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Flexural response of skew-curved concrete box-girder bridges

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ABSTRACT

The flexural response of the box-girder bridges, having curvature and skewness together referred as skew-curved bridges, cannot be predicted by simply superimposing the individual effect of skewness and curvature due to the coupling of these effects. Moreover, the complexity of such thin-walled box-girder bridges increases under eccentric vehicular loads causing additional torsional and warping stresses in the box-sections. The present study focuses on predicting the flexural response of simply supported single cell skew-curved concrete box-girder bridges. In order to investigate the effect of curvature and skewness, the central curvature angle has been varied from 0° to 48° at an interval of 12° while the skew angle is swept from 0° to 50° at an interval of 10°. Three-dimensional analysis models of the bridges are created using CSiBridge and a finite element analysis has been carried out for gravity loads and Indian Road Congress (IRC) specified Class 70R tracked vehicular Live Load (LL) plying at a minimum specified clearance from the kerb. The parametric study results indicate that the flexural response of the inner girder (web) becomes more pronounced in case of skew-curved bridges. In general, it has been observed that presence of skewness in highly curved bridges significantly improves the flexural response of the bridge. Furthermore, the critical position of LL producing the absolute maximum longitudinal moment as well as the location of the critical section for moment has been found significantly affected by skewness and curvature. These critical positions have been presented in the framework of newly developed 'skew-curve' coordinate system for systematic representation.

1. Introduction

Reinforced concrete (RC) box-girders are widely used in highway bridges and flyovers due to their high torsional capacity and aesthetic considerations. Generally, concrete box-girders are constructed with thin webs and flanges in order to reduce self-weight and these sections are referred to as thin-walled or deformable sections. The structural response of the thin-walled box-girder bridge subjected to eccentric live load differs considerably from that observed for the thick-walled section, owing to its significant distortion and out-of-plane warping deformations. Due to the out-of-plane axial deformations, the usual assumption made in the elementary beam theory (plane sections remain plane after deformation) no longer remains valid. Moreover, in the box sections, enormous shear flow is transmitted from vertical webs to the horizontal flanges, which causes in-plane shear deformation in flanges and results in an unpredicted extra longitudinal displacement at the web-flange junction. Consequently, the central portion of the flange lags behind that of the web-slab junction and this phenomenon is known as the shear lag effect [1]. Thus, the overall structural response of the thin-walled box-girder bridges becomes complex since it comprises of distortion, warping, and shear lag, in addition to usual flexure (in longitudinal and transverse directions), shear and torsional actions [2]. For the simplified elastic analysis of straight box-girder bridges, longitudinal bending, transverse bending, torsion, shear, warping and distortional actions are decoupled and global response of bridge is obtained by superimposing the effect of all these actions. However, the overall structural response without decoupling these structural actions may be obtained using methods such as orthotropic plate theory, grillage method, folded plate method, finite difference method, finite strip method, and finite element method [3,4].

The geometric layout of the highway bridges and urban highway interchanges often necessitates the use of curved bridges for smooth and comfortable traffic transition. However, sometimes due to highway alignment layout and site restrictions, it becomes necessary to provide skewed supports for the curved bridges and these bridges are referred to as skew-curved bridges. In addition to overcoming these geometrical constrains, construction of skew-curved box-girder bridges is becoming increasingly popular for economic and aesthetic reasons. In skew bridges angle of skew is defined as the inclination of the centerline of traffic to the normal of the abutment(s) of the bridge. A clockwise rotation of the bridge abutment normal with respect to the traffic direction is denoted as positive skew (θ_1 and θ_2) while a counter-clockwise

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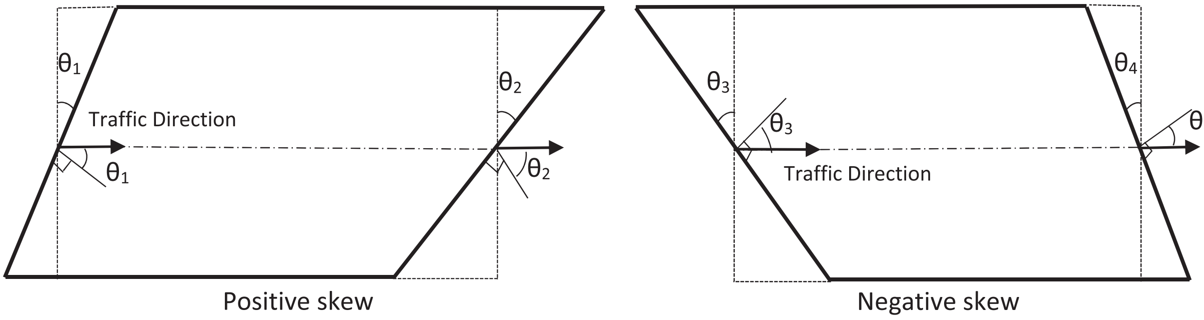

Fig. 1. Types of Skew bridge decks.

rotation represents negative skew (θ_3 and θ_4) as shown in Fig. 1.

