed. The decks could be of steel, reinforced concrete, or prestressed concrete. Curved composite box girders have a number of unique qualities that make them suitable for such applications, such as 1). Their structural efficiency allows designers to build long slender bridges that have an aesthetically pleasing appearance; and 2). Composite box girders are particularly strong in torsion and can be easily designed to resist the high torsional demands created by horizontal bridge curvature and vehicle centrifugal forces. Curved composite box girder bridges generally comprise one or more steel U-girders attached to a concrete deck through shear connectors. Diaphragms connect individual steel U-girders periodically along the length to ensure that the bridge system behaves as a unit. The cross section of a steel box is flexible (i.e., can distort) in the cross-wise direction and must be stiffened with cross frames that are installed in between the diaphragms to prevent distortion. Web and bottom plate stiffeners are required to improve stability of the relatively thin steel plates that make up the steel box.

During construction, overall stability and torsional rigidity of the girder are enhanced by using top bracing members. These bracing members become unimportant once the concrete decks hardens, but are usually left in place anyway. Paper will cover the references related to the development of guide specifications, including the behavior of curved box girders, load distribution and codes of practice for straight and curved box girder bridges, dynamic response, Shear Lag & Torsion effect and ultimate strength of such bridges.

II. Literature review

Khaled M. Sennah & John B. Kennedy [1] performed (1) elastic analysis and (2) experimental studies on the elastic response of box girder bridges. In elastic analysis they represent the orthotropic plate theory method, grillage analogy method, folded plate method, finite element method, thin-walled curved beam theory etc. The curvilinear nature of box girder bridges along with their complex deformation patterns and stress fields have led designers to adopt approximate and conservative methods for their analysis and design. Recent literature on straight and curved box girder bridges has dealt with analytical formulations to better understand the behavior of these complex structural systems. Few authors have undertaken experimental studies to investigate the accuracy of existing method.

Kenneth W. Shushkewich [2] performed approximate Analysis of Concrete Box Girder Bridges. The actual three dimensional behavior of a box girder bridges as predicted by a folded plate, finite strip or finite element analysis can be approximated by using some simple membrane equations in conjunction with plane frame analysis. This is a useful method since virtually all structural engineers have access to a plane frame computer program, while many have neither the access nor the inclination to use more sophisticated programs. In particular, the method allows the reinforcing and prestressing to be proportioned for transverse flexure, as well as the stirrups to be proportioned for longitudinal shear and torsion in single celled precast concrete segmental box girder bridges. The author considers the following points for explanations: (1) the webs may be inclined or vertical. (2) Self-weight, uniform load, and load over the webs may be considered with respect to transverse flexure. (3) Both symmetrical (flexural) and anti-symmetrical (torsional) loads may be considered with respect to longitudinal shear and torsion. This paper is particularly useful in the design of single celled precast concrete segmental box girder bridges without considering the effect shear leg and warping torsion. The author represents the three examples of box girder bridges with different load cases and concluded that the results of a folded plate analysis which is considered to be exact can be approximated very closely by using some simple membrane equation using in conjunction with a plane frame analysis.

Y. K. Cheung et al. [3] discussed on curved Box Girder bridges based on the curvilinear coordinate system, the spline finite strip method is extended to elasto-static analysis. As the curvature effect cannot be ignored, the webs of the bridges have to be treated as thin shells and the flanges as flat curved plates. The shape functions for the description of displacement field (radial, tangential, and vertical) are given as product of B-3 spline functions in the longitudinal direction and piece-wise polynomials in the other directions. The stress-strain matrices can then be formed as in the standard finite element method. Compared to the finite element method, this method yields considerable saving in both computer time and effort, since only a small number of unknowns are generally required in the analysis. This paper represents three examples box girder bridges of different geometrical shapes to demonstrate the accuracy and versatility of the method. This method was recently devised by Cheung et al. (1982) for the analysis of right straight plates and box girders. It was then subsequently extended to cover skew plates (Tham et al. 1986) and the plates of arbitrary shape (Li et al. 1986).

