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Three Dimensional Modeling for Steel-Concrete Composite Bridges using Systems of bar elements- Modeling of Skewed Bridges

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Abstract

A new improved way for modeling steel composite straight bridges has been presented (Vayas, 2009; Vayas, 2010). The proposed model is based on the representation of steel I-girders through the use of equivalent trusses. The concrete slab is suitably represented by a set of bar elements. Diaphragms and stiffeners may also be taken into account. In contrast to the grillage model, which is usually used for the analysis of bridges, the recommended three dimensional model allows for a more reliable prediction of deformations and internal forces. This paper discusses the extension of the model to skewed composite bridges. The presence of skew makes the analysis complicated and for this reason the grillage analysis is not always recommended. Phenomena like differential deflections of the main girders during concreting and lateral displacements of the flanges can be adequately predicted using the proposed model. The new way for modeling composite bridges, using a spatial system of beam-like structural elements, can also be used for stability analysis of skewed bridges. Worked examples are provided to illustrate the set up procedure of the proposed modeling and to compare the different ways of analysis.

Keywords: Skewed composite bridges, modeling, spatial system, buckling analysis, modal analysis

1. Introduction

The most popular computer-aided modelling method for the analysis of steel-concrete composite bridges is the simulation by means of a plane grillage system (Hambly, 1990; Unterweger, 2001). The grillage analysis is used both for the analysis and design of the bridge for the most common design situations, as well as for the construction stages. In this model, the structure is idealized by means of a series of 'beam' elements. Each element is given an equivalent bending and torsion inertia to represent the relevant portion of the deck. The longitudinal composite girders are represented by beam elements with equivalent cross sectional properties that include the steel beam and the concrete flange, while the deck slab is idealized by a series of transverse beams.

Although this model is generally accepted as sufficiently accurate and has the advantage of almost complete generality, it is associated with some drawbacks. Eccentricities among the structural elements of a bridge cannot be taken into account in the model and inevitably additional internal forces and possible load distributions are ignored. Torsion and distortional warping effects are difficult to be predicted while buckling phenomena of the steel girders during erection stages cannot be easily investigated. Besides, the transverse beams of a grillage model do not offer a realistic representation of the dispersed structural behaviour of the deck slab, in which bending takes place in two directions.

On the other hand, the finite element analysis that is widely used in bridge engineering has also some limitations. Thus the quantity of computations can be large and the engineer is not always able to verify the large computer data. Furthermore, the choice of element type, shape and meshing can be extremely critical and if incorrect can lead to inaccurate results.

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2. Bridge Analysis Using a 3D Model

To overcome the above difficulties of the grillage and finite element models, a three dimensional truss model was proposed where the steel I-girders were modeled by equivalent trusses (Vayas, 2009; Vayas, 2010), while the

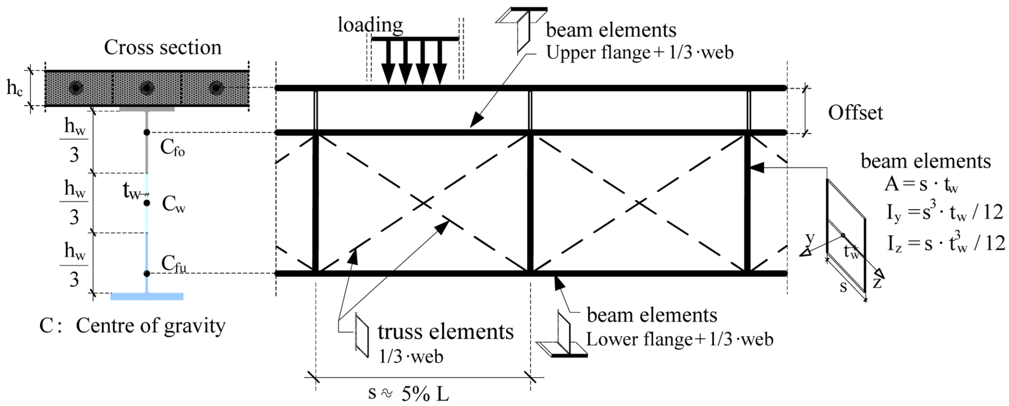


Figure 1. Truss idealization for a single steel and composite girder.

deck slab by a grillage of concrete beams. The main intention is the set up of a global model, which can be used without any serious modifications during the erection stages, deck concreting as well as for the serviceability and ultimate limit states.

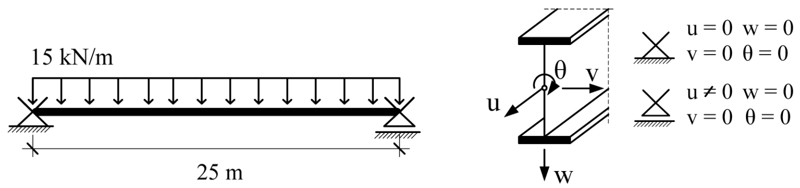
The set up procedure of the model is explained further below and numerical investigations for simply supported steel and composite girders are demonstrated. A comparative analysis among the proposed model, a grillage system and an "exact" finite element model for a simply supported composite bridge are presented and discussed.

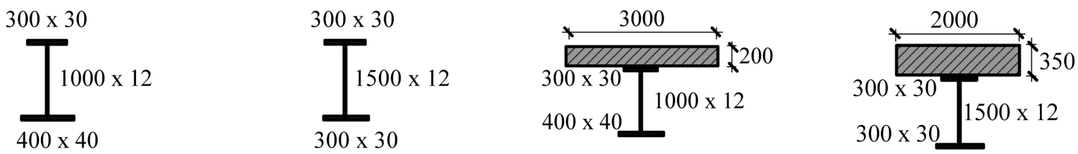
2.1. Representation of steel I-girders

Figure 1 illustrates the modeling of a composite girder through the use of an equivalent truss. The flanges of the truss are beam elements with cross section composed of the flange and part (1/3) of the web of the steel girder. The flanges are connected by a "hybrid combination" of truss and beam elements that represent the web of the steel girder. The concrete section is represented by another beam element connected with the upper flange of the truss through the appropriate offset. This modeling has been selected after numerous worked out examples

Table 1. Comparison of the proposed model, a single line girder model [1D] and a FE-Model

System:





