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COMPOSITE STEEL CONCRETE BRIDGES USING SINUSOIDAL CORRUGATED STEEL WEB BEAMS

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ABSTRACT: The paper describes some problems with the design of road bridges using welding sinusoidal corrugated steel web beams. The deck is made of two main steel girders, transversally connected by steel beams and by a reinforced concrete slab, prestressed and not. The design is carried out for a category I bridge that is 13.70 m wide and 52.00 m length. It is examined the behavior of steel girders, loaded of its own weight and of the weight of the r.c. plate, as the independent beam, as well the beams connected by transversal elements. The effects due to the shrinkage and the permanent loads are considered by taking into account the viscosity.

The solutions analyzed have been compared with similar structures with stiffened web. The analyses performed are validated with reference to the Italian and to the European Codes.

KEYWORDS: Bridge; Corrugated Steel Web; Concrete-Steel Deck.

1 INTRODUCTION

In the construction of decks for road bridges with light spans between 40 and 120 m, composite systems consisting of steel girders connected by transversal beams and by a plane or pre-stressed concrete slab are suitable. For these bridges, a significant component of the cost is due to the weight of the webs of the girders and the machining operations required for the insertion of the longitudinal and transverse stiffeners, necessary to prevent local buckling.

In recent years, steel beams with webs shaped in a trapezoidal or sinusoidal pattern have been proposed. This solution has led to the possibility of using automatic procedures, with the consequent savings in time and improved precision of execution. In previous articles [7, 8, 9] the behavior of a composite 2 beam deck has been analyzed. The girders are connected by transverse beams and by a reinforced concrete slab, simply supported at the ends, comparing the solutions with stiffened web and sinusoidal web; the latter treated as an equivalent orthotropic plate [5,6].

Subsequently decks with longitudinal continuous schemes on four supports, with 2 beams or with a walled box [8,9] are examined.

In all examples, it is considered a road bridge in class I, according to the European Code, subject to permanent loads, shrinkage and to the action of moving loads.

In this study we analyze a composite concrete-steel deck with two girders, simply supported at the ends with a 52,00 m span; the scheme is shown in Figure 1. The beams with a sinusoidal shape are modelled using the Finite Element Method.

Considering the rules contained in the Italian Code and in the Eurocodes 1, 3 and 4, the traditional solution is compared to the one with the sinusoidal web beams, by varying the geometric characteristics of the sinusoids.

For the beams with sinusoidal webs in Figure 2, the geometrical characterizing parameters, made up of the wavelength l and the amplitude a, are highlighted.

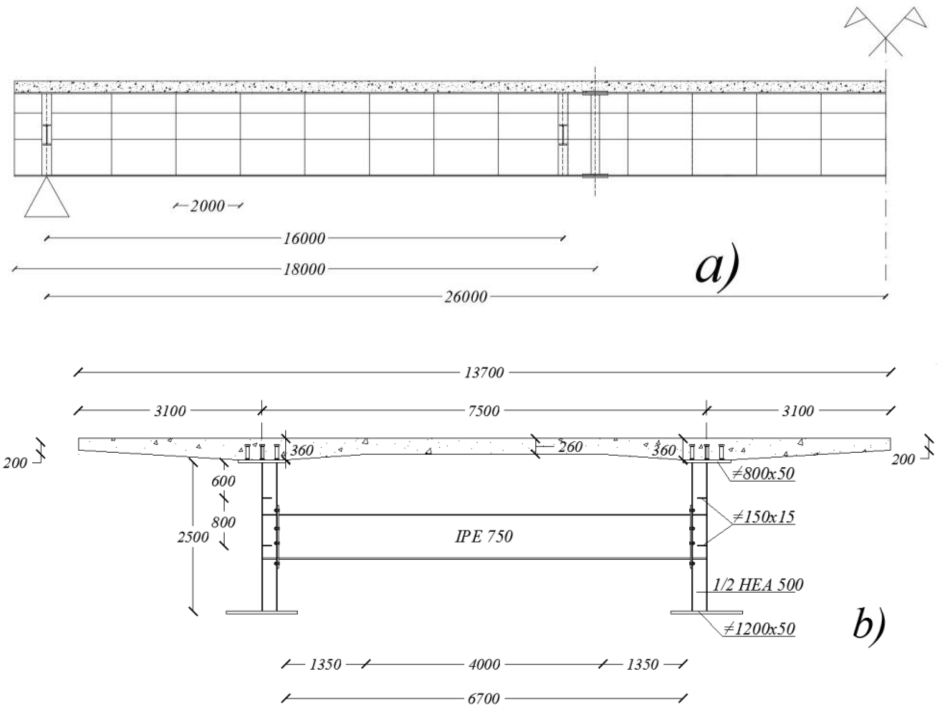

Figure 1. Composite deck with a stiffened web beams:(a) longitudinal and (b) cross section

