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Internal Forces in Different Types of Lateral Bracing Systems for Open Steel Box Girders

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Abstract: Trapezoidal composite steel box girders are becoming increasingly popular as a bridge system due to their torsional efficiency and aesthetic appearance. These bridge systems utilize one or more trapezoidal steel girders with a cast-in-place composite concrete roadway. The critical design stage occurs during pouring of the bridge deck, when the steel superstructure must support the weight of the fresh concrete. A lateral bracing system is usually installed at the top flange level to form a quasi-closed box, thereby increasing the torsional stiffness during construction. Typical lateral bracing includes single-diagonal types (SD-W and SD-N) and a crossed-diagonal type (XD). Analytical equations were formulated in previous studies to compute the brace forces in bracing members by taking into account bending and torsional actions of tub girders with single or cross diagonal bracing systems. This paper presents a comparison between brace force values calculated by analytical methods which results from three-dimensional finite element analysis due to the bending and torsion behaviors of trapezoidal box girder systems during construction for straight and horizontally curved bridges. The results of the analytical methods have good accuracy in case of box girders with XD type lateral bracing systems. It has been observed, that there are significant discrepancies between the member forces computed from Fan & Helwig method and those obtained from FEA in case of box girders with lateral bracing including a single diagonal (SD type) bracing system (warren or pratt). On the other hand, the results of member forces computed from Kim & Chai Yoo method have good accuracy.

Key words: Ansys · Bracing systems · Finite elements · Steel bridges · Trapezoidal box girder

INTRODUCTION

Due to advances in fabrication technology, the use of steel, trapezoidal box-girders for straight and curved highway interchanges has become popular. The rapid erection, long span capability, economics and aesthetics of these girders make them more favorable than other structural systems. A typical box-girder system consists of one or more U-shaped steel girders that act compositely with a cast-in-place concrete deck. The composite action between the steel girder and concrete deck is achieved through the use of shear studs welded to the top flanges of the girders (Fig. 1). The major structural advantage of the trapezoidal box is its large torsional stiffness. A closed box has a torsional stiffness 100–1000 times greater than a comparable I-section [1]. Before hardening of the concrete deck, however, the steel box is an open U-section with very low torsional stiffness and strength. To stabilize the girders during construction and to increase the torsional stiffness prior to hardening of the deck, lateral braces are provided.

Lateral bracing systems are provided at the top flange level to increase the torsional stiffness and internal cross frames are used to control distortion of the box cross section due to applied torques. The open box girder with the lateral bracing at top flange level is often referred to as a quasi-closed box girder. Although fragmented research results are available in previous studies, a comprehensive design guide is not in existence for addressing the strength requirement for bracing members [2]. Examination of current design specifications and codes throughout the world reveals that there are little or no guidelines available for the design of top lateral bracing systems and internal t ransverse bracing in the box [3]. Trapezoidal box girders

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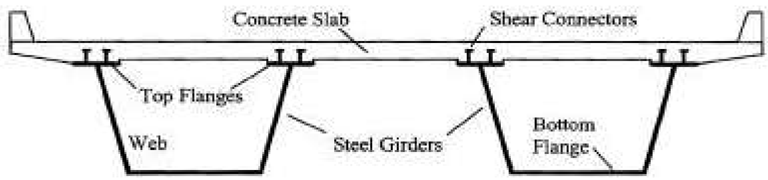

Fig. 1: Cross section of box girder bridge.

are ideal structural shapes in curved bridge applications due to the large torsional stiffness. However, while the hardened concrete creates a closed box in the finished bridge, during transport and erection the steel girder is an open section that is relatively flexible in torsion. To improve the torsional behavior during construction, a top flange lateral truss is incorporated. The stability bracing requirements for box girders have been discussed by Chen *et al*. [4].

The geometry of the top flange lateral truss system plays an important role in the behavior of the truss. There are a variety of truss systems that might be employed, Warren truss (SD-W); Pratt truss (SD-N) and X-type truss (XD) as shown in Fig. 2. The design procedures for these systems will be the most comprehensive. The primary function of the top flange lateral truss is to increase the torsional stiffness of the girders; the trusses can also develop significant forces due to vertical bending of the box girders. A difficult aspect in the analysis of horizontally curved box girders is the combination of bending and torsion under general applied loads [5].

Fan and Helwig [6] believed to be the first to make a significant distribution to the understanding of the mechanisms involved in lateral bracing systems. They successfully presented an analytical method that can be used to estimate the brace forces in both (SD-W) and (XD) lateral bracing systems of box girder subjected to vertical and/ or applied torque. According to the equations given by Fan and Helwig [6], strut forces are assumed to be induced only by the bending of the box girder and its lateral force components due to the inclined webs, regardless of whether it is (SD-W)- type or XD- type lateral bracing system. It is reasonable to assume that strut forces are induced only by the bending of the box girder and its lateral force components in all XD-type lateral bracing systems, but in the case of SD type lateral bracing system, a considerable portion of the strut force developed is induced by the torsional moment. In addition to the torsional effect, brace forces in a (SD-W) -type system subjected to vertical bending can be more exactly evaluated by considering a logical redistribution of lateral force components. Kim and Yoo [7] developed new analytical equations to compute brace forces in (SD-W)-types. They tacked the effect of torsion and the distortion in the calculation of internal forces for struts and diagonals.

