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Parametric Study of the Intermediate External Bracing System of Composite Steel Box Girder Bridges

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Abstract

During the pouring of concrete deck, the installation of external bracing between the inner and outer girders may be necessary when the bridge has sharp curve in order to control the deflection and rotation of the girders. However, it is important to minimize the number of external bracing members, as they have expensive cost and they also have opposite effects for the fatigue features of the steel tub girders. The analysis of curved box girder bridges is carried out numerically by the use of finite element method through (ANSYS 19.2) software. The curved box girder with the intermediate external diaphragms was modeled and the analysis was carried out for many parameters like external bracing sections, girders with or without concrete deck, girders with end diaphragms or without them. The study concluded that ANSYS program has a good ability in evaluating the external bracing force comparing with code equations.

Keywords: External bracing, Curved box girder, Fatigue features, Finite element method, Ansys software.

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1. Introduction

The purpose of using external bracing is to prevent the relative deformation between girders during the pouring of concrete deck. In most cases, external bracing members can be removed after the concrete deck stiffens because field tests have shown that the external bracing has little effect on distribution of live load, the cross frames elements are usually removed due to fatigue concerns, but when they are not taken away after construction, they will help on load transferring between the girders.

Figure 1 shows a twin girder system, the outer girder (E) will be free to twist during construction if the external bracing is not found to connect the two girders. The exterior girder (E) having the larger deflection and twist angle in comparison with the inner girder (I). Because of the girder flexibility, then a relative vertical displacement Δ_{rel} will be found between point B and point C in (c) that leads to a variation in the thickness of deck and steel reinforcement cover. In order to control the displacement Δ_{rel} stiffer girders must be used, but they are very expensive, also when they are too stiff then there will be a problem with bolted field splices during erection the external bracing shown in Fig. 1 (b) can be used to increase the constructability [1]. The force of intermediate bracing members will be smaller by using more bracing elements. Usually, the axial forces in external bracing from the construction loading are small except for girders with very sharp curve (R < 76 m).

In the case of horizontally curved girders the external bracing must be added but straight girders don't need this type of bracing when end diaphragms and lateral bracing are used.

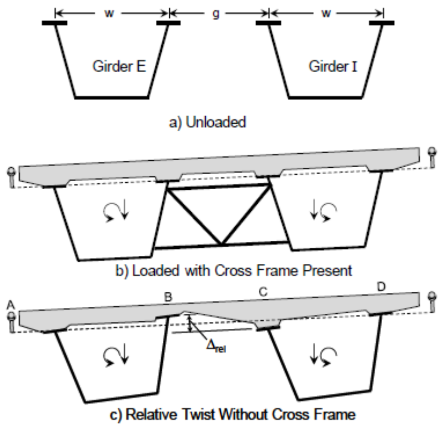


Fig. 1 Relative deformation between adjacent girders [1].

The approximate method outlined was used for determining the number of needed intermediate cross-frames. The equation for calculating spacing depends on the following assumptions: for a simply supported curved bridge with twin girder symmetrical system, there is no relative twist between the bridge supports and same cross-section properties for both girders. Since the two girders have the same cross-sectional properties, the vertical displacement (Δ_{rel}) is a function of the spacing between the girders, (w + g), and the angle (β_o = L/R) of the bridge, the relationship of the spacing between the external bracing and Δ_{rel} is

$$L_{max} = \frac{1.2\,\Delta_{rel}}{\frac{5\,w\,\beta_0\,(w+g)}{384\,EI}\left(\frac{EI}{GJ}-3\right)} \quad (1)$$

If L_{max} is larger than the length of the bridge, no external bracing will be needed for bridge constructability [1].

Many studies have been dealt with the using of external bracing in box Girder Bridge.

Cheplak in 2001, carried out a field measurement of intermediate external diaphragms. In this study bridge with trapezoidal section and three spans built in Austin, Texas was used, the axial force of lateral members and three external bracing members were summarized, also the stresses were checked [2]. Memberg in 2002, carried out a design approach developed for external frame for curved bridges with trapezoidal girders from a study of torsion on the steel girders and their effect on bridge systems. The design approach was checked by examining results with Austin, Texas Highway Bridge. Strain gauges were applied on two external bracing during the pouring of concrete deck also the live load was examined after the concrete hardening [3]. AASHTO LRFD (Bridge Design Specifications, (2005) [4] recommends in section (6.7.4) that bridges with two or more boxes, external diaphragms may be used between the boxes. The need for external diaphragms should be evaluated through consideration of torsional stability. At locations of external diaphragms, there shall be bracing inside the boxes at those locations to receive the forces from the external bracing.