	Steel girder 1			Steel girder 2			Composite girder 1			Composite girder 2		
	3D	1D	FEM	3D	1D	FEM	3D	1D	FEM	3D	1D	FEM
$w^{(1)}$	51.0	49.4	**53.7**	27.1	26.1	**27.7**	17.6	16.6	**19.6**	10.1	9.1	**10.5**
$\sigma_c^{(2)}$	-	-	-	-	-	-	-2.6	-2.6	**-2.8**	-1.9	-1.9	**-2.0**
$\sigma_{s1o}^{(3)}$	-101.6	-100.4	**-99.0**	-66.4	-65.7	**-66.5**	-5.9	-5.5	**-6.4**	-1.4	-1.7	**-1.7**
$\sigma_{s1u}^{(4)}$	70.7	70.2	**72.1**	66.6	65.7	**66.5**	52.2	51.8	**54.3**	46.8	44.1	**45.6**
$n_{cr}^{(5)}$	0.72	0.64	**0.68**	0.51	0.43	**0.52**	-	-	-	-	-	-
$f_{dyn}^{(6)}$	2.51	2.59	**2.43**	3.46	3.57	**3.36**	4.28	4.48	**4.00**	5.69	6.04	**5.37**

(1) Max. deflection in mm
(2) Stress at the top of the concrete slab in N/mm^2
(3) Stress at the top of the upper flange in N/mm^2
(4) Stress at the bottom of the lower flange in N/mm^2
(5) Critical load factor for lateral torsional buckling
(6) Eigenfrequency for vertical bending in Hz
All dimensions are given in mm.
For the critical load factors of the 1D-Model beam elements with 7-DOF were used.

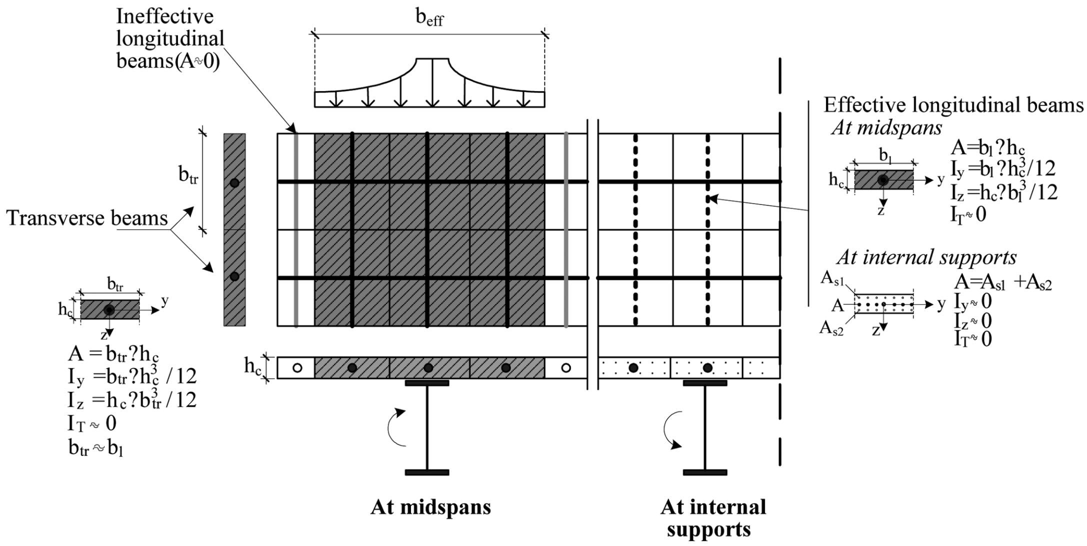


Figure 2. Grillage idealization for the slab of a steel-concrete composite beam.

in very good agreement with those of FE-models.

In order to verify the validity of the proposed model, numerical investigations for deformations, stresses, buckling and dynamical modes are performed for a simply supported beam with either steel or composite cross sections. Table 1 compares the results among the proposed 3D-Model, a single line girder model (1D), which would be introduced in a grillage analysis and a FE-Model. For these examples the modulus of elasticity for concrete and structural steel are 33,500 N/mm^2 and 210,000 N/mm^2 respectively. For the beams of steel section, the critical load factor for lateral torsional buckling is calculated using some buckling analysis appropriate software.

2.2. Grillage representation of the slab

According to grillage analysis (Hambly, 1990) the concrete slab of a composite bridge can be represented by a grillage of interconnected beams. The longitudinal stiffness of the slab is concentrated in the longitudinal beams, the transverse stiffness in transverse beams. The grillage is connected to the upper flange of the truss as shown in Figs. 1 and 2. Attention must be paid so that the grillage has its longitudinal members coincident with the centre lines of the steel sections.

The longitudinal beams, which are located inside the effective width of the slab, are considered at midspans with their uncracked properties. At internals supports the cross sectional area of the longitudinal beams is equal to the total reinforcement amount, which can be assumed at the centre of the slab. The effect of *tension stiffening* can be taken into account with the help of the following equation (Hanswille and Stranghöner, 2003):

$$A = \frac{A_{s,tot}}{1 - \dfrac{0.5 \cdot f_{ctm}}{\rho_{s,tot} \cdot f_{sk}}} \qquad (1)$$

where f_{ctm} is the mean tensile strength of concrete; $A_{s,tot}$ is the total amount of reinforcement in the slab; $\rho_{s,tot}$ is the total reinforcement ratio; f_{sk} is the characteristic yield strength of steel.

The longitudinal beams, which are located outside the effective width b_{eff}, do not participate in the distribution of the normal stresses. Therefore, their cross sectional area A is set equal to zero.

The slab reinforcement can be calculated from the bending moment diagrams both of the transverse and the longitudinal beams. In cases of pre-stress the actual sections must be replaced from transformed sections, in which the pre-stress steel is included (Ghali and Favre, 1994).

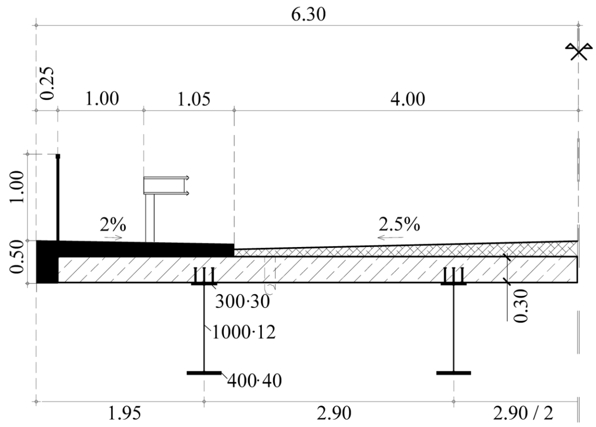
The grillage mesh depends generally on the geometry of the slab. The spacing of the beams shouldn't be less than 2 times the slab depth. If the local dispersion of concentrated loads has to be considered, then smaller values have to be adopted. Generally, the grillage mesh must be sufficiently fine so that the grillage system deflects as a smooth surface. It has been also recommended by (Hambly, 1990) that the row of longitudinal beams at each edge of the grillage should be located in a distance of $0.3h_c$ from the edge of the slab, where h_c is the slab depth. Since the torsional stiffness of the deck slab is much lower than the bending stiffness of the composite girders a torsionless approach can be adopted (I_T=0).