Background: For a quasi-closed box girder, the torsional analysis can be performed using the equivalent plate method (EPM) in which the truss system is transformed into a fictitious plate with a uniform thickness. Kollbrunner and Basler [1] developed equations for the equivalent thickness of several types of bracing systems by evaluating strain energy stored in the system. Dabrowski [8] presented similar equations for X-shaped and K-shaped bracing systems to determine the fictitious plate thickness based on the consistent deformation theory. The quasi-closed box theory or EPM allows the torsional properties of the box girder to be approximated. The value of the equivalent plate thickness is dependent on the bracing configuration and cross-sectional areas of bracing members. The resulting shear flow in a closed section, q, is equal to T/ (2A0) where T and A0 are the torsional moment and the enclosed area of the box. The shear flow acting on the fictitious plate is then transformed to axial forces in diagonal members only in the lateral bracing system as:

$$D_{tor,SD} = \pm\frac{qb}{\sin\alpha} = \pm\frac{b}{2A_0\sin\alpha}T \quad (1)$$

$$D_{tor,XD} = \pm\frac{qb}{2\sin\alpha} = \pm\frac{b}{4A_0\sin\alpha}T \quad (2)$$

where $D_{tor,SD-W}$, $D_{tor,XD}$ = forces in W and X truss type diagonals due to applied torque, respectively; b = distance between the centers of top flanges; T = applied torque and α = angle between the diagonal and the top flange.

According to EPM it was assumed that the applied torque is resisted totally by diagonal members only; i.e. no effect of torsion in strut members [$D_{tor,XD}$, = $D_{tor,SD-W}$ = 0] as shown in Fig. 3.

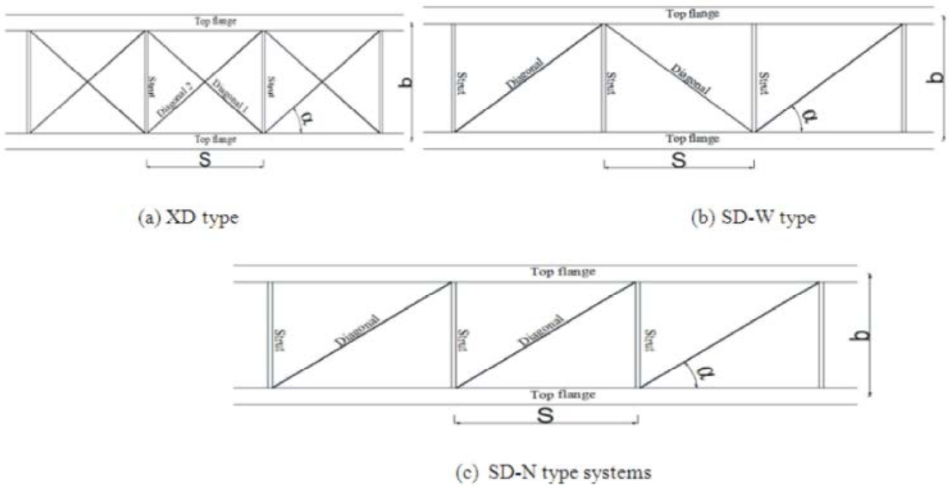

Fig. 2: Lateral bracing.

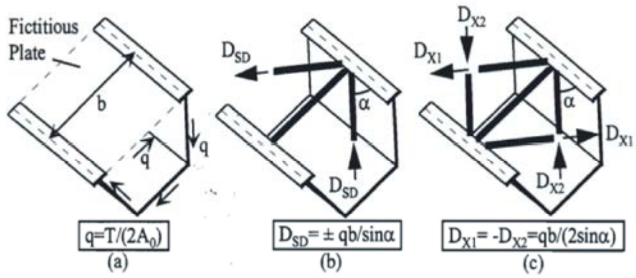

Fig. 3: Diagonal Brace forces due to torsion according to EPM

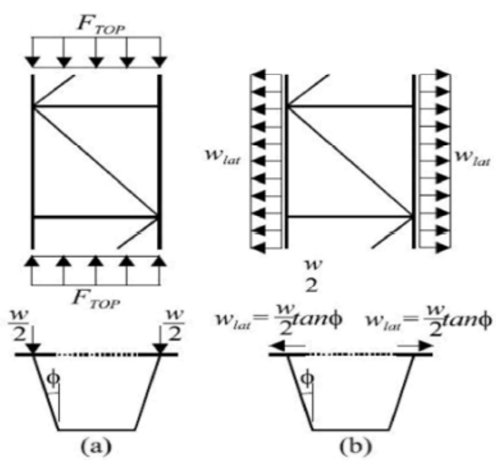

Fig. 4: Forces affecting bracing members: (a) Longitudinal deformation; (b) Lateral force components due to inclined webs.