2 BRIDGES EXAMINED

A category I road bridge, whose cross section consists of two longitudinal beams, is considered.

The girders with stiffened webs have flanges and webs of variable thickness in the two segments (external and internal beams), in relation to bending and shear stress. In the cross section shown in figure 1, the concrete slab has variable thickness from 200 to 360 mm and the connection between the slab and the steel beams is ensured by studs with heads, whose deformability should be neglected.

In the decks with sinusoidal webs (figs. 3 and 4) the beams have the same characteristics along their entire length, the plate in r.c. has a height variable from 200 to 300 mm and it is transversely pre-stressed.

This solution allows the weights of the structure to be reduced and allows the slab to easily absorb the transverse actions produced on the flanges by the presence of the corrugation of the web.

The collaborating width of the slab is 6.85 m, lower than the effective width $b_{eff}=b_c+b_{e1}+b_{e2}$, being b_{ei} one eighth of the distance of the zero points of the diagram of moments.

The transverse beams consist of IPE750, with the upper and lower flanges and

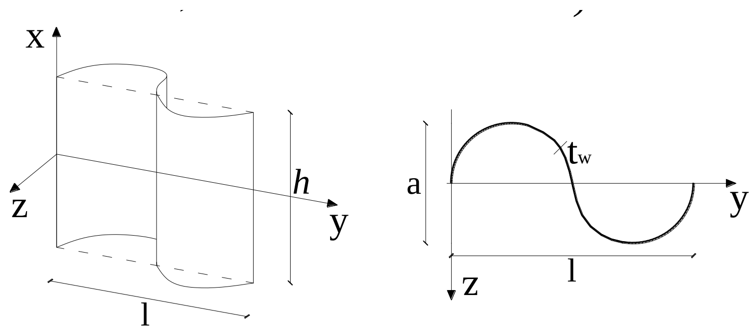

Figure 2. Shape of sinusoidal profile

the web connected to an half HEA 500, with flanges and high strength bolts (10.9). The transverse beams are spaced from the slab, to allow the insertion of the mobile formwork. The distance between the transversal beams is assumed to be 16.00 m for both types of beams (in flat and corrugated web).

The web of the longitudinal beams is 2500 mm high and the upper and lower flanges have a width of 800 mm and 1200 mm respectively. The webs are stiffened with 150x15 mm longitudinal ribs, the first placed at 600 mm from the top flange and the second at 800 mm from the first and with transversal ribs.

The steel beams with the stiffened webs, are divided into three segments 18.00 m long each. The following two types of sections are considered:

Table 1. Geometric characteristics of the longitudinal beams

Type	$b_{f,i}$ x $t_{f,i}$ [mm]	$b_{f,s}$ x $t_{f,s}$ [mm]	t_w [mm]	J [m^4]
1–external elements	1200x50	800x50	14	0.1770
2–internal elements	1200x60	800x60	12	0.2071

where $b_{f,i}$ and $b_{f,s}$ indicate the width of the upper and lower flanges, $t_{f,i}$ and $t_{f,s}$ the thickness of the flanges, t_w the thickness of web and J is the moment of inertia of the section.

The steel structural is S355 J2 class, having the yield tensile strength equal to 355 N/mm^2, and the resilience equal to 27 J at T=-20°C.

The concrete is C35/45 class, having the cylinder characteristic strength equal to 35 N/mm^2 and the reinforcement rebar is B450C class, having the yield tensile strength equal to 450 N/mm^2

The mechanical characteristics are:

- Concrete elastic modulus $E_c = 34.07$ kN/mm^2
- Coefficient of thermal expansion $\alpha = 1\ 10\text{-}5\ C^{-1}$
- Steel elastic modulus $E_a = 210$ kN/mm^2

The steel beams with the corrugated webs have the same shape for all the length. The flanges are made of S460 J2 and their thickness is 60 mm, while the webs are made of S355 J2 and their thickness is 12 mm.