The creep of concrete can be taken into account through the use of an age-adjusted modulus of elasticity $E_{c,eff}$:

$$E_{c,eff} = \frac{E_c(t_0)}{1+\varphi_t} \qquad (2)$$

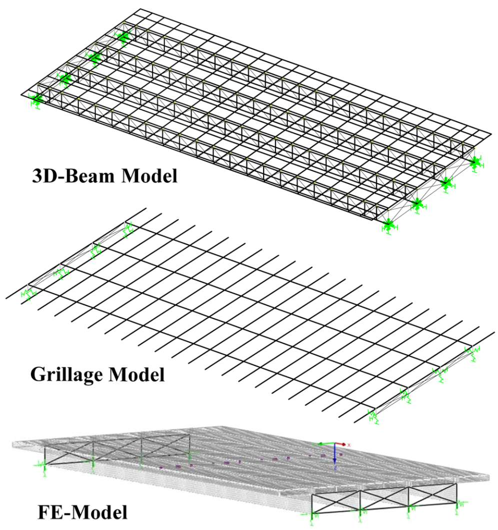
where $E_c(t_0)$ is the modulus of elasticity of concrete at age t_0, the time of application of the loading; φ_t is the creep coefficient.

Cross section



Bridge span: 25m

Structural systems



Load cases

LC1	Dead load	8 kN/m^2
LC2$^{(*)}$	Wheel loads	4x120 kN
LC3	Shrinkage of concrete	-447·10^{-6}

*The wheel loads are applied to an outer lane at midspan.

Materials

Concrete: E_c = 33500 N/mm^2

Steel: E_s = 210000 N/mm^2

Bearings: c_{hor} = 1562.5 kN/m

c_{ver} = 915469 kN/m

Figure 3. Bridge cross section, load cases and structural systems.

2.3. Comparative analysis for a simply supported orthogonal bridge

In Fig. 3, three different models (proposed model, grillage and FE-Model) for three load cases are compared. The grillage model was set up according to existing recommendations (Hambly, 1990; Unterweger, 2001). In FE-model, the steel girders are simulated using shell elements. Solid elements are used for the simulation of the deck slab. Common nodes are created between the lower surface of the concrete elements and the shell elements representing the upper flange of the steel girders. In this way, the composite action between steel and concrete is ensured. The same procedure is followed in all the worked-out examples of this paper where FE-models are used for the analysis. The results for the flexural stresses, the support reactions and the deflections are given in Table 2. In all models the bearings are represented by springs of equivalent stiffness.

Table 2 shows that the results of the three different models correlate very well between each other regarding deformations stresses and support reactions for all the three loading cases. It is worth mentioning that the 3D-model accommodates very well the stress and deformation behaviour of the whole structure comparing its results with a finite element model or the classic grillage theory.

The main advantage of the three dimensional model over finite element analysis is its ability to simulate the whole structure using relatively few members offering at the same time a faster solution.

2.4. Analysis of erection stability during deck concreting

When a simple beam is loaded in flexure, the compression flange is subjected to lateral torsional buckling. A linear buckling analysis allows the determination of the buckling modal shapes and the critical load factors n_{cr}, which is the ratio by which the applied load must be increased to cause the structure to become unstable. For the erection stability of the steel girders during concreting of the deck, lateral bracings connected at the upper flanges are needed. Figure 4 demonstrates the stability analysis for the bridge of the previous section with the help of the proposed 3D-Beam model. The results are compared with those of a FE-Model.

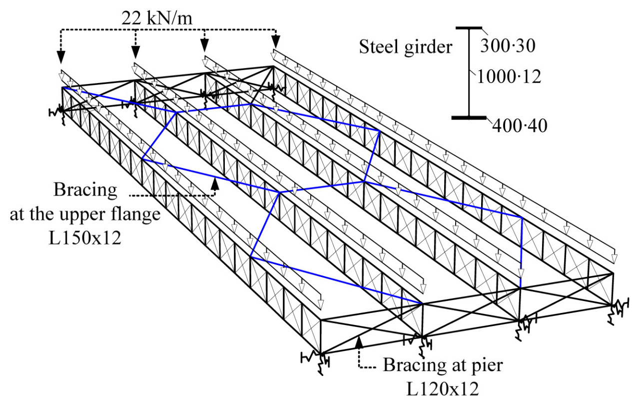
The proposed 3D-Beam model is deemed accurate for the purpose of investigating the static and dynamic behaviour of beam-and-slab composite bridges. In contrast to grillage models, it can also be used for the stability analysis during erection stages and deck concreting providing both the critical load factors and the buckling modal shapes.

Table 2. Comparison of results at mid-span for the proposed 3D-Beam model, the grillage and the FE-Model (simply supported bridge, L=25 m)

	3D-Beam Model				Grillage Model				FE-Model			
	σ_c	σ_s	w	R	σ_c	σ_s	w	R	σ_c	σ_s	w	R
LC1	-3.7	78.6	26.7	312.8	-3.7	81.9	26.0	339.9	-3.7	85.8	30.2	351.1
LC2	-4.8	70.2	22.8	156.9	-3.2	69.5	21.3	158.8	-5.1	62.0	19.8	167.0
LC3	2.7	12.1	30.2	108.4	3.6	12.2	30.6	72.6	2.9	13.0	31.8	112.4

σ_c: min. stress in concrete in N/mm^2
σ_s: max. stress in structural steel in N/mm^2
w: max. deflection at mid-span in mm
R: max support reaction in kN

3D-Beam Model



Critical load factors n_{cr}

Modal Shape	3D - Beam Model	FE-Model
1st	1.586	1.539
2nd	1.591	1.589
3rd	1.703	1.673
4th	1.707	1.716

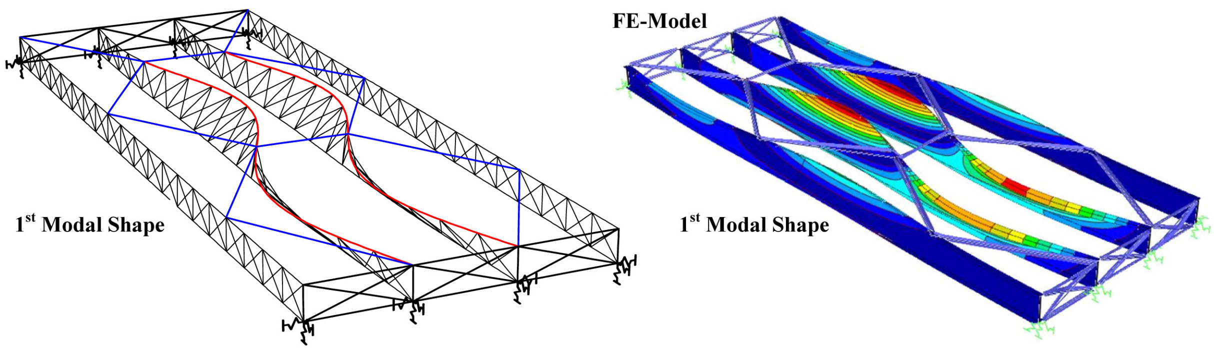


Figure 4. Modal shapes and critical load factors for the load case of concreting.