Fan and Helwig [6] used EPM in the calculation of brace forces due to torsion which are limited by its assumptions. The diagonals in the lateral bracing systems are subjected to the same total longitudinal deformation as the top flanges as shown in Fig 4-a. In addition, the lateral force component resulting from the sloping webs also affects member forces in the lateral bracing system. The magnitude of lateral force component is evaluated from the equivalent moment induced by the applied load on the top flange as shown in Fig 4-b. Fan and Helwig [6] considered the effects of lateral forces were carried by the struts only; i.e. no brace forces in diagonal members due to lateral forces:

$$S_{lat} = W_{lat} \times S \quad (3)$$

$$D_{lat} = 0 \quad (4)$$

where S = Spacing between struts;
W_{lat} = Lateral load component.

$$= \frac{W}{2} \tan\phi$$

Fan and Helwig [6] developed the following equations to calculate the braces forces in diagonals and struts due to effect of vertical bending for XD and SD trusses systems:

For XD Truss:

$$D_{bend} = \frac{F_{xTop} \times S}{K_2} \times \cos\alpha \quad (5)$$

$$K_2 = \frac{l_d}{A_d} + \frac{2b \times \sin^2\alpha}{A_s} \quad (6)$$

$$S_{bend} = -2D_{bend} \times \sin\alpha \quad (7)$$

For SD Truss:

$$D_{bend} = \frac{F_{xTop} \times S}{K_1} \times \cos\alpha \quad (8)$$

$$K_1 = \frac{l_d}{A_d} + \frac{b \times \sin^2\alpha}{A_s} + \frac{S^3}{2b_f^3 t_f} \sin^2\alpha \quad (9)$$

$$S_{bend} = -D_{bend} \times \sin\alpha \quad (10)$$

Fan and Helwig [6] developed equations to predict the total brace forces in SD-W types and XD types and proposed the following expressions for design purposes:

$$S_{total} = S_{bend} + S_{lat} \quad (11)$$

$$D_{total} = D_{bend} + D_{tor} + D_{lat} \quad (12)$$

where S_{total} and D_{total} = total force in the strut and diagonal, respectively; S_{bend} and D_{bend} = force in the strut and diagonal due to bending of box girder, respectively; S_{lat} = force in the strut due to lateral force components; D_{tor} = diagonal force from the torsional moment determined using the EPM suggested by Equations (1) and (2).

Fan and Helwig [6] didn't consider the effect of distortional components in the calculation of brace forces for truss elements. This is acceptable in case of XD type while in the case of SD truss where there are distortional components found due to the unsymmetrical shape of SD-W truss about the rotation axis due to applied torque.

Kim and Yoo [7] developed other analytical equations to predict brace forces in SD-W types and tacked into consideration the effect of distortion due to the applied torque in the brace forces and proposed the following expressions for design purposes:

$$S_{total} = S_{bend} + S_{lat} + S_{tor} + S_{dist} \quad (13)$$

$$D_{total} = D_{bend} + D_{tor} + D_{lat} + D_{dist} \quad (14)$$

where: D_{dist}, S_{dist} = forces due to distortion in the strut and diagonal, respectively and other symbols defined as mentioned before by Kim and Yoo [7].

Objectives: The objectives of this research are enumerated as follows:

- To conduct a comprehensive literature search pertinent to research carried out on steel box girders.
- To check of accuracy of the analytical equations developed for estimating member forces induced in lateral bracing systems due to bending and torsion reflecting different types of lateral bracing systems.
- To verify the assumptions of Fan and Hewilg [6]; that the lateral deformations due to vertical bending and torsion are fully resisted by struts and diagonals, respectively.

Finite Element Modeling: Three dimensional FEA models were performed to verify the analytical equations. The finite element program, *ANSYS*, was used in the numerical analysis [9]. The top and bottom flanges and the webs of the quasi-closed box girders were built up with shell elements (*SHELL 63*), while the bracing members in the top lateral bracing and the internal *K*- frames were modeled with truss element *LINK 8*. The solid diaphragms were also modeled with *SHELL 63* elements and were placed at both supports for simply supported box girders and additionally at interior piers for continuous girders. A simple span straight girder and continuous curved girder were considered in this study as shown in Fig. 5 and 12, respectively.

