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Curved Span PSC Box Girder Bridges : A Review

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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, Normal & Skew Box Girder with different geometrical combination has been included.**

***Keywords* – Curved Bridges, Curved PSC Box, Structural Analysis & Design, Prestressing, Wrapping Stress, Torsion, Bridge Design, Shear Lag, etc…**

I. INTRODUCTION

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

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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).

Ricardo Gaspar & Fernando Reboucas Stucchi [4] presented Web Design of Box Girder Concrete Bridges. An experimental investigation was undertaken with the purpose verifying the validity of the newly developed approach. The following failure modes were considered: excessive plastic deformation of stirrups, crushing of the compressed struts and failure of the stirrups due to fatigue. The experimental results showed good agreement with the results of the proposed approach. Furthermore, the tests revealed new aspects of the fatigue behavior, the failure of the stirrups due to fatigue occurred in stages, one at a time in gradual manner. In all cases, failure took place near the connection between the web and the bottom flange. In this paper the approach of reinforcement sum, approach of reinforcement comparison, thurlimann's approach, and stucchi's approach is considered. Newly developed approach: This new approach assumes that the most realistic model is the one which considers that the force increment ΔT, due to the transverse bending moment, is balanced at the same time by an increase of the concrete compression ΔT_C and a decrease of the tension force ΔT_tin the stirrups leg adjacent to the compression strut. Therefore, $\Delta T = \Delta T_C + \Delta T_t$. This proposal considers both ideas proposed in Thurlimann's and in stucchi's approach. Similarly to Thurlimann's and in stucchi's, this method proposes that until a certain level of transverse bending moment mmax1, the equilibrium is reached by the strut eccentricity alone, whose width should be limited by the shear strength TRwdwithout the need for additional reinforcement. For higher values of transverse bending moment, this model proposes that the force increment ΔT would increase the compression force and at the same time would reduce the tension force T in the stirrups leg adjacent to the strut. Equation of the equilibrium of moment is given by,

$$m_{max2} = C\, e_{max} + \Delta T_C \left(e_{max} + \frac{bw}{2}\right) + \Delta T_t\, b_w$$

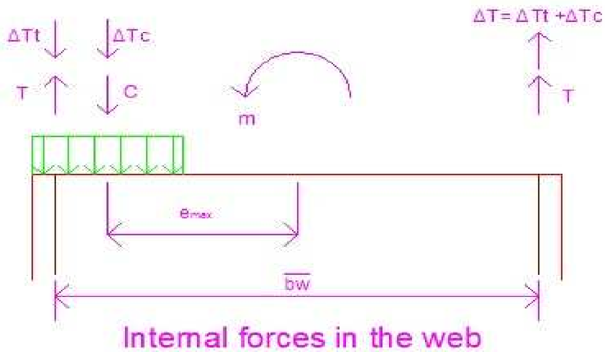

Figure:1 Newly Proposed Design Approach

Ayman M. Okeil & Sherif El Tawil[5] 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 [6] 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.

Pure bending collapse mechanism:

The equation for collapse load $P = \frac{4}{L}(F_b h + 2 F_W h_1)$

F_b & F_W = Total yield force of the reinforcement provided in bottom flange and one web

h = distance from the c.g of bottom flange steel to centroidal axis of top flange