3. Skewed Bridges

3.1. General

In skewed bridges the support abutments or piers are placed at angles other than 90 degrees (in plan view) from the longitudinal centerlines of the girders. There are different ways of defining the skew angle. Usually, it is defined as the angle between the major axis of the substructure and a perpendicular to the longitudinal axis of the superstructure, although a different convention may be used.

The presence of skew affects the geometry and the behavior of the structure. Special phenomena, like twisting and out of plane rotation of the main girders during concreting (Whisenhunt, 2004; Beckman, 2005), concentration of reaction forces (Gupta, 2007) and fatigue problems due to out-of-plane web distortion (Berglund, 2006) makes the analysis and design of skewed bridges intricate.

Figure 5 shows three different cases of skewed bridges with different skew angles. The third case corresponds to the orthogonal type of bridge where the skew angle is equal to 90 degrees, with the skew angle measured clockwise.

3.2. Differential deformations of steel girders during concreting

During the bridge construction sequence, the girders deflect under their own weight and the weight of the

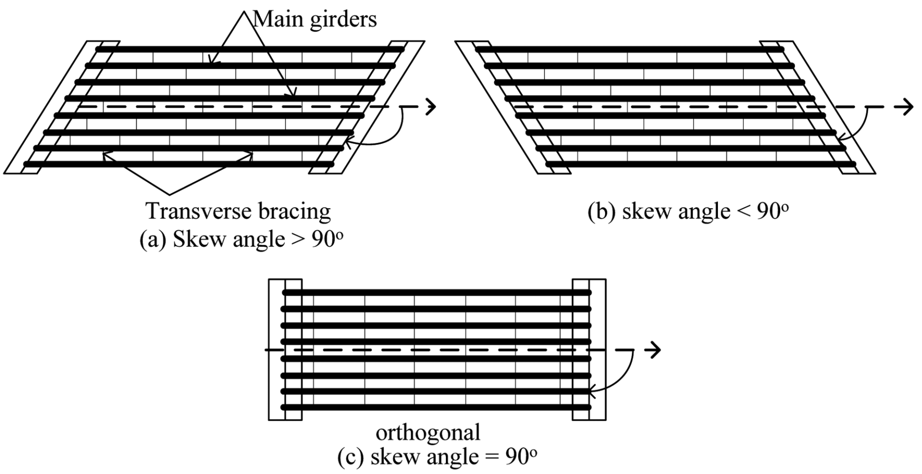


Figure 5. Different skew angles for composite bridges (Whisenhunt, 2004).

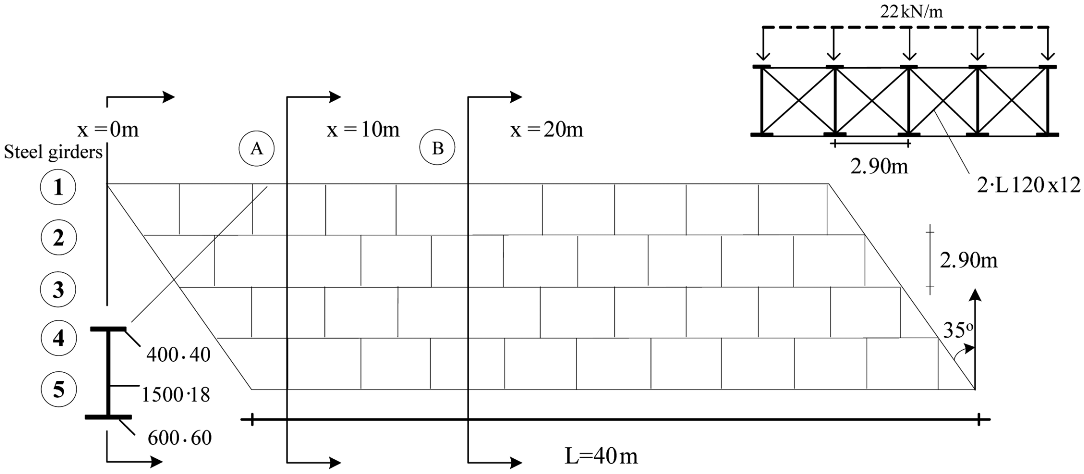


Figure 6. Steel structure of a single span skewed bridge with intermediate crossframes.

deck. On non-skewed bridges, the deflections across any section of the bridge due to the deck weight are almost identical. The point of maximum deflections for each steel girder will be at midspan of each girder. On a square bridge these points align across the width of the bridge.

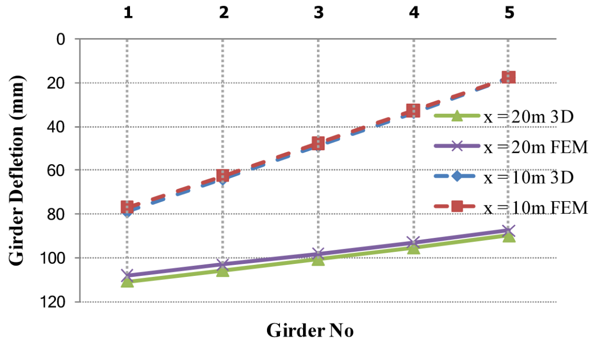
By contrast, on a skewed bridge the deflections are not the same across the width of the bridge, since the girders are longitudinally offset from each other by the skew. Generally, typical cross-frames are placed transversally in order to prevent lateral torsional buckling of the steel girders during the concreting. When cross-frames are installed, they may restrain deflections causing girders to rotate out of plumb and lateral stresses to be developed into the flanges (Coletti, 2005). This out of plane rotation varies, depending on the location along the girder span. The theoretical causes of twisting and lateral flange bending are discussed in (AASHTO/NSBA, 2002; Beckman *et al*., 2008; Coletti, 2005). It is important for the design to predict the real deformations of the steel non composite girders during the construction, as any items connected to the top flange at these locations may also be a problem (Whisenhunt, 2004). According to (AASHTO/NSBA, 2002), it is also very important to decide whether the intermediate cross-frames should be placed skewed or normal.

In order to show the differential deflections that occur on a skewed bridge during concreting and to make a first comparison between the two models, the skewed bridge of Fig. 6 is investigated using a finite element analysis and a 3D analysis as described in 2.1. The steel girders are connected with intermediate cross-frames in every 4m in a direction perpendicular to the longitudinal direction of the bridge. A uniform load of 22 kN/m is applied on each girder representing the weight of fresh concrete.