Ayman M. Okeil & Sherif El Tawil[4] carried out detailed investigation of warping-related stresses in 18 composite steel-concrete box girder bridges. The bridge designs were adapted from blueprints of existing bridges in the state of Florida and encompass a wide range of parameters including horizontal curvature, cross-sectional properties, and number of spans. The bridges after which the analysis prototypes are modeled were designed by different firms and constructed at different times and are considered to be representative of current design practice. Forces are evaluated from analyses that account for the construction sequence and the effect of warping. Loading is considered following the 1998 AASHTO-LRFD provisions. Differences between stresses obtained taking warping into account and those calculated by ignoring warping are used to evaluate the effect of warping. Analysis results show that warping has little effect on both shear and normal stresses in all bridges.

Babu Kurian & Devdas Menon [5] performed an estimation of Collapse Load of Single-cell Concrete Box-Girder Bridges. The simplified equations available at present to predict the collapse loads of single-cell concrete box girder bridges with simply supported ends are based on either space truss analogy or collapse mechanisms. Experimental studies carried out by the various researchers revealed that, of the two formulations available to predict the collapse load, the one based on collapse mechanisms is found to be more versatile and better suited to box sections. Under a pure bending collapse mechanism, existing formulation is found to predict collapse load with higher accuracy. However, in the presence of cross sectional distortion, there are significant errors in the existing theoretical formulation. This paper attempts to resolve this problem, by proposing a modification to the existing theory, incorporating an empirical expression to assess the extent of corner plastic hinge formation, under distortion-bending collapse mechanism. The modified theoretical formulations are compared with the experimental results available in the literature. New sets of experiments are also conducted to validate the proposed modified theory to estimate the collapse load. In all the cases, it is seen that the modified theory to predict the collapse load match very closely with the experimental results.

Robert K. Dowell & Timothy P. Johnson [6] discussed Closed-form Shear flow Solution for Box Girder Bridges under Torsion. To provide desired stiffness and strength in torsion, bridge super structures are often constructed with a cross section consisting of multiple cells which have thin walls relative to their overall dimensions and resist Saint- Venant torsion through shear flow (force per unit length) that develops around the walls. For a single thin-walled cell subjected to torsion, shear flow is constant along each of its wall while shear stresses vary around the section based upon changes in wall thickness. When the cross section contains multiple cells they all contribute resistance to applied torsion and for elastic continuity each cell must twist the same amount. With these considerations, equilibrium and compatibility conditions allow simultaneous equations to be formed and solved to determine the shear flow for each cell. A second approach is relaxation method that distributes incremental shear flows back and forth between cells, reducing errors with each distribution cycles, until the final shear flows for all cells approximate the correct values. A major advantage of this method is that it does not require setting up and solving simultaneous equations, favoring situations where hand calculation is desired. In this paper, a closed-form approach is introduced to determine, exactly, both the torsional constant and all shear flows for multi-cell cross sections under torsion; no simultaneous equations are required and there is no need to distribute shear flows back and forth between cells. Simple closed-form equations are derived which give shear flows for cross-sections with any number of cells of arbitrary shape.