h_1 = distance from the c.g of web steel to centroidal axis of top flange

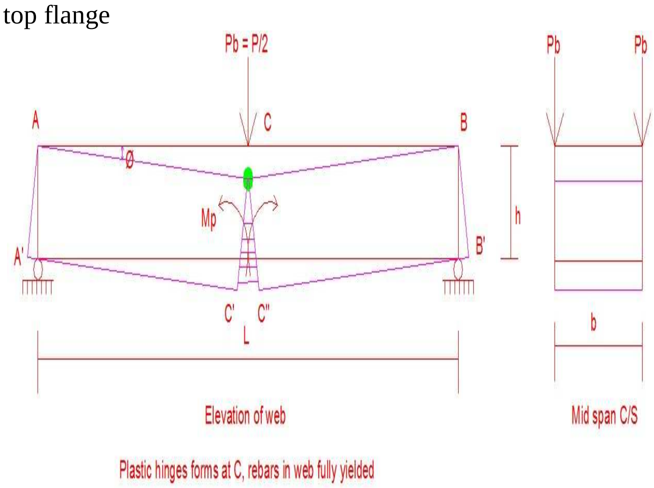

Figure: 2 Pure Bending Collapse Mechanism

Shi-Jun Zhou [7] performed Shear Lag Analysis in Prestressed Concrete Box GirdersThe shear lag effect is one of the very important mechanical characteristics of box girders. Numerous research efforts on theoretical as well as analytical method of shear lag effect in thin-walled box girders have been made for many decades, and much progress has been achieved. Most studies on shear lag effect in box girders are only concerned about concentrated loads and uniformly distributed loads. In this paper, a finite-element method based on the variational principle is presented to analyze the effect of prestressing on shear lag in box girders. The procedures and main steps are listed to demonstrate how to use the proposed FEM, which is verified by the analytical method and numerical examples. The shear lag effect in box girders with different type of support conditions under prestressing is analyzed in detail. The shear lag effect in box girders under prestressing is more apparent than that under uniformly distributed loads or vertical concentrated loads. The values and distribution of shear lag coefficients are related to the anchorage locations of prestressing and the distribution of internal forces along the girder under the combined uniformly distributed load and prestressing. Among the conclusions of the study is that negative shear lag under the uniformly distributed load and prestressing may occur both at the mid span of a simply supported box girder and at the fixed end of a cantilever box girder.

Robert K. Dowell & Timothy P. Johnson[8] 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 [9] 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

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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, $\frac{L}{R}$, 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 $L^2/BR \leq 0.5$, 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 > 90m. 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. [10] 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.

Alok Bhowmick [11] presented Detailing Provisions of IRC: 112-2011 Compared with Previous Codes (IRC: 21 & IRC: 18) Part-2: Detailing Requirement for Structural Member & Ductile Detailing for Seismic Resistance (Section 16 & 17 of IRC: 112). The unified concrete code (IRC: 112) published by the Indian Road Congress (IRC) in November 2011 combining the code for reinforced concrete and prestressed concrete structures. The new unified concrete code (IRC: 112) represents a significant difference from the previous Indian practice followed through IRC: 21 & IRC: 18. The code is less prescriptive and offer greater choice of design and detailing methods with scientific reasoning. This new generation code, when used with full understanding, will bring benefits to all sectors of our society as it will eventually lead to safer construction make a tangible contribution towards a sustainable society. The present situation in the industry is that most of the consulting officers are struggling to understand this code, which is not so user friendly. Since the designer is hard to pressed for time, majority of the consultants are unfortunately spending their valuable time only in fulfilling the prescribed rules of the code, acting as a technical lawyer, with very little understanding of the subject.

The new code covers detailing in much greater detail than the previous codes. There are three sections dedicated to detailing in the new code (i.e. Section 15, 16 & 17). General rules on detailing are covered in section 15. In addition section covers specific detailing rules for beams, columns, walls, brackets, corbels and zones below bearing etc. Section 17 covers ductile detailing from seismic consideration. The objective of this paper is to provide an explanation to various clauses of section 16 & 17 of IRC: 112 and to provide a comparative analysis with the previous codes. This paper is sequel to part-1 published in the IRC journal which covered section 15 of the code.

Khaled M. Sennah & John B. Kennedy [12] 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.

T. Vishwanathan [13] explained the section 8 of IRC: 112 ultimate limit states of linear elements for bending covering flexural analysis of beams. It covers the basic principles, different stress block and also design of rectangular beams, T-beams and doubly reinforced beams. Uses of horizontal branch and sloping branch of stress strain diagrams for steel also have been explained. An example of designing beams as well as checking of beams has been covered in great detail. The code describes three types of stress blocks for calculating the ultimate moment of resistance which as shown in below figure.

The value of εcu_3,εcu_2, εc_3, εc_2 can be obtained from table 6.5 of IRC: 112 and the value of λ and η can be obtained from clause 2.9 of annexure A2. Designer can use any of the stress blocks, but the most common are, the parabolic stress block and rectangular stress block. The design value of concrete compressive strength fcd = $\frac{0.67\,fck}{\gamma m} = \frac{0.67\,fck}{1.5} = 0.446$ fck. For accidental combination $\gamma m = 1.2$

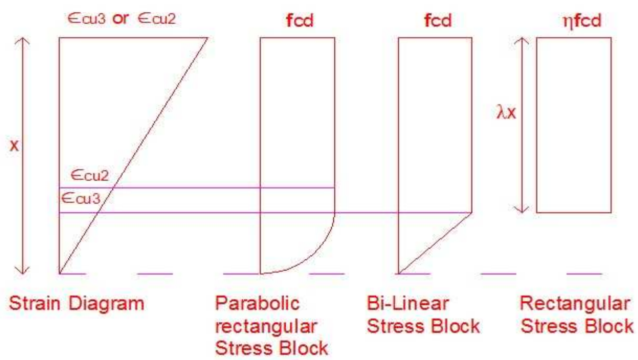

Figure: 3 Stress Blocks

The parabolic-rectangular stress block will be converted in to equivalent rectangular stress block having uniform compressive stress spread up to neutral axis giving the same total compressive force. The CG of the diagram will be maintained same as that of the parabolic rectangular stress block. For the design it will become very easy to handle the rectangular stress block. When the parabolic-rectangular stress block is converted in to equivalent rectangular stress block, obviously the average stress far will work out to be lesser than fcd. As a first step we need to work-out the equivalent stress factor for arriving at fav for various grades of concrete from fcd value as shown in figure.