In straight bridges, the load path (Force transfer mechanism) is found along the direction of span, while in skew bridges load tends to take the shortest path along the obtuse corners. Due to change in load transfer mechanism, higher reactions are developed at obtuse corner while lower reactions are observed at acute corners. Moreover, due to skewness in the bridges, additional torsional and transverse moments are developed, however, the longitudinal moments are reduced [5]. It is well documented in the literature that the bridges with small skew angles (< 15–20°) may be analyzed and designed similar to the straight bridges with little modifications [6–10]. Nevertheless, the structural behavior of the bridges with significant skewness substantially differs as compared to counterpart straight bridges [11,12]. On the other hand, in case of the horizontally curved bridges, significant torsional moments are developed and due to the coupling of torsional and longitudinal moments, the structural response of the curved bridges becomes more complex. To deal with such complexities, several international codal provisions have been developed. These codes also stipulate the circumstances under which a curved bridge can be analyzed as an equivalent straight bridge. Canadian Highway Bridge Design Code [13], AASHTO-LRFD Bridge Design Specifications [14], and the AASHTO Specifications for horizontally curved Bridges [15] specify that curved bridges can be treated as straight bridges with curvature angle up to 12°. In contrast, the skew-curved bridge geometry, even within individual specified safe limits of skewness and curvature (12° for curvature and 15° for skew), cannot be analyzed and designed similar to their straight counterpart due to the coupling of curvature & skewness, and needs a robust analytical technique for analysis and design.

Several analytical studies have been undertaken in past to understand the structural response of curved, skew and skew-curved box-girder bridges using different methods of analysis.

Sisodia et al. [16] studied the behavior of curved and skewed box-girder bridges using finite element method. They modeled the bridge using the elements having parallelogrammic shape, consequently, the skew-curved box geometry was poorly discretized. Chu and Pinjarkar [17] analyzed the simply supported curved box-girder bridges without intermediate diaphragms by direct stiffness element formulation. Although their solution was exact and economic but it contained limitations such as not being applicable to: arbitrary geometry, sloping deck, inclined webs and non-orthotropic material properties. Heins and Oleinik [18] developed a finite difference program for determining deformations, forces and stresses in curved single- and multi-span box-girder bridges. Their computer program was capable of allowing the inclusion of internal diaphragms in curved box-girder, however, data preparation for the program was a cumbersome process. Turkstra and Fam [19] investigated the effect of warping on longitudinal and transverse normal stresses in single-cell curved bridges using self-developed finite element program which was capable of generating element properties automatically. Zhang and Lyons [20] discovered a thin-walled box beam element with three additional degrees of freedom to incorporate warping, distortion, and shear into account for finding the accurate structural response of curved box-girder bridges in lesser computational time as compared to 3D shell elements. Use of such element was found useful for preliminary design stage of curved bridges. Li et al. [21] analyzed curved concrete box-girder bridge using finite strip method. As the analytical formulation was based upon the curvilinear coordinate system, it could handle complex layout geometries such as parabolic curve, elliptical curve, hyperbolic curve in addition to circular curved box-girder bridges. Razaqpur and Li [22] developed a grillage based curved box element capable of handling torsional warping, distortional warping and shear lag for multi-cell curved or straight box-girder bridges. They introduced rigid connector modeling for the analysis of nonlinear (curvilinear geometrical profile) box-girder intersection regions. Qiao et al. [23] studied the influence of prestressing upon shear lag factor in curved box-girder bridges using the 3D finite element modeling. In order to evaluate bridge operational consequence after earthquakes, Shirazi et al. [24] developed analytical fragility curves for single column bent curved reinforced concrete box-girder bridges using 3D nonlinear computation models generated in OPENSEES.

In order to examine the structural response of simply supported skew box-girder bridges, Brown and Ghali [25] used semi-analytical finite strip method and compared the results for four-cell box-girder with experimental data, however, they were not in good agreement. Wasti and Scordelis [26] tested large-scale models of straight, curved and skew RC box-girder bridges to compare their structural response (deflection, reactions and moments) with analytical results. The study revealed that especially for skew bridges structural response was highly dependent upon the transverse positioning of the externally applied load. Paavola [27] developed a numerical model based on Vlasov's theory [28] to analyze thin walled skew box-girder and coded a computer program in FORTRAN77. He preferred to use orthogonal coordinate system than curvilinear one to keep the formulation simple. Aravindan et al. [29] tested four syndanyo skew (0°, 15°, 30°, 45°) box-girder bridge models in the elastic range and developed a FORTRAN based finite element program to compare deflections, longitudinal stresses, and in-plane shear stresses. They provided design charts to analyze skew box-girder as a straight one, but their findings were limited to the case study undertaken. He et al. [30] presented experimental results for static and dynamic testing of skew box-girder bridge, establishing design and constructions basis for the use of skew bridges in high-speed railways. Their study revealed that due to increase in skew, vertical bending moments and deflection response decreased, however, increase in the torsional moment and differential reactional level made authors believe that skew of 45° or more is not suitable for high-speed railway construction. Han et al. [31] evaluated the seismic performance of prestressed multi-cell skew box-girder bridges via nonlinear time history analysis in SAP 2000. They found out that longitudinal displacement and rotational response of bridge increases with increasing skew angle, while transverse displacement exhibit a severe response for skew angle greater than 30°.

Although, substantial research has been carried out to understand the structural response of curved – and skewed – box-girder bridges individually, however, limited research has been carried out for skew-