Imad Eldin Khalafalla & Khaled M. Sennah [7] discussed Curvature Limitations for Slab-on-I-Girder Bridges. In recent years, horizontally curved bridges have been widely used in congested urban areas, where multilevel interchange structures are necessary for modern highways. In bridges with light curvature, the curvature effects on bending, shear, and torsional stresses may be ignored if they are within an acceptable range. Treating horizontally curved bridges as straight bridges with certain limitations is one of the methods to simplify the design procedure. Certain bridge design specifications and codes have specified certain limitations to treat horizontally curved bridge as straight bridge. However, these limitations do not differentiate between bridge cross section configurations, in addition to being inaccurate in estimating the structural response. Moreover these specifications were developed primarily for the calculation of girder bending moments. In this paper, the author discusses the curvature limitation for Canadian Highway Bridge Design Code (CHBDC), AASHTO-LFRD Bridge Design Specification, and AASHTO Guide Specification for Horizontally Curved Bridges. The AASHTO Guide Specification for Horizontally Curved Bridges states that for composite steel I-girder bridges, the effect of the curvature may be ignored in the determination of the vertical bending moment, when the following three conditions are met: (1) girders are concentric; (2) bearing lines are not skewed more than 10° from the radial; and (3) the arc span divided by the girder span, L/R, is less than 0.06 radians. AASHTO Guide specifies that the arc length, L, is the arc length of the girder in the case of simple span bridges, that is, 0.9 times the arc length of the girder for end spans of continuous bridges and 08 times the arc length of the girder for the interior span of the continuous bridges. If such conditions are met, the AASHTO Guide specifies that the dead load applied to composite bridge should be distributed uniformly to steel girders, and the live load distribution factors for the straight bridges should be used. At the same time CHBDC specify for the bridges that are curved in plan and that are built with shored construction, a simplified method of analysis can be applied by treating the bridge as a straight one, when the following two conditions met: (1) there are at least two intermediate diaphragms per span; and $L2/BR \leq 0.5$, where B is the width of the bridge, L is the center line curved span length, and R is the radius of the curvature. The CHBDC curvature limit equation does not include the continuity effect in the span length. Also it does not differentiate bridges with open or closed sections. In contrast, clause C10.13.30.2 of Chapter 10 "steel structures" of commentaries of the CHBDC states that "for bridges of more than 90m radius, the longitudinal moments can be assessed for a straight span. The third edition of the Ontario Highway Bridge Design Code (OHBDC), published by the Ministry of Transportation of Ontario, stated that the effect of curvature may be neglected in the structure design considerations as long as two conditions are met: (1) $L^2/BR \leq 0.5$ and (2) $R > 90$m. To investigate the accuracy of above codes curve limitations, a series of horizontally curved, braced concrete slab-over steel I girder and slabs on concrete I girder bridges were analyzed by the author using three dimensional finite-element modeling, to investigate their behavior under dead loading. The parameters considered as girder longitudinal bending stresses, vertical deflections, vertical support reactions, and the bridge fundamental flexural frequencies for different degree of curvature, span length, bridge width, and span continuity. Empirical equations for these straining were developed as a function of those for straight bridges. The stipulations made in bridge codes for treating a curved bridge as a straight bridge were then correlated with the obtained values from the finite element modeling. On the basis of the results author concluded that codal curvature limitations were unsafe. And empirical expressions developed to determine such limitations more accurately and reliably.

Dereck J. Hodson et al. [8] evaluated flexural live load distribution factors for cast in place box girder bridges. The response of typical live load test was recorded during a static live load test. This test involved driving two heavily loaded trucks across the instrumented bridge on selected paths. The instruments used to record the response of the bridge were strain gauges, displacement transducers, and tilt sensors. The measured data were then used to calibrate a finite element modeling scheme using solid elements. From this finite element model, the theoretical live load distribution factors and the load rating for the test bridge were determined and compared with the factors and ratings predicted in AASHTO-LFRD specification. A parametric study of cast-in-in place, box girder bridges using the calibrated finite element modeling scheme was then used to investigate how various parameters such as span length, girder spacing, parapets, skew, and deck thickness affect the flexural live load distribution factor. Based on the result of parametric study, a new equation which more accurately predicts the exterior girder distribution factor, is proposed.

Khaled M. Sennah & John B. Kennedy [9] discussed on various subjects such as (1) different box girder bridge configuration; (2) construction issue; (3) deck design; (4) load distribution; (5) deflection and camber; (6) cross bracing requirement; (7) end diaphragms; (8) thermal effects; (9) vibration characteristics; (10) impact factors; (11) seismic response; (12) ultimate load carrying capacity; (13) buckling of individual member forming the box sections; (14) fatigue; (15) curvature limitations provided by the codes for treating a curve bridge as a straight one. The objective of this study is to provide highlights of most important reference related to the development of current guide specification for the design of straight and curved box girder bridges. The construction of curved box girder bridges in interchanges of modern highway system has become increasingly popular for economic and aesthetic reasons. Box girder cross section may take the form of single cell, multi-spine, or multi-cell with a common bottom flange.