2. Axial force in external bracing

The external force is induced by the tendency for the girders to independently displace and rotate as shown in Fig. 1 (c). In order to estimate these forces, Helwig et al. in 2007 found equations based on the assumption that the external members experience forces proportional to the independent girder rotations and the relative vertical displacements that occur at their positions if the cross-frames were not present.

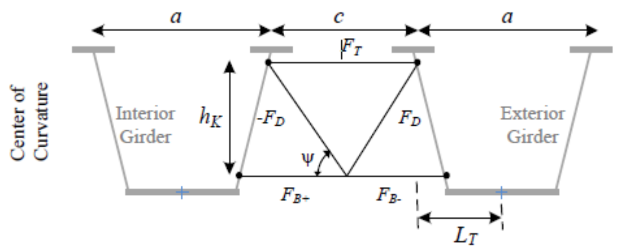


Fig. 2 External intermediate cross-frame forces.

The forces on the external cross-frame diagonals, F_D, and top and bottom chords, F_T and F_B, are expressed as Helwig et al., 2007:

$$F_D = 4\,GJ\,\frac{(L_i\,\varnothing_{w,\,ext} + L_e\,\varnothing_{w,int} - K_{e1}\,\Delta_{w,\,rel}}{K_{e2}} \tag{2}$$

$$F_D = \frac{4\,GJ\,(\varnothing_{w,\,ext} - \varnothing_{w,\,int}) - F_D\,L_K\,(L_e - L_i)}{h_K\,(L_i - L_e)} \tag{3}$$

$$F_B = \pm\,F_D\cos\psi - F_T \tag{4}$$

Where the variables in these equations are

$$L_K = \pm\,h_K\cos\psi + L_T\sin\psi \tag{5}$$

$$K_{e0} = 1 + (1 + \frac{EI}{GJ})\,(1 - \cos\frac{\beta_0}{2}) \tag{6}$$

$$K_{e1} = \frac{L_i + L_e}{a + c} \tag{7}$$

$$K_{e2} = K_{e0}\,K_{e1}\,\frac{L_i^3 + L_e^3}{12\,(EI/GJ)}\,\sin\psi + 2\,L_i\,L_e\,L_K \tag{8}$$

$$\Delta_{w,\,rel} = K_{e0}\,\frac{5\,w}{384\,EI}\left(L_e^4 - L_i^4\right) \tag{9}$$

$$\varnothing_{w,\,int} = \frac{5\,w\,L_i^4}{384\,EI\,R_{int}}\left(1 + \frac{EI}{GJ}\right) \tag{10}$$

$$\varnothing_{w,\,int} = \frac{5\,w\,L_e^4}{384\,EI\,R_{ext}}\left(1 + \frac{EI}{GJ}\right) \tag{11}$$

Where,
c : is the tub spacing along the girder length.
Ψ : is the external cross-frame diagonal angle.
h_K : is the top to bottom chord distance.
L_T : is the external cross-frame top chord distance to girder centerline.
β_0 : is the span subtended angle.

Figure 3 illustrates the internal and external girder centerline lengths, L_i and L_e. Fig. 4 shows the relative vertical displacement between girders at the external cross-frame location, $\Delta_{w,rel}$ and the internal and external girder twist rotations, $\varnothing_{w,ext}$ and $\varnothing_{w,int}$ [5].

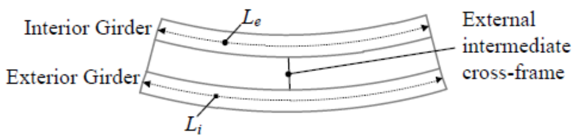


Fig. 3 Girder lengths for the external intermediate cross-frame component force equations.