Table 3 shows the differential vertical deflections, transversally, of each one of the five steel girders, for two different sections along the steel structure. The difference is higher in regions adjacent to skewed supports. In section A (x=10 m) the maximum differential deflection takes place between the fourth and the fifth girder (15.8 mm according to the 3D-Model). The existence of end and intermediate cross-frames causes girders to rotate out

Table 3. Vertical deflections (mm) of each girder at midspan (x=20 m) and at L/4 (x=10 m) for the skewed bridge of Fig. 6 under the weight of fresh concrete (FE-model vs. 3D model)

Girder No.		1	2	3	4	5
x=10 m	**3D**	**78.8**	**63.9**	**48.9**	**33.6**	**17.8**
	FEM	**76.9**	**62.4**	**47.7**	**32.8**	**17.5**
x=20 m	3D	110.7	105.8	100.7	95.4	89.9
	FEM	108.0	103.1	98.1	92.9	87.5



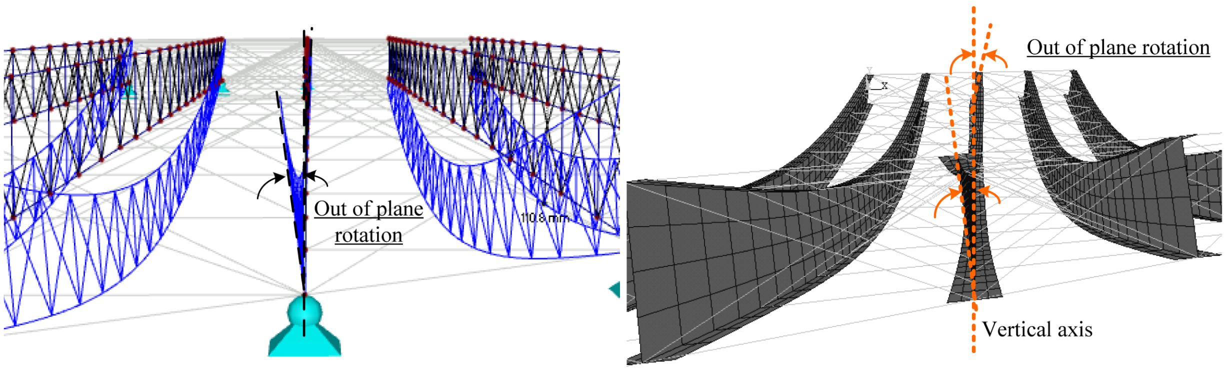
Vertical deflection of each girder in mm

of plan as shown in Fig. 7. Both models seem to lead to almost identical results, while the 3D model is able to predict the out of plumb deformation of the steel girders.

3.3. Modeling of composite skewed bridges

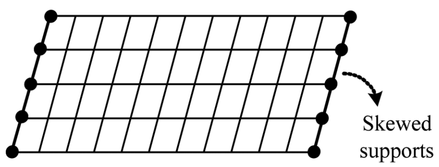
According to the proposed three dimensional representation of a composite bridge (Fig. 2), the deck of a skewed bridge may be represented through a grillage of beam-like elements. A suitable grillage model of a skew deck will largely depend on the angle of skew, the span length and the width of the deck. There are different ways for modeling a skewed concrete deck (Hambly, 1990; O'Brien, 1999).

According to Hambly, 1990, the longitudinal grillage members can usually be placed parallel to the main girders direction, while the transverse members should generally be oriented perpendicular to the longitudinal members (Fig. 8b). Alternatively, the transverse members

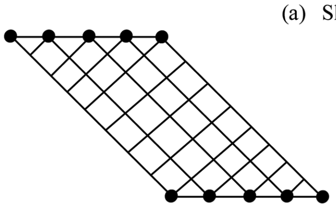


(a) 3D-Model (b) FE-Model

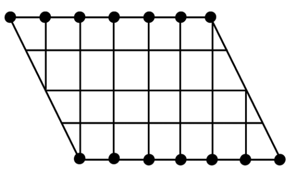
Figure 7. Out of plane rotation of the steel girders during concreting in a skewed bridge.



(a) Skewed mesh

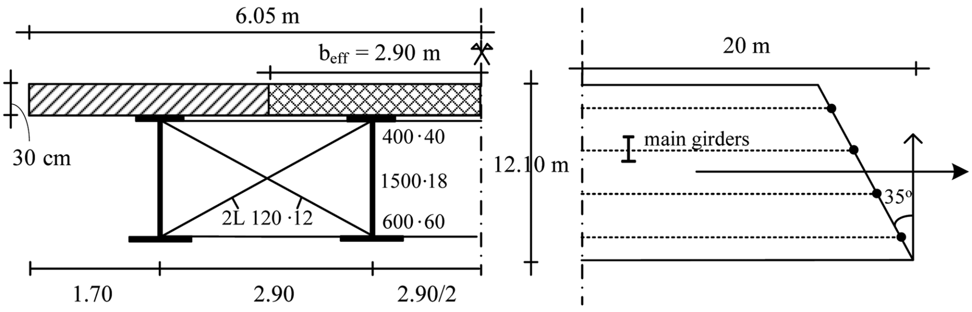


(b) mesh orthogonal to span



(c) mesh orthogonal to supports

Figure 8. Different grillage meshes for skewed bridges (Hambly, 1990).



(a) Cross-section (b) plan view

Figure 9. Skewed composite bridge (a) cross section and (b) plan view.

can be placed as illustrated in Fig. 8a, using a skew mesh. Generally the skew mesh of Fig. 8a is convenient for low skew angles (Gupta, 2007).

The procedure that is followed for the proposed model of a composite skewed bridge is based on the grillage representation of the deck slab as discussed in paragraph 3.3, with the difference that the mesh of the slab is developed according to Fig. 8c. The composite girders are modeled in the same way as described in paragraph 2.1.

3.4. Three dimensional representation of a single span skewed bridge

In the following example, a simply supported composite bridge of 40 m span is modeled according to the proposed method. The bridge geometry is shown in Fig. 9. The bridge is simply supported at one edge (hinged supports), while on the other edge there is free translation along the longitudinal axis. The material constants are as in Fig. 3.

Figure 10 illustrates the procedure for the 3D representation of this composite bridge following the recommendations of paragraph 2.1. The composite main girders are represented by equivalent trusses as in Fig. 1. The beams modeling the slab are connected to the upper flanges of the truss through an appropriate offset.

For the representation of the slab an orthogonal mesh was chosen (Fig. 8c). The concrete slab is divided transversally in twelve longitudinal members of 0.97 m and two of 0.25 m width. The longitudinal members have been placed along the lines of the steel girders and parallel to them in order to maintain the transversal geometry (Fig. 10b). The longitudinal members, at each edge, are located in a distance of $0.3h_c$ from the edge of the slab (Hambly, 1990); that is a distance of 0.64 m from the outer intermediate members.