Jefeena Sali et al. [10] carried out Parametric Study of Behaviour of Box Girder Bridges under Different Radius of Curvature. The analysis of one straight box girder and four curved box girders of different radius of curvature are carried out in CSI Bridge software. The results presented in this paper highlight the effects of radius of curvature of the box girder on the behaviour in terms of development of deflection longitudinal bending stresses and torsion. The conclusions that are drawn from the analysis of box girders of different radius of curvature are as follows

- As radius of curvature of box girder increases the deflection, bending moment, torsion and longitudinal bending stress along the span decreases.
- There is no significant variation in bending moment, deflection longitudinal bending stresses under DL+SIDL, moving load and prestressed load for specific span length with different radii.
- The torsional moment increases greatly with decrease in radius of curvature under all loading conditions.
- There is more variation in torsion with span radius below 100m therefore its better to avoid such sharp curves and if they are unavoidable then structural changes to cross sectional dimension, must be made to stabilise the box girders.

Mulesh K. Pathak [11] carried out Parametric Study on Performance of RCC Box type Superstructure in Curved bridges. In this paper, various behaviours like bending, shear, axial & torsion are presented for horizontally curved RCC box bridges considering 3-D FEM using SAP software. FEM models are prepared for four different span lengths keeping the same material properties with varying degree of curvature from 0° to 90° for different load conditions & combinations to get multiplication factor for various actions like BM, SF, AF & TM w.r.t to straight bridge to multiply the desired parameters of straight bridge to get that for curved bridge. This approach simplifies analysis & the preliminary design of curved bridge section. Fourty Models were prepared for four different span lengths (15m, 20m, 25m and 30m) keeping the same material properties with varying degree of curvature from 0° to 90° at 10° increment for different load conditions and load combinations. Loads, load combinations and end conditions were applied to the models as per IRC specifications. Finite element software SAP-2000 was used for the analysis. The conclusions obtained from the present study are shown in tables and graphs above and can be described as below.

- From the graphs of the results shown above it can be inferred that the increase in the torsion for any set of graph is comparatively steeper than that of bending moments, shear forces and axial carrying capacities which indicates that box section is having higher torsional stiffness and is nonlinearly vary with degree of curvature.
- The study also provides multiplication factors for all the parameters for varying degree of curvature (i.e. 10° to 90°) w. r. t. a straight bridge (0°) and for varying spans (between 15m to 30m) as shown in fig 6. These can be useful to simplify the analysis by considering straight bridge instead of curved bridge, in which multiplication factor is used multiply to the corresponding action of the straight bridge. This can be very much useful in the preliminary design of the section.
- From the study it is observed that for different span, the multiplication factor for variable degree of curvature is varying linearly for axial force & bending moment, which is about 1.2 to 1.3 for 90° curvature. Multiplication factor for torsion moment is varying nonlinearly having 1.8 to 1.9 for 90° curvature, while there is no need to apply multiplication factor for shear force.

Nila P Sasidharan and Basil Johny [12] carried out the analysis of various curved box girder models are carried out in ABAQUS software by varying span and radius of curvature. The span to depth ratio is kept constant. The models are created by varying the depth according to a span to depth ratio of 16. The variations in reactions, bending stress, shear stress and mid span deflections are observed by conducting the parametric study. From the results obtained after the analysis of curved single cell rectangular box girder, the following conclusions are made

- The graph plotted between reaction and radius of curvature shows that reaction decreases with increase in radius of curvature and with decrease in span length. So the minimum reaction can be obtained by increasing the radius of curvature.
- If minimum deflection is the criteria for selecting a particular radius of curvature, it can be concluded that for 40m span the mid span deflection is minimum at radius of curvature equal to 200m. But for 30m span, the minimum is observed at 150m radius of curvature. In the case of 20m span, the mid span deflection is minimum at a radius of 100m.
- The bending stress decreases with increase in radius of curvature. For 20m span bending stress remains the same with respect to radius of curvature. It is better to use radius of curvature below 200m as span increases to get maximum bending strength.
- The decrease in radius of curvature will increase the shear stress. Also with increase in span shear stress increases. For each span considered, the shear stress distribution is uniform above 150m radius of curvature.