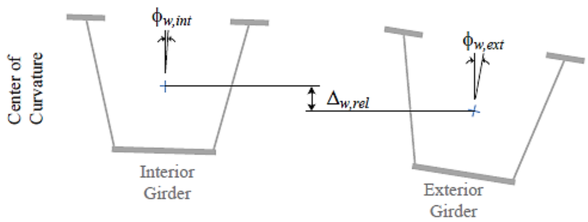


Fig. 4 Girder twist rotations and relative vertical displacement for the external intermediate cross-frame component force equations [5].

3. Finite Element Modelling

A three-dimensional finite element (ANSYS 19.2) program, was used for the analyses of composite box girder. The box girders and diaphragms were built up with three-dimensional SHELL181 element with four-node with six degrees of freedom at each one. The concrete deck modeled with solid 65, link 180 used for modelling the steel reinforcement, all bracing system were modeled by using (beam188) with two-node and six degree of freedom at each one. Internal K-frames were placed at every strut location. When using K-frames type in internal bracing then the lateral bracing struts also act as top transverse elements of the internal diaphragms. The boundary conditions at one of the middle bearings are restrained in all x, y and z directions, and while at the end's bearings are restrained against y and z directions only. The material properties are shown in Table 1.

Table 1 Materials specification that utilized in F. E. analysis.

Properties of Steel girders			
Modulus of Elasticity, *E* (MPa)	200000		
Poisons Ratio, ν	0.3		
Yield Stress, fy (MPa)	420		
Tangent Modulus, (MPa)	2000		
Density, (kg/mm^3)	7.85 e-6		
Properties of Concrete			
Modulus of Elasticity, (MPa)	27806	Stress	Strain
Poisons Ratio, ν	0.2	10.5	0.0003776
Compressive Strength, fc'	35	15.787	0.0006
Density, (kg/mm^3)	2.4 e-6	28.538	0.0013
Thickness of concrete cover	25	33.659	0.0019
		35	0.0025175
Properties of Steel Reinforcement			
Modulus of Elasticity, (MPa)	200000	Diameter, D (mm)	
Poisons Ratio, ν	0.3	Top reinforcement	16, 20, 25
Yield Stress, fy (MPa)	420 (grad 60)	Bottom reinforcement	12, 16, 20, 25
Tangent Modulus, (MPa)	2000	Straps	16
Density, (kg/mm^3)	7.85 e-6	Curb reinforcement	12
		Curb Straps	16

4. Case study

The bridge for this case study is located in Basrah city. A continuous bridge with two spans and two steel trapezoidal girders, each span having (40 m) length and (150 m) radius of curvature at the centerline of the cross-section. The concrete deck of this bridge has a width of (9500 mm) and (250 mm) thickness, all details are shown in Fig. 5. This bridge modeled by using FEM and compared its result with the numerical results.

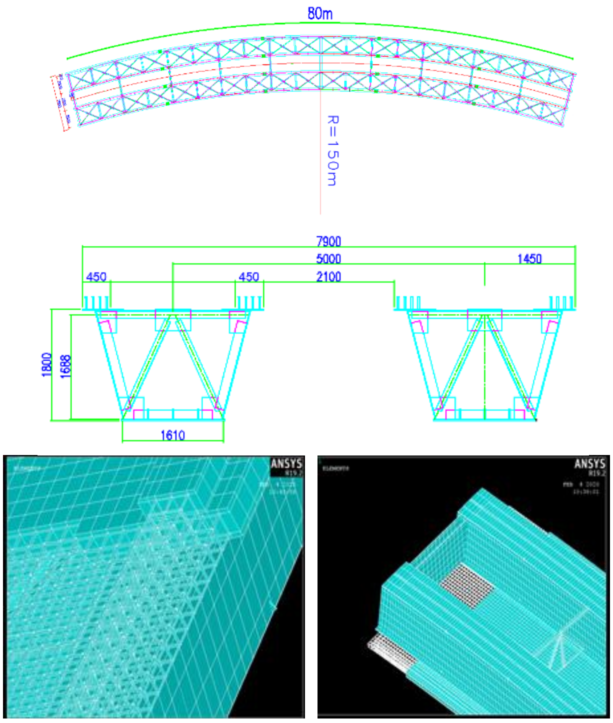


Fig. 5 Details and finite element model for Basrah Bridge.