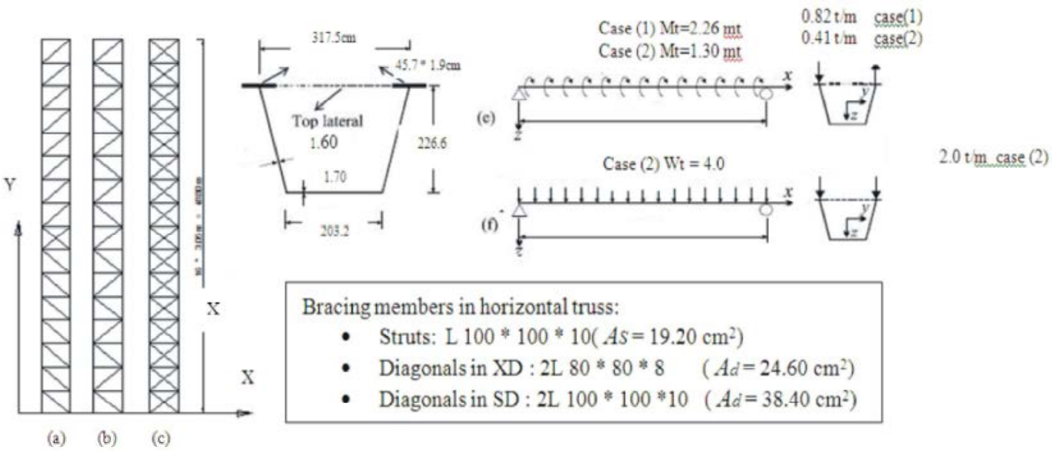

Fig. 5: Simply Supported Straight box girder and cases of loading considered in study.

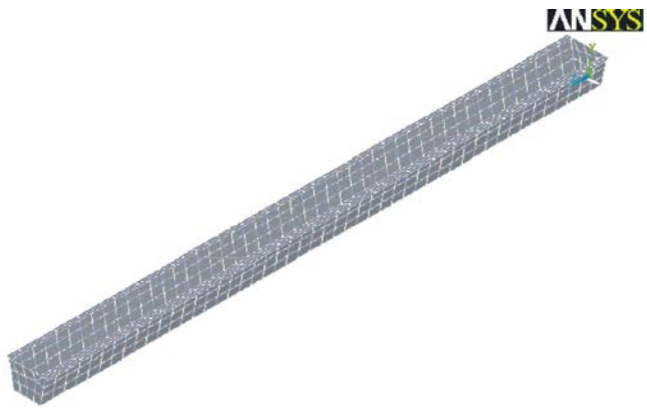

Fig. 6: 3D-FEM for Simply Supported Straight box girder with horizontal truss SD-W truss.

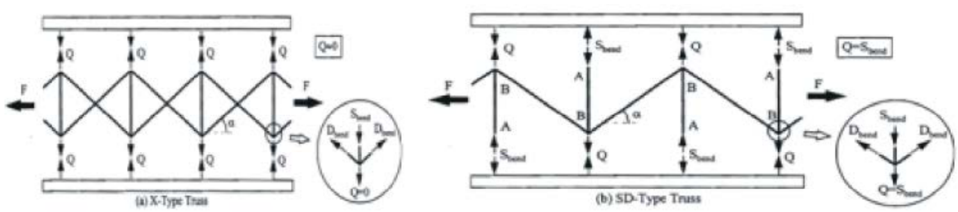

Fig. 7: Interactive forces between top flanges and horizontal truss (a) X-type truss; (b) SD-W type truss.

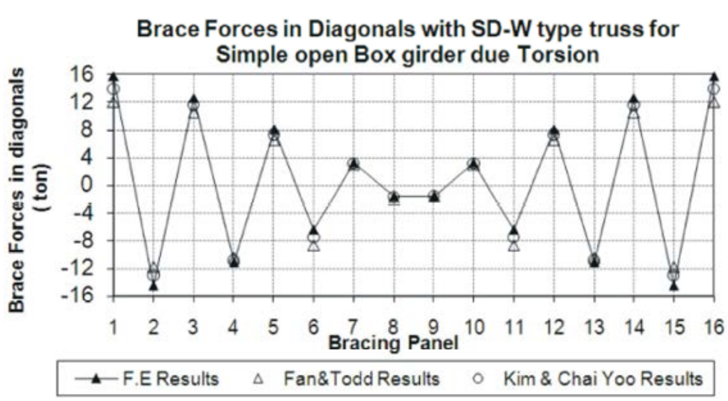

Fig. 8: Brace Forces in Diagonals with SD type truss for Simple open Box girder due Torsion.

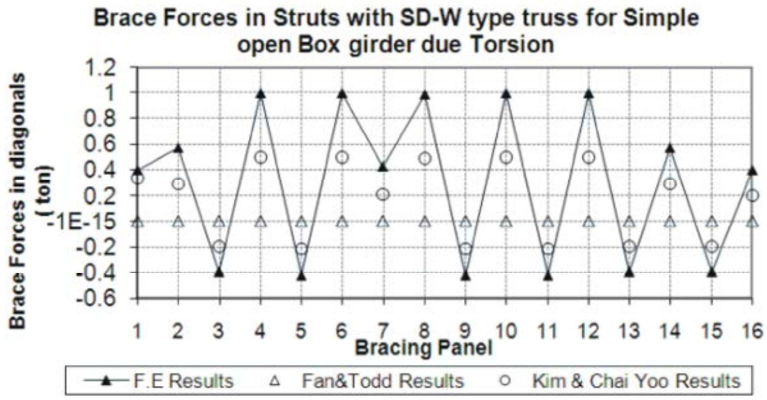

Fig. 9: Brace Forces in Struts with SD type truss for Simple open Box girder due Torsion.