Ali R. Khaloo and M. Kafimosavi [13] carried out the parametric Study on enhancement of flexural design of horizontally curved prestressed bridges. In this paper, flexural behaviour of horizontally curved prestressed _posttensioned_ box bridges is studied by using three-dimensional and refined finite-element modelling and analysis. Bridge length, section geometry, and material properties are the same in all the models, while angle of curvature varies from 0 to 90°. The results of analysis show that in curved bridges, stress distribution is significantly different in comparison to straight bridges. Also, the level of stresses at some locations of section width is considerably high. It is proposed to vary the distribution of the pressurising tendons across section width in order to optimize the bridge capacity. Results show that by proper redistribution of pressurising in section width, significant reduction in resultant stress is possible.

III. CONCLUSION

1) The results of a folded plate analysis (which is considered to be exact) can be approximated very closely by using some simple membrane equations in conjunction with a plane frame analysis. In particular, the method allows the reinforcing and prestressing to be proportioned for transverse flexure, as well as the stirrups to be proportioned for longitudinal shear and torsion in single-celled precast concrete segmental box girder bridges. [1]

2) The effects of different practical support conditions ~free and constraint with respect to thermal effects! can be represented only by the 3D finite-element method. These effects need further investigation, because they affect the flexibility of the bridge structure and, hence, its static and dynamic responses. [2]
3) Based on the curvilinear coordinate system, the spline finite-strip method is extended to cover the analysis of circular and noncircular curved box-girder bridges. [3]
4) As indicated in the paper, additional work is needed to define relevant parameters that can be used to identify such bridges where warping calculations are not required. This will be particularly useful to designers because warping calculations are complicated and time consuming. [4]
5) The proposed theoretical prediction of the length of plastic hinges, in the longitudinal direction at the web–top flange junctions, is validated in the case involving the predictable distortion– bending collapse mechanism. [5]
6) The proposed method gives final results without the need to setup and solve simultaneous equations or to distribute shear flows back and forth multiple times. It can be used in its own right or to spot-check computer results by hand. The example problem demonstrates the new method for torsion of a prestressed concrete box–girder bridge superstructure. [6]
7) The proposed method gives final results without the need to setup and solve simultaneous equations or to distribute shear flows back and forth multiple times. It can be used in its own right or to spot-check computer results by hand. The example problem demonstrates the new method for torsion of a prestressed concrete box–girder bridge superstructure. [7]
8) It was determined that the controlling distribution factor for both the Lambert Road Bridge model and AASHTO LRFD specifications was based on the three loaded lane case for the interior girder, which had values of 0.51 and 0.66, respectively. [8]
9) The study of load distribution in curved box-girder bridges due to dead load and truck loads was not covered for all cross-section configurations, span continuity, and different support conditions. [9]
10) As radius of curvature of box girder increases the deflection, bending moment, torsion and longitudinal bending stress along the span decreases. The torsional moment increases greatly with decrease in radius of curvature under all loading conditions. [10]
11) It can be inferred that the increase in the torsion for any set of graph is comparatively steeper than that of bending moments, shear forces and axial carrying capacities which indicates that box section is having higher torsional stiffness and is nonlinearly vary with degree of curvature. [11]
12) If minimum deflection is the criteria for selecting a particular radius of curvature, it can be concluded that for 40m span the mid span deflection is minimum at radius of curvature equal to 200m. But for 30m span, the minimum is observed at 150m radius of curvature. In the case of 20m span, the mid span deflection is minimum at a radius of 100m. [12]
13) Based on numerous analyses performed in this study, it is proposed to redistribute prestressing tendons across the section width. This approach reduces critical stresses substantially and leads to enhanced design of prestressed curved bridges. [13]

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