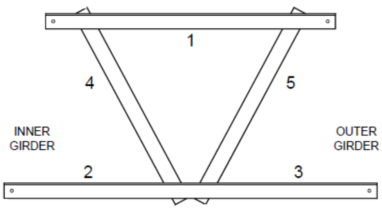


Fig. 6 External bracing.

Table 2 External bracing force without end diaphragms (kN).

Span (m)	1(FT)		2(FB$^-$)		3(FB$^+$)		4(FD$^-$)		5(FD$^+$)	
	Eq.	FEM	Eq.	FEM	Eq.	FEM	Eq.	FEM	Eq.	FEM
8	12.95	12.64	- 48	- 36	22.25	20.7	- 51	- 48.5	51	50.24
16	19.44	21.66	- 75.6	- 67	36.56	25.1	- 81.9	- 79.1	81.9	80.87
24	19.44	21.58	- 75.6	- 68	36.4	25.84	- 81.9	- 80.3	81.9	81.29
32	12.95	12.45	- 48	- 37	22.25	21.75	- 51	- 50.2	51	49.77
Sym.										

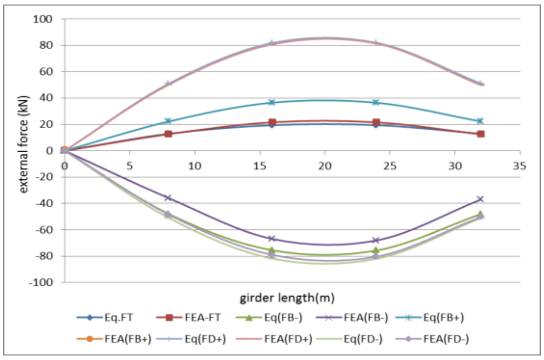
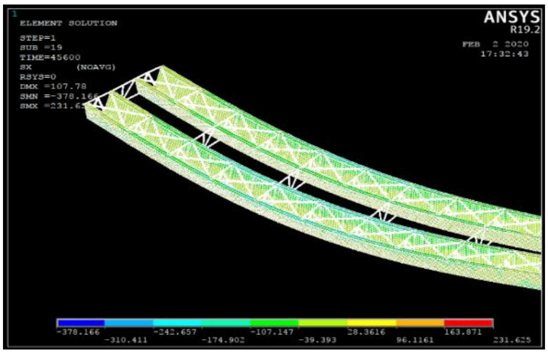
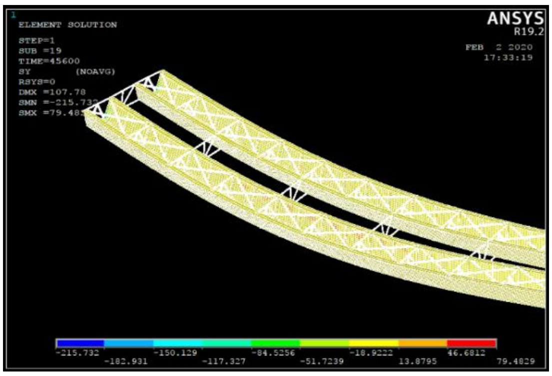


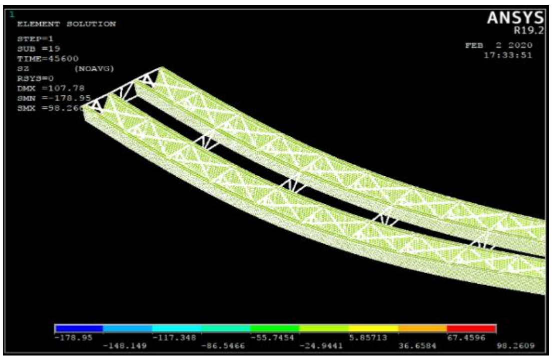
Fig. 7 Comparison between equations and FEM results of external bracing force of bridge without end diaphragms.



X-direction



Y-direction



Z-direction

Fig. 8 Stresses on bridge without end diaphragms.

Table 3 External bracing force with end diaphragms (kN).