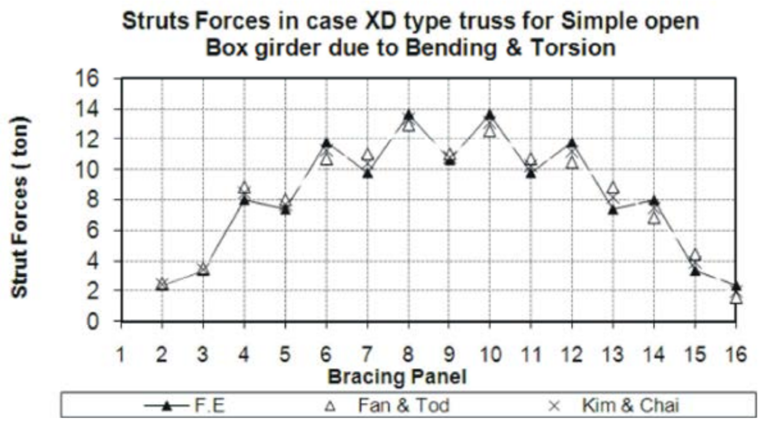

Fig. 10: Strut Forces in case XD type truss for Simple open Box girder due to Bending & Torsion.

The straight girder studied was a simple span quasi-closed box girder with span 48.8 m, subjected to distributed top flange loads by two cases of loading. Case of distributed torsion moment only (m_t= 2.26 m.t/m) and case of combined torsion moment (m_t= 1.30 m.t/m) and vertical bending moment due to (W_t= 4.00 t /m) as shown in Fig 5. The girder dimensions as well as the bracing member sizes are shown in Fig 5. Both XD, SD-W and SD-N type horizontal trusses were considered.

The internal forces in struts and diagonals for different types of bracing according to the two cases of loading were required and compared with another values calculated by the two analytical methods as shown in Figs 8 to 11. It is found that the braces forces in struts are mainly affected by the values of the bending moment in the girder, where the chart of brace forces in struts have the same shape of bending moment in case of girder loaded by case (2) as shown in Fig.10. The forces in struts have minimum values in case of girder with (SD-W or SD-N) and loaded by case (1) [distributed torsion moment only] as shown in Fig. 9. In this case according to Fan and Helwig method [6] the forces in struts are equal to zero. Thus, the values which were found from the F.E model appears that the forces in struts are affected by torsion and distortion as the assumptions of Kim and Yoo [7], but with small values. Therefore the accuracy of Kim and Yoo method [7] is higher than that of Fan & Helwig [6]; especially in case of single diagonal truss (SD-W or SD-N) as shown in Figs 8 to 11. The lateral interactive forces, Q, between the truss and the top flange must be identical at all joints due to symmetry of structure in case of X-type truss, as shown in Fig. 7a. Equilibrium of the top flange yields Q=0 and then the lateral bending stress due to vertical bending and distortion will be equal to zero. The lateral interactive forces, Q, will have values in case of SD-type truss due to asymmetry of structure, as shown in Fig. 6b. Thus, the lateral bending stress due to vertical bending and distortion will affect the internal forces of bracing members. Kim and Yoo [7] tacked the effect of distortion into consideration in the calculation of bracing forces, but Fan & Helwig neglected it. Therefore (Kim and Yoo)

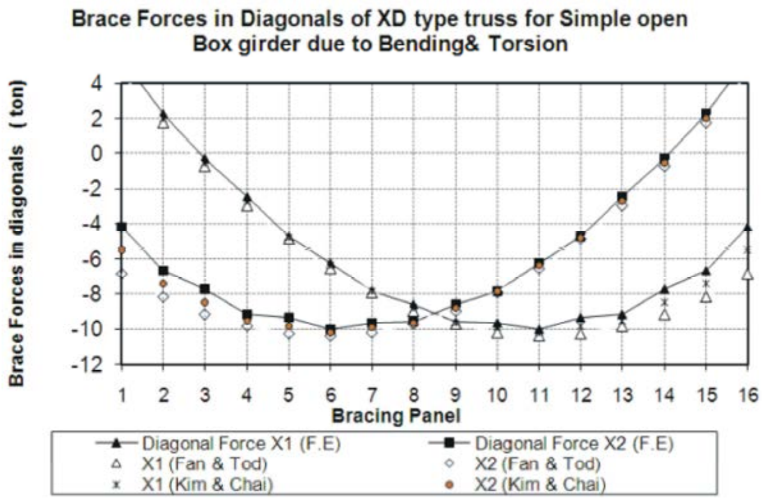

Fig. 11: Brace Forces in Diagonals of XD type truss for Simple open Box girder due to Bending& Torsion.

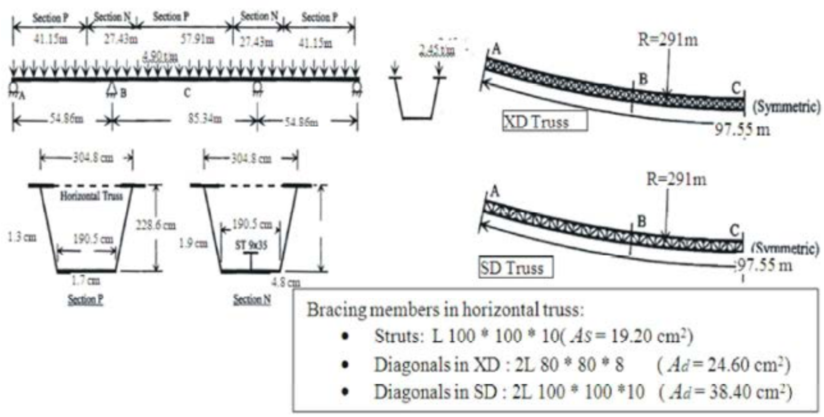

Fig. 12: Dimensions of the three span horizontally curved continuous box girder.