The transverse members have been placed generally at a spacing of 2.00 m at midspan. Transverse beams should have spaces similar to that of the longitudinal beams. A ratio between one and three times the longitudinal spacing is generally accepted. A closer distance is adopted for the transversal members near the skewed supports with the transverse members to be at a spacing of 0.67 m near supports, as it is shown in the detail of the obtuse corner of the slab (Fig. 10b).

Since the torsional stiffness of the deck slab is much lower than the bending stiffness of the composite girders a torsionless approach has been adopted (I_T=0).

4. Worked example of a simply supported skewed bridge

To verify the ability of the 3D model to simulate properly the behavior of a composite skewed bridge during its different stages, the simply supported skewed composite bridge of Fig. 9 is studied further below.

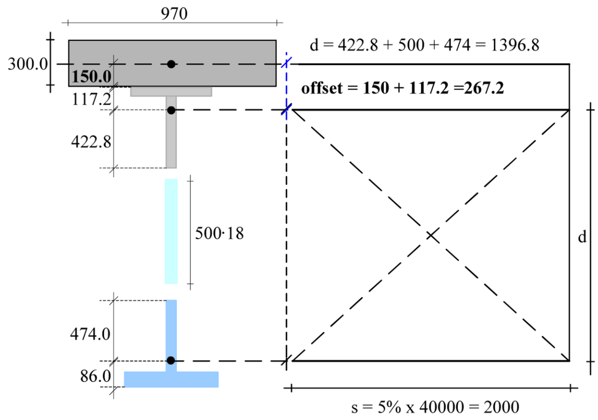
4.1. Static analysis during concreting

On the steel structure of the composite bridge in Fig. 9 a dead load of 22 kN/m is applied on every steel girder representing the weight of fresh concrete (considering that the slab extends beyond the edge beams so that all beams are equally loaded, Fig. 11). In order to demonstrate the influence of the transverse bracing, only for the analysis during the concreting, the steel girders are connected by intermediate cross-frames of the same geometry as the end cross-frames.

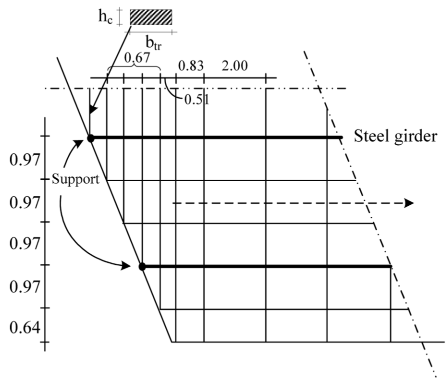
The cross-frames are perpendicular to the direction of the steel girders and are placed every 8 m. The steel structure is modeled by the use of the three dimensional model presented in this paper and a finite element model. The same analysis is carried out for a single span straight bridge of the same transversal geometry and of the same length so as to demonstrate the difference in the deformation of the steel girders.

Table 4 shows the results of the three different models that have been used for the analysis. Except for the 3D model and the FE-model, the 1D model corresponds to single girder line models, where the steel girders are studied independently without taking into account the presence of bracing.

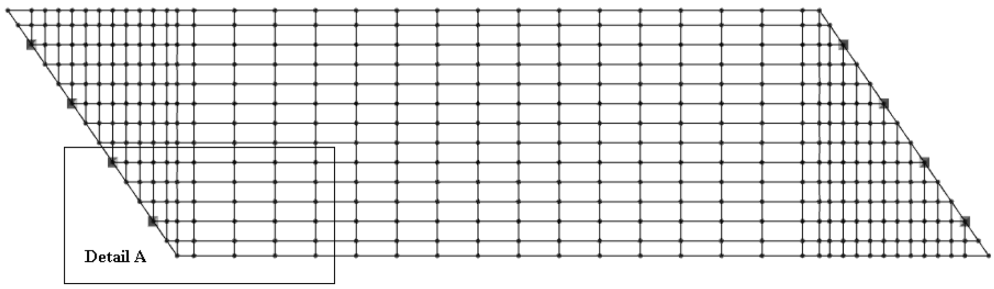
As it is described in paragraph 3.2, both for the FE-Model and the 3D-Model, the steel girders of the skewed bridge are out of plumb after concreting, as shown in Fig. 7. On the contrary, the grillage analysis provides only



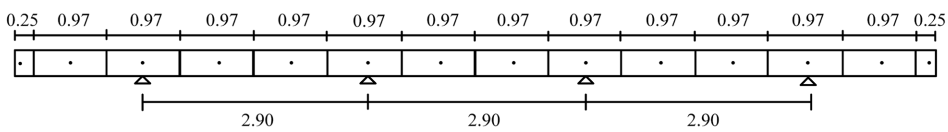
(a) Composite girder representation



(b) Grillage mesh for slab – Detail A



(c) Grillage mesh for slab – plan



(d) Grillage mesh for slab - section

Figure 10. 3D representation of a simple supported skewed bridge with 4 main girders. Modeling of the composite section and grillage mesh for the concrete slab.

displacements in the vertical direction. Table 4 shows the maximum and minimum stresses and the maximum deformations of the steel girders for all the three different models.

For both the skewed and the straight bridge, the results of the finite element analysis and the 3D representation correlate very well regarding stresses and deformations, showing that the 3D proposed model is able to predict these out of plumb deflections and the out of plane rotation of the steel girders like those shown in Fig. 7. On the contrary, the single line girder model is not able to predict neither any lateral displacement of the flanges of the steel section nor the out of plane rotation of the girders.

Table 4. Results of stresses and deformations for the steel girders under the concreting load for the FE-model (FEM) the 3D model and the single line girder model (1D)

	Skewed Bridge				Non-skewed bridge			
	w	**u**	σ_{so}	σ_{su}	**w**	**u**	σ_{so}	σ_{su}
FEM	107.0	9.0	-131.0	80.6	105.6	0	-129.0	79.7
3D	**109.5**	**8.3**	**-134.1**	**81.6**	**108.6**	**0**	**-132.1**	**80.9**
1D	104.8	0	-130.7	80.6	104.8	0	-130.7	80.6

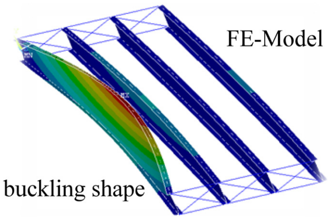
σ_{so}: minimum stress in upper flange in N/mm^2
σ_{su}: maximum stress in lower flange in N/mm^2
w: maximum vertical deflection (mm)
u: maximum horizontal deflection (mm)

Table 5. Critical buckling factors for the skewed bridge during concreting

Buckling factors n_{cr}

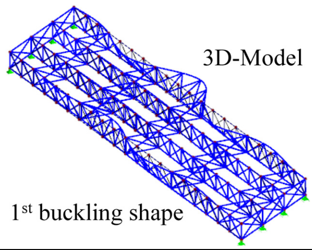
Without intermediate bracing

Buckling shapes	3D	FEM	deviation (%)
1st	0.390	**0.367**	6.3%
2nd	0.390	**0.367**	6.3%



With intermediate bracing (every 8m)

Buckling shapes	3D	FEM	deviation (%)
1st	3.370	**3,472**	-2.9%
2nd	3.419	**3.498**	-2.3%



The total lateral divergence of the flanges is significant (18 mm for the finite element analysis and 16.6 mm for the 3D analysis). It seems that the skew angle and the presence of the bracing do not affect the vertical displacement of the girders and the magnitude of the stresses.