Span (m)	1 (FT)		2 (FB⁻)		3 (FB⁺)		4 (FD⁻)		5 (FD⁺)	
	Eq.	FEM	Eq.	FEM	Eq.	FEM	Eq.	FEM	Eq.	FEM
8	12.95	15.5	- 48	- 31	22.25	22.97	- 51	- 47	51	47.69
16	19.44	21.22	- 75.6	- 66	36.56	26.01	- 81.9	- 79	81.9	80.2
24	19.44	21.13	- 75.6	- 67	36.4	26.81	- 81.9	- 80	81.9	81.4
32	12.95	15.86	- 48	- 31	22.25	17.55	- 51	- 41	51	41.5
Sym.										

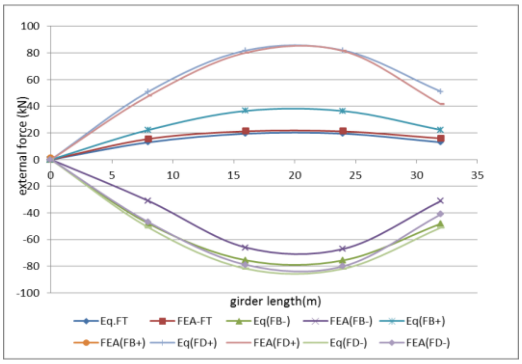
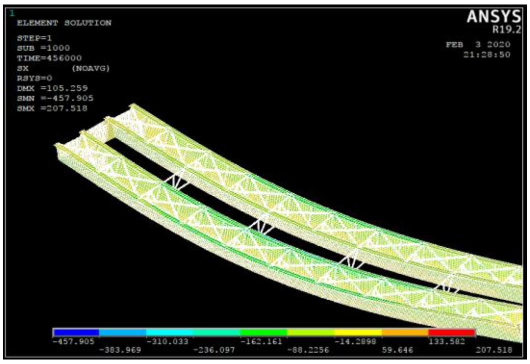
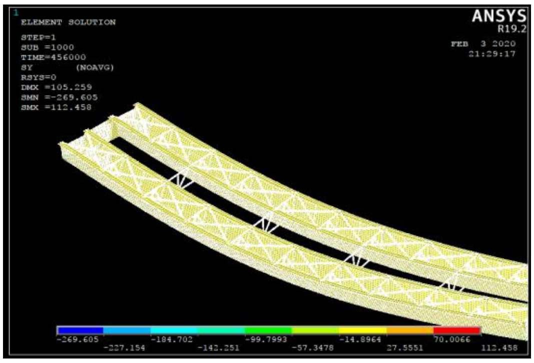


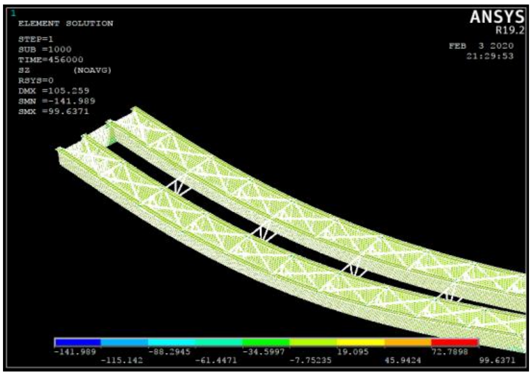
Fig. 9 Comparison between equations and FEM results of external bracing force of bridge with end diaphragms.



X-direction



Y-direction



Z-direction

Fig. 10 Normal stresses on bridge with end diaphragms.

Table 4 External bracing force with concrete deck (kN).

Span (m)	1 (FT)		2 (FB⁻)		3 (FB⁺)		4 (FD⁻)		5 (FD⁺)	
	Eq.	FEM	Eq.	FEM	Eq.	FEM	Eq.	FEM	Eq.	FEM
8	12.95	2.47	- 48	- 12.9	22.25	12.37	- 51	- 9.11	51	9.76
16	19.44	3.86	- 75.6	- 13	36.56	9.457	- 81.9	- 18.9	81.9	19.8
24	19.44	3.94	- 75.6	- 11.2	36.4	6.938	- 81.9	- 15.2	81.9	16.2
32	12.95	2.53	- 48	- 7.6	22.25	3.3	- 51	- 21.5	51	22.12
Sym.										