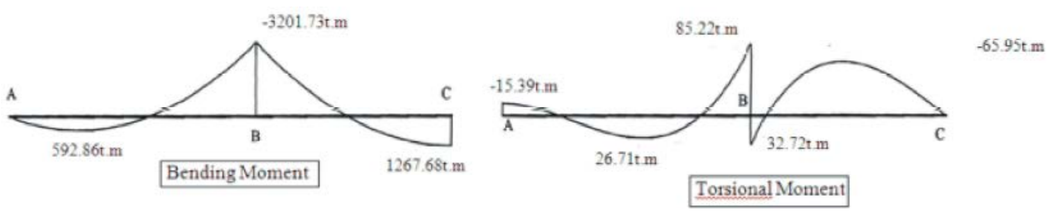

Fig. 13: Bending and Torsional moment diagram in curved continuous girder due to vertical bending loads.

method has higher accuracy in cases of unsymmetrical trusses, such as SD-W type and SD-N type than that calculated by Fan & Helwig [6] as shown in Figs 8 & 9. The forces in bracing and strut members for X-type truss as calculated by Fan & Helwig [6] have a good accuracy as that calculated by Kim and Yoo [7] compared with the finite element results as shown in Figs. 10 & 11. Here, the effect of distortion in the values of brace forces in case of XD truss can be equal zero as has been discussed before.

To verify the accuracy of the analytical methods in case of horizontal curved girders, three span horizontally curved continuous box girder are treated. The girder dimensions as well as the bracing member sizes are shown in Fig 12. Both XD, SD-W and SD-N type horizontal trusses were considered. It is subjected to distributed top flange loads by vertical loads equal to (W_t= 4.90 t /m) as shown in Fig. 12, which leads to the existence of internal straining actions such as bending moment and torsion due to the curvature as shown in Fig 13.

Fig. 14: 3D-FEM for three spans horizontally curved continuous box girder with horizontal XD type truss.

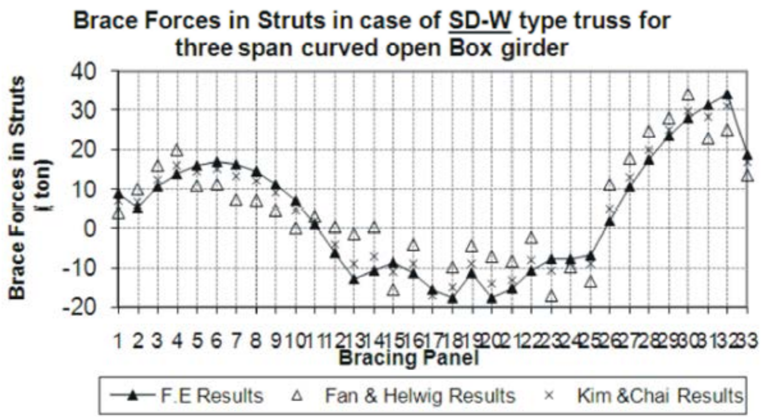

Fig. 15: Struts Forces in case of SD-W type truss for three span curved open Box girder.

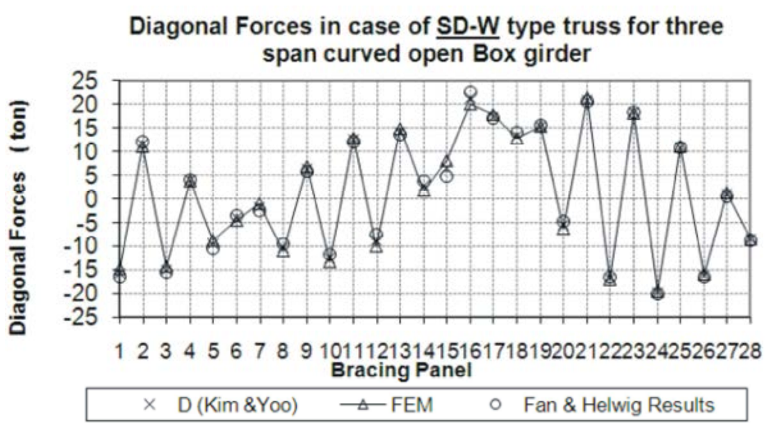

Fig. 16: Diagonals Forces in case of SD-W type truss for three span curved open Box girder.