4.2. Buckling analysis during concreting

During the construction stages the upper flange of the steel section is under compression in the span regions. Plate girders have low torsional stiffness and a high ratio of major to minor axis second moment of area, so that in the absence of a slab they are sensitive to lateral-torsional buckling (Table 5).

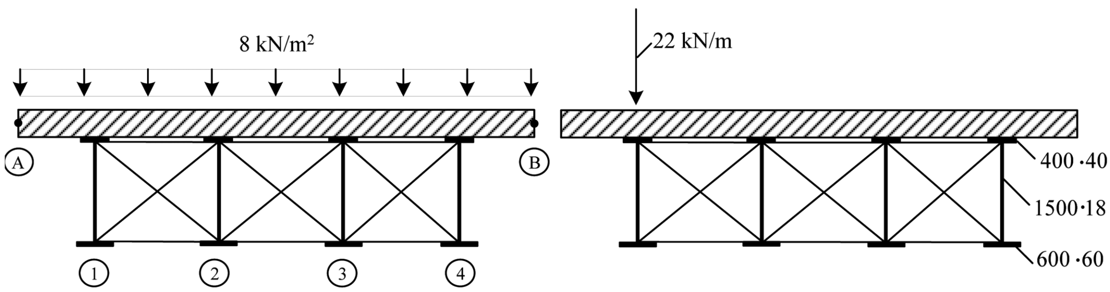
A separate analysis must be carried out during the construction stages in order to verify the resistance of the steel girders towards lateral-torsional buckling. A linear buckling analysis allows the determination of the buckling modal shapes and the critical load factors.

Two different analyses have been carried out in order to demonstrate the importance of the bracings in the ensuring of the stability during the concreting. In a first step, the steel girders are studied without any intermediate cross-frames. In a second step, the transversal bracing of Fig. 9 has been added in the structure. The bracings have been placed at a spacing of 8 m. Table 5 shows the first buckling shape and the correspondent buckling factors for the braced and the unbraced steelwork of the skewed bridge.

From Table 5 it is obvious that the buckling factors of the two different analysis show a very good agreement between each other, with the deviation percentage always under 7%, concluding that the 3D model can also be used for the buckling analysis of the structure. Besides, the importance of the transverse bracing is demonstrated. The first buckling factor of the unbraced structure is 0.390 (according to the 3D model), showing that the steel girder is very susceptible to buckling if it is not supported laterally. The buckling factor changes into 3.370 with the use of intermediate cross-frames.

4.3. Composite skewed bridge

To verify the ability of the 3D model to simulate properly the composite structure, the single span skewed



(a) Load case 1- uniform load on concrete slab (b) Load case 2 - eccentric linear load on edge girder

Figure 11. Load cases applied on the skewed and non skewed composite bridge.

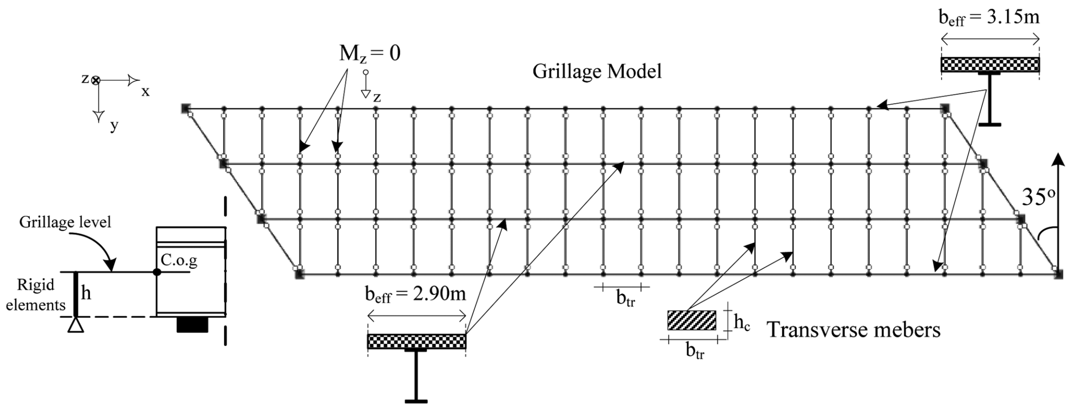


Figure 12. Grillage representation of the skewed bridge.

bridge of Fig. 9 is studied under a uniformly distributed and an eccentric linear load, applied on the composite structure as it is shown in Fig. 11. No intermediate bracing is considered but the end cross-frames.

Three different models are used for the analysis. The proposed 3D-Model, a FE-Model and a grillage model according to (Unterweger, 2001; Hambly, 1990). For the grillage model an orthogonal mesh is used. As the skew angle is higher than 20° the transverse grid lines are set perpendicular to the longitudinal members.

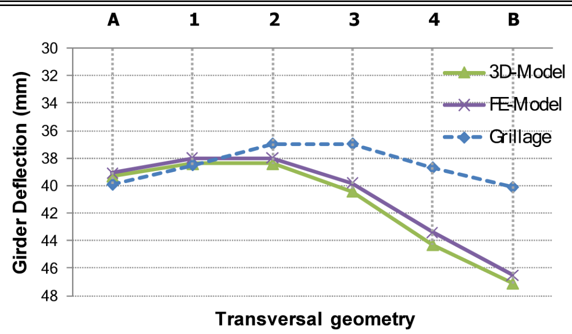
The longitudinal composite girders are represented by beam elements with equivalent cross sectional properties

Table 6. Results for stresses and deformations for the 1st loading case for all the three models (FE-model, 3D-model, Grillage model) for the skewed and non skewed bridge

Skewed Bridge (uniform load of 8 kN/m²)

	w_A	w_B	u	σ_{s1}	σ_{s4}	σ_c
FEM	39.0	46.5	4.5	61.0	71.0	-4.3
3D	**39.3**	**47.1**	**4.0**	**61.2**	**72.2**	**-4.6**
Grillage	39.9	40.1	1.6	65.8	66.1	-4.2

(a) maximum stresses and displacements (skewed bridge)