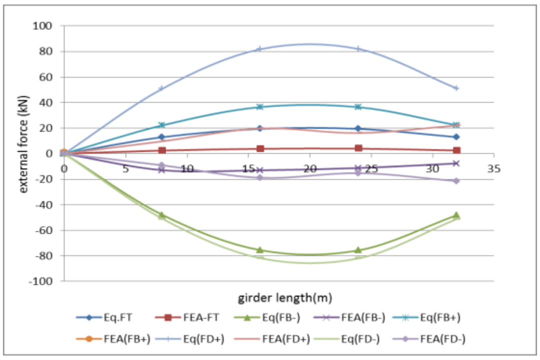
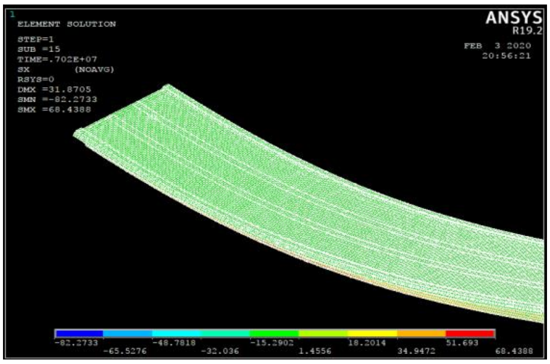
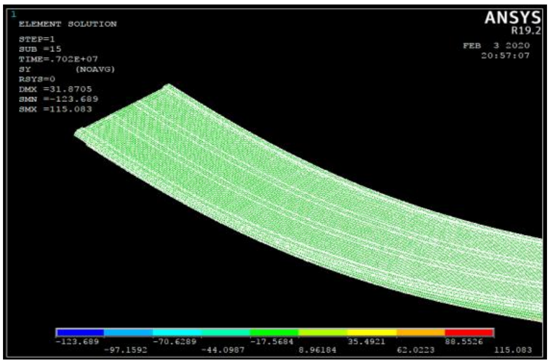


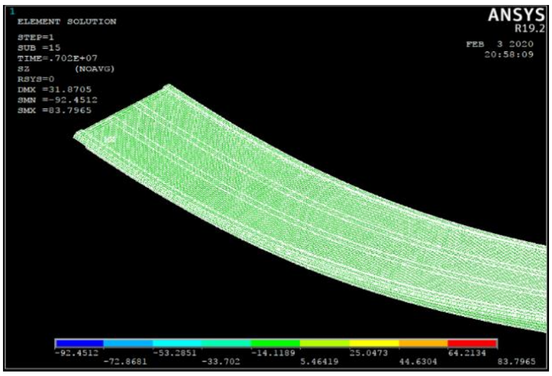
Fig. 11 Comparison between equations and FEM results of external bracing force of bridge with concrete deck.



X-direction



Y-direction

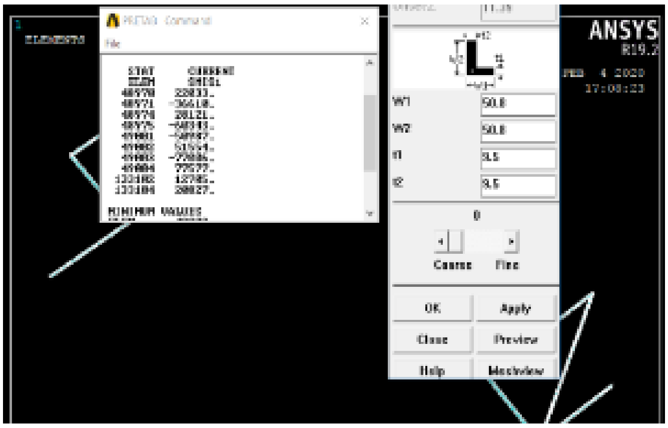


Z-direction

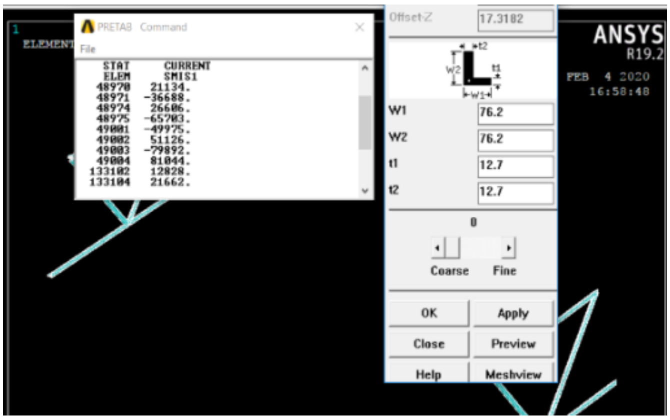
Fig. 12 Normal stresses in box girder bridge with concrete deck.