The internal forces in struts and diagonals for different types of bracing systems were required and compared with other values calculated by the two analytical methods as shown in Figs 15 to 20. It is found that the distribution of brace forces in struts is the same as in the case of straight girders and has the same shape of the bending moment as shown in Figs 15, 17 and 19. It is shown that the accuracy of results for internal forces in struts and diagonals which were calculated by Kim and Yoo [7] analytical method are closed to the results of the finite element models. The results calculated by Fan and Helwig [6] analytical method are reasonably accurate and close to Kim and Yoo method [7] in case of XD type, but they have low accuracy in case of SD-W or SD-N types of trusses especially for truss members which located at mid of spans and at the internal supports as shown in Figs 15, 16, 17 and 18.

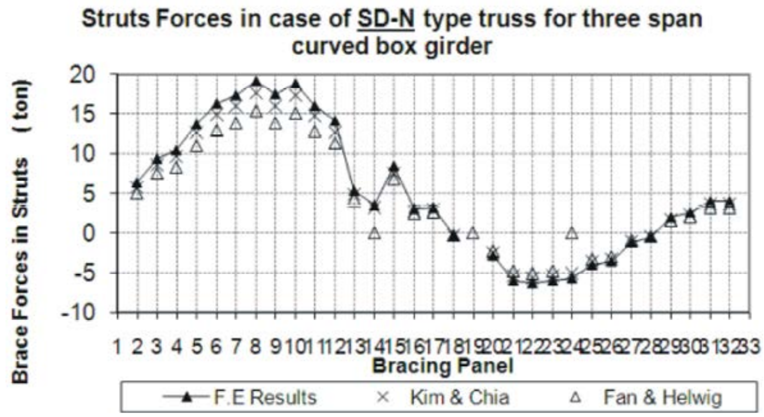

Fig. 17: Brace Forces in Struts with X- type truss for three span curved open Box girder.

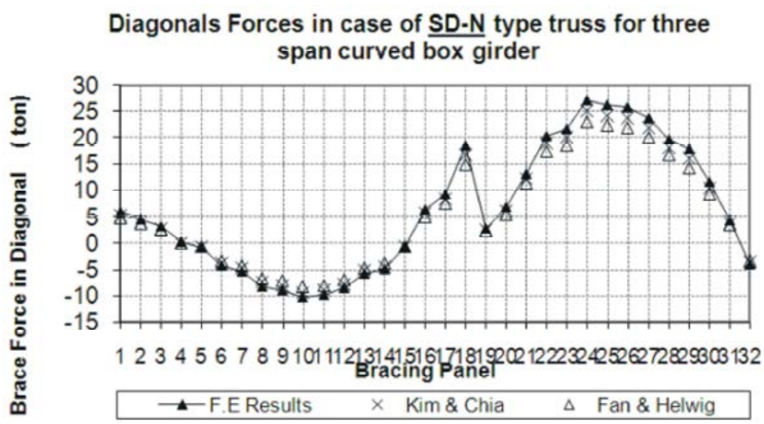

Fig. 18: Diagonal Forces in case of SD-N type truss for three span curved box girder.

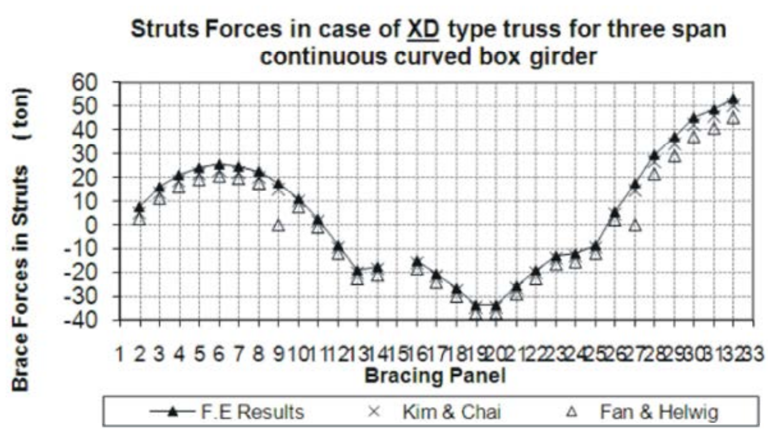

Fig. 19: Brace Forces in Struts with X- type truss for three span curved open Box girder.

To search the reasons for this difference in accuracy, all components of internal forces in struts and diagonals for truss type SD-W are calculated and drawn along the continuous curved girder as shown in Figs 21 & 22, respectively. It is shown that for struts the forces due to bending is the most influential component. They are followed in values by the forces due to torsion which is neglected in Fan and Helwig method [6]. The forces due to distortion and lateral deformations are small and absolutely constant along the girder length as shown in Fig.21. The chart of forces due to torsion is like a zigzag line, i.e. tension force in strut member and compression in