The rectangular stress block which is comparatively easier stress block can also be converted in to average stress block diagram concept. The CG of the equivalent stress block shall be kept at the same distance of the original stress block in order to have the moment capacity unaltered. λ And η are defined in equation A2-33, 34, 35, and 36 of appendix A2 of IRC: 112. As the stress block is spread over large depth, compared to the actual stress block, in order to have same force, the outer fiber stress has to be reduced to arrive to fav, when compared with ηfcd.

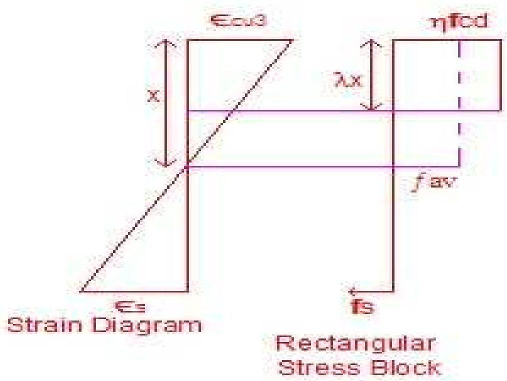

Figure: 4 Stress Strain Diagram for Rectangular Stress Block

In Hwan Yang [14] proposed a method of uncertainty analysis and sensitivity analysis of the effects of creep and shrinkage in prestressed concrete (PSC) box girder bridges. Also, a method to reduce the uncertainty of long term prediction of time dependent effect due to creep and shrinkage of concrete is developed. The study deals with the uncertainties in the long term prediction of creep and shrinkage effects using sampling method. Partial rank correlation coefficient and standardized rank regression coefficient computed on the ranks of the observations are examined to quantify the sensitivity of the outputs to each of the input variables. Updating of long term prediction is achieved using Bayesian statistical inference. The proposed theory is applied to long term prediction of prestress force of an actual PSC box girder bridges. The numerical results indicate that the creep model uncertainty factor and relative humidity appear to be the most dominant factors with regard to the model output uncertainty. The present study indicates that the width of mean ± two standard deviation for prior prediction of prestress forces. Therefore, the adoption of an approach developed in this study would reduce the uncertainties of prediction of time-dependent effects due to creep and improve greatly the long-term serviceability of PSC box girder bridges. to the other two types, while the other two types show almost the same stiffness. The amount of ultimate resistance for chevron bracing is around 50% higher than the X bracing. This means that using the same value for response modification factor of all types of concentric bracing does not seem appropriate, and the design codes needs some revision in this regard.

III. Conclusion

[1] The literature deals with: - (1) elastic analysis and (2) experimental studies on the elastic response of box girder bridges. In elastic analysis the author represents the orthotropic plate theory method, grillage analogy method, folded plate method, finite element method, thin-walled curved beam theory etc.[1]

[2] Transverse flexure, Moment due to self weight, uniform load & load over webs have a uniform distribution in longitudinal direction, and this distribution is completely independent of the span length..[2]

[3] Reinforcement & Prestressing to be proportioned for transverse flexure, Stirrups to be propositioned for longitudinal shear & tortional..[2]

[4] As the curvature effect cannot be ignored, the webs of the bridges have to betreated as thin shells and the flanges as flat curved plates..[3]

[5] Vertical displacements continued to increase with the transverse bending load application, even though the shear force was kept constant, indicating decrease of the beam stiffness. [4]

[6] Warping calculation is complicated & time consuming, its effect is very small so it can be ignored in design calculation [5]

[7] The simplified equations available at present to predict the collapse load of concrete box-girder bridges have been reviewed in this paper. The errors were found to be in the wide range −21 – +51% in comparison with the experimental result. [6]

[8] The shear lag effect in box girders under prestressing is more apparent than that under uniformly distributed loads or vertical concentrated loads. The values and distribution of shear lag coefficients are related to the anchorage locations of prestressing and the distribution of internal forces along the girder under the combined uniformly distributed load and prestressing.[7]

[9] For a single thin-walled cell subject to torsion, shear flow is constant along each of its walls while shear stresses vary around the section based upon changes in wall thickness. [8]

[10] Two sets of empirical expressions for curvature limitations were developed steel I-girder bridges & concrete I- Girder Bridges considering 5 and 10% underestimation in design, respectively. [9]

[11] 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. [10]

[12] The article gives the fundamentals, average stress concept, design and checking of rectangular, beams, use of upper branch of stress-strain diagram of steel, doubly reinforced beams and T beams. [13]

[13] The most influential factors in the long-term prediction of structural response in PSC box girder bridges and the results indicate that the creep modeling uncertainty factor and the variability of relative humidity are two most significant factors on time-dependent effects. [14]

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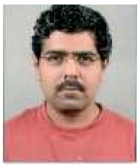

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