Table 5 External bracing force with different cross section (kN).

Section\force	1 (FT)		2 (FB^-)		3 (FB^+)		4 (FD^-)		5 (FD^+)	
Section\span (m)	**8 m**	**16 m**	**8 m**	**16 m**	**8 m**	**16 m**	**8 m**	**16 m**	**8 m**	**16 m**
Section\eq. force	12.95	19.44	- 48	- 75	22.25	36.56	- 51	81.9	51	81.9
L 2 × 2 × (3/8)	12.71	20.83	- 36.6	- 60.3	22.03	28.12	- 51	- 77	51.55	77.58
L 3 × 3 × (1/2)	12.83	21.66	- 36.7	- 65.7	21.13	26.61	- 50	- 79.9	51.13	81.04
L 4 × 3 × (5/16)	12.79	21.5	- 36.6	- 63.3	21.11	26.59	- 49.9	- 77.7	50.8	78.64
L 5 × 3 × (1/2)	12.83	21.96	- 35.8	- 67.2	20.55	26.08	- 48.4	- 80.5	50.2	82.24
L 6 × 4 × (3/8)	12.8	21.71	- 35.7	- 66.8	20.43	26.06	- 48.1	- 79.7	50.1	81.66
L 5 × 5 × (5/8)	12.6	21.7	- 34.2	- 69.5	20.31	26.5	- 46.6	- 82.1	49.71	85.1
L 6 × 6 × (1/2)	12.57	21.49	- 34.3	- 69.4	20.21	26.57	- 46.4	- 81.6	49.9	84.76
L 7 × 4 × (3/4)	12.51	21.78	- 33.2	- 70.5	20.45	27.16	- 45	- 83	49.84	87.4
L 8 × 8 × 1	12.1	20.62	- 30.1	- 71.6	21.34	29.88	- 42.9	- 84.1	53.73	93.6



(a) L 2 × 2 × (3/8)



(b) L 3 × 3 × (1/2)

Fig. 13 External bracing force for different cross section beams.

The external bracing forces found from the equations (2), (3) and (4) were checked with the results from FEM (ANSYS19.2) as shown in Fig. 7. The results from both three-dimensional full model and grid analysis methods are in fairly good agreement.

When the concrete hardens, the steel girders and concrete slab act compositely, this composite action results in a very stiff section with large moment of inertia, so the external bracing can be removed immediately after the construction is complete. This is an acceptable assumption, as in this type of bridges there are no known failures in torsion after removing the external diaphragms [6].

Table 4 shows that the external force in bracing elements is reduced when the concrete is placed and hardens, which means that the external frames does not have a significant effect after the concrete hardens, so it can be removed.

In order to investigate the effect of bracing stiffness on the forces induced in the external cross-frames, nine different structural members were used in the analyses. Table 5 shows the forces induced in the individual structural members used for external K-frames. The member forces in external bracing members are not affected by the member size as mentioned in eq. (2), (3) and (4), but it will be useful in the selection of member sizes.

5. Conclusions

A composite trapezoidal twin-box girder system is frequently utilized for both curved and straight highway bridges due to its advantageous structural characteristics, in particular its superb torsional rigidity, favorable long term maintenance considerations, and aesthetically pleasing appearance. Installing temporary shoring or external cross-frames is considered to be a more efficient way of controlling differential deflections. The bracing forces in these cross frames were investigated for horizontally curved bridge with two trapezoidal girders connected by external K-frames with different parameters,

The following points can be presented as a conclusion for this study:

1. The comparison of ANSYS program results and LRFD AASHTO equations have been very well.
2. The external bracing force decreased after the concrete are placed and harden so they can be removed safely.
3. Using the different sizes of external bracing members does not affect on axial force induced in this element.

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