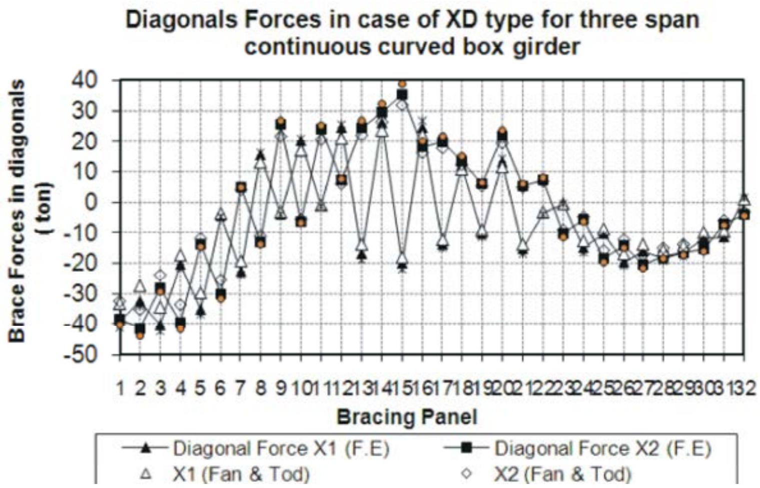

Fig. 20: Diagonal Forces in case of SD-N type truss for three span curved box girder.

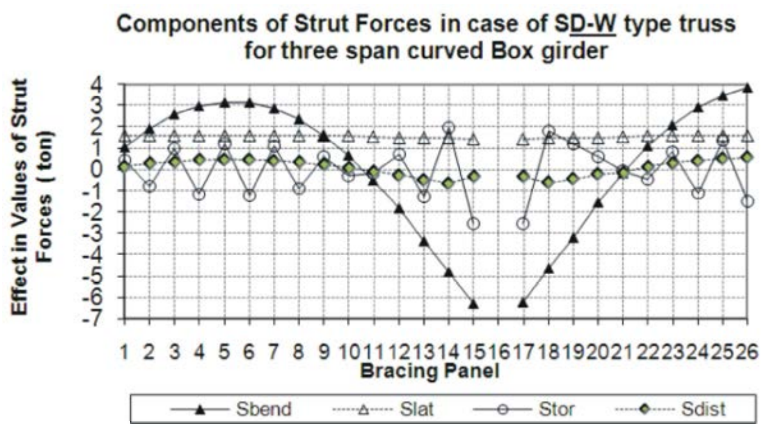

Fig. 21: Components of Strut Forces in case of SD-W type truss for three span curved box girder.

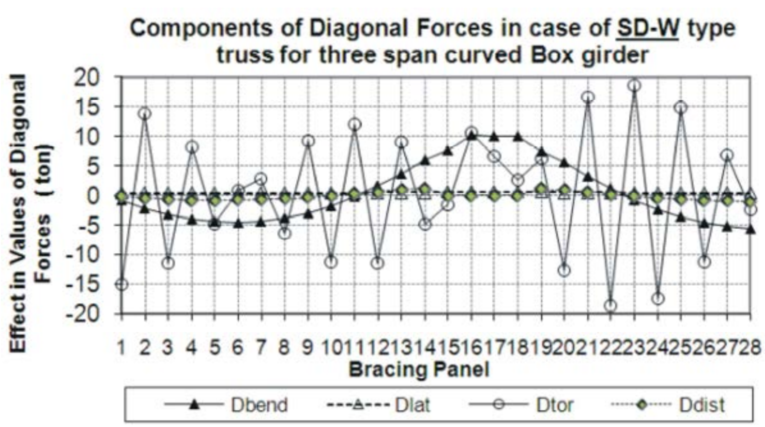

Fig. 22: Components of Diagonal Forces in case of SD-W type truss for three span curved box girder.

the other due to effect of unsymmetry of SD-W and SD-N truss about axis of torsion. Although this type of forces has high percent from the total internal forces in the struts, Fan and Helwig [6] neglected it. Therefore accuracy of Fan and Helwig method [6] is lower than Kim and Yoo method [7] in case of trusses having unsymmetrical geometry about axis of torsion such as SD trusses. The internal forces due to torsion represent the most influential component for diagonal members as shown in Fig. 22 followed by the forces due to bending. The other components due to lateral deformations and distortion have very small effect on the total values of internal forces for diagonal members.

CONCLUSION

Analytical equations from previous studies reported by Fan & Helwig [6] and Kim & Yoo [7] estimate the brace forces for box girders with typical lateral bracing including a single diagonal bracing system and a crossed diagonal bracing system. Member forces due to bending and torsion computed from these equations are compared with those evaluated by three-dimensional finite element analysis. Excellent correlation exists between Kim & Yoo equations [7] and the finite element analysis. The member forces computed from these equations are in good accuracy compared to those obtained from 3D-FEA in case of box girders with XD type lateral bracing systems. It has been observed, that there are significant discrepancies between the member forces computed from Fan & Helwig method [6] and those obtained from FEA in case of box girders with single diagonal (SD type) bracing system (Warren or Pratt), while the member forces computed from Kim & Yoo[7] have good agreement with those obtained from FEA. This difference in accuracy has been found high especially in some horizontally curved box girders; however, it has been found that substantial axial forces are developed in struts due to induced torsion and distortion although Fan & Helwig equations [6] do not take them into consideration. Thus, for box girders with SD type bracing, brace forces can be much better estimated with Kim & Yoo equations [7] than Fan & Helwig method [6].

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