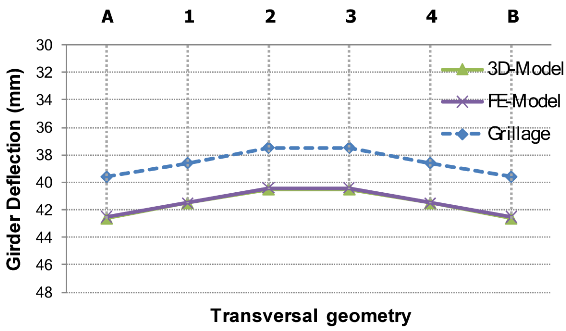


(b) Vertical deflections transversally at midspan (skewed bridge)

Non skewed bridge (uniform load of 8 kN/m²)

	w_A	w_B	u	σ_{s1}	σ_{s4}	σ_c
FEM	42.5	42.5	0.7	66.3	66.3	-4.3
3D	**42.7**	**42.7**	**0.7**	**66.1**	**66.1**	**-4.2**
Grillage	39.6	39.60	66.0	66.0	-4.2	

(c) maximum stresses and displacements (Non skewed bridge)



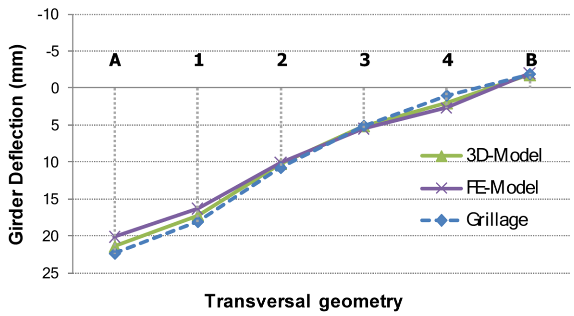
(d) Vertical deflections transversally at midspan (Non skewed bridge)

w_A: Maximum vertical deflection at the edge of the deck close to steel girder 1 (mm)
w_B: Maximum vertical deflection at the edge of the deck close to steel girder 4 (mm)
u: Maximum lateral displacement of the upper flanges (mm)
σ_{s1}: Maximum stress for the steel girder 1 in N/mm²
σ_{s4}: Maximum stress for the steel girder 4 in N/mm²
σ_c: Minimum stress in concrete in N/mm²
Numeration of girders according to Fig. 11

Table 7. Results for stresses and deformations for the 2nd loading case for all the three models (FE-model, 3D-model, Grillage model) for the skewed bridge

	Skewed Bridge (uniform load of 8kN/m^2)					
	w_A	w_B	u	σ_{s1}	σ_{s4}	σ_c
FEM	20.1	-2.0	4.3	26.3	6.0	-2.4
3D	**21.7**	**-1.8**	**3.7**	**29.8**	**6.0**	**-2.4**
Grillage	22.4	-1.9	1.1	30.4	2.0	-2.3

(a) maximum stresses and displacements (skewed bridge)



(b) Vertical deflections transversally at midspan (skewed bridge)

w_A: Maximum vertical deflection at the edge of the deck close to steel girder 1 (mm)
w_B: Maximum vertical deflection at the edge of the deck close to steel girder 4 (mm)
u: Maximum lateral displacement of the upper flanges (mm)
σ_{s1}: Maximum stress for the steel girder 1 in N/mm^2
σ_{s4}: Maximum stress for the steel girder 4 in N/mm^2
σ_c: Minimum stress in concrete in N/mm^2
Numeration of girders according to Fig. 11

that include the steel beam and the concrete flange, while the deck slab is idealized by a series of transverse beams. Introducing $I_z \neq 0$ for the concrete elements can lead to wrong results and therefore their rotation around the z global axis is released. The total in plane second moment of area of the slab is equally shared to the two extreme main girders. On the contrary, the intermediate girders have $I_z=0$. The grid lines coincide with the centre of gravity of the composite sections while rigid elements are used to take into consideration the distance between the centre of gravity of the longitudinal elements and the upper face of the bearing.

As shown in Table 6, for the first load case, the maximum stresses and deformations for the finite element and the 3D model are in very good agreement between each other. The main girders are subjected to an out of plane rotation like it is described in Fig. 7. At the same time, the deck of the bridge rotates around the longitudinal axis but also around the vertical axis. The out of plane rotation of the main girders and the rotation of the deck lead to different stresses and deformations for the two extreme main girders. As it is shown by the curves of diagram 6(b), the one edge of the deck is subjected to higher vertical deformations and consequently, the maximum stress of the one outer girder is higher than the stress of the other girder (71 N/mm^2 vs. 61 N/mm^2, according to FEM values).

On the contrary, the grillage model is not able to predict this phenomenon giving almost uniform vertical deflections and the maximum stress reduced by 7.0% while it ignores the out of plane rotation of the girders and the rotation of the deck. For the eccentric load of the second load case, all the three models give almost equivalent results.

Table 6 shows also the results of the non skewed, orthogonal bridge under the first load case. There is no practical out of plane rotation of the girders while the maximum stresses and deformations for the two extreme girders are the same representing a symmetrical deformation of the bridge. For the orthogonal bridge, all the three models (FEM, 1D, 3D) give almost identical vertical deflections and stresses with the 3D-Model being in better agreement with the FE-Model.

In table 7, the maximum stresses and the deformations for the second load case of the eccentric load are presented for the skewed bridge. As it is shown in Table 7, the three different models conclude in slight deviations regarding stresses and vertical displacements, while the 3D model can offer a better prediction of the lateral displacements after comparison with the FE-model results.

By comparing the skewed and non skewed results, it is concluded that the skew angle affects the maximum stresses and the maximum vertical deflections of the main girders. For the first load case, the structure is subjected to coupled torsion and bending because of the skew and as a consequence the deflections and the stresses of the two outer girders are not the same. Moreover, if the supports are skewed, girder rotation displaces the top flange transversally to the bottom flange and causes the web to be out of plumb as it happens during the construction stages. The 3D model seems able to predict the magnitude of stresses and displacements while it predicts the real deformation of the structure concluding in results very close to those of FE-models.

5. Summary

In the present paper, a new way for modeling steel-concrete composite bridges, using a spatial system of beam-like structural elements, is presented. The implementation and validation of the new method has been studied through the use of worked examples. The results show that the three dimensional modeling can be as accurate as a relatively fine mesh finite element model both for orthogonal and skewed bridges, while it has the advantages of being quicker and easier to set up.

In contrast to grillage models, the three dimensional models are able to predict the real 3D behavior of a skewed bridge and the out of plane rotation of the steel girders during the concreting. In addition, they can also be used for the stability analysis during erection stages, providing the modal shapes of the structure as together with the corresponding critical load factors.

The proposed model that is presented in this paper is a part of a research project, which is carried out in the National Technical University of Athens, for the modeling of steel and composite bridges. The project is always under development so as to be able to simulate properly the three dimensional structural behavior of bridges. Alternative techniques are being examined for an eventual amelioration of the model, in order to obtain the best possible results for different types of bridges.

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