The concrete is the same (C35/45) and the pre-stressing wires are Y1860 S7, having the ultimate tensile strength equal to 1860 N/mm^2.

For the shrinkage, assuming an environment with relative humidity of 75% from Tab. 11.2Va (It. Code) a value of $\varepsilon_{co} = -0.00025$ is obtained.

The effects of the creep related to time t_p of application of the load and at infinite time, are considered, adopting a concrete reduced elastic module E_{cs}. This value depends on the creep through the ψ_L and the $\varphi(\infty, t_p)$ factors, according to the following relationship:

$$E_{cs} = \frac{E_c}{1 + \psi_L \varphi(\infty, t_p)} \tag{1}$$

For the shrinkage we refer to 11.2.10.6 of the It. Code, which considers the total strain ε_{cs} as the sum of two components: the drying shrinkage ε_{cd} and the autogenous shrinkage ε_{ca}. These amounts are expressed as:

$$\varepsilon_{cs} = k_h\, \varepsilon_{c0} + \beta_{ds}\, \varepsilon_{cd\infty} \tag{2}$$

where all the coefficients are provided by the code.

The change in length associated with the shrinkage, in the case of longitudinal movements prevented, induces tensile stresses in the concrete deck N_{cs} expressed by the following relation:

$$N_{cs} = E_{cs}\, A_c\, \varepsilon_{cs} \tag{3}$$

The effort N_{cs} is transformed by applying two equal and opposite axial forces to the composite section. These forces are divided into a compression force applied in the center of the end sections and a bending moment N_{cs} d, being d the distance between the centers of the concrete slab and the center of the mixed section.

It is assumed a concrete age t_p equal to 30 days, ψ_L= 1.1 (EC4) and $\varphi(\infty, t_p)$=1.9 (Tab. 11.2.VI Italian Code). The value of reduced elastic modulus of the concrete at the infinite time is E_{cp} equal to 11.03 kN/mm^2, and the relative coefficient of homogenization n_{cp} is 19.

Assuming a time at which we consider shrinkage t_s of 1 day and an end time of 10000 days, the following values are obtained:

β_{ds} = 0.98 $\varepsilon_{ca,\infty}$= - 0.62 10^{-4} ε_{cs}= - 2.432 10^{-4}

Since the concrete area A_c is equal to 1.78 m^2 for the traditional girders and to 1.65 m^2 for the girders with corrugated web, the from (3,4), assuming t_0= 3 days, ψ_L=0.55 (EC4), $\varphi(\infty, t_0)$=3 (Tab. 11.2.VI) the following values are obtained:

stiffened web	E_{cs}=12.86 kN/mm^2	n_{cs}=16	N_{cs} =5567 kN
corrugated web	E_{cs}=12.86 kN/mm^2	n_{cs}=16	N_{cs} =5160 kN

The following actions applied on the deck, deducted in compliance with Eurocodes and Italian Code, are considered here:

- Weight of the traditional steel beams, of the ribs, of the transverse beams and of the concrete slab (g_1) related to each of the two beams is assumed to be equal to 83 kN/m for the external segments and equal to 80 kN/m for the internal segment;
- Weight of the steel beams with corrugated web, of the transverse beams and of the concrete slab (g_1) is assumed to be equal to 75 kN/m;
- The weight of the pavement and guardrails (g_2) is assumed to be equal to 3 kN/m^2 and 2 kN/m respectively, supported by the composite structure;
- Live loads;
- Shrinkage ε_{cs} and creep ε_2.

The variable actions are made up of 3 columns of loads, each with a width of 3.00 m and spaced 0.56 m (Figure 3). Each column consists of 2 pairs of equal concentrated forces Q_{ik} settled in the longitudinal direction at 1.2 m and in the transversal direction at 2.00 m, and strips of uniform load of q_{ik} entities.

The transverse distribution of loads, represented in Figure 3, is such as to induce the maximum eccentricity, which determines an increase of stresses in the beam nearest to the resultant.

A longitudinal scheme of beam hinged at the ends with the theoretical length L is considered, bearing the following load conditions:

- Cond. 1: Q_{ik} forces located at the center of the span;

- Cond. 2: Q_{ik}: forces located at the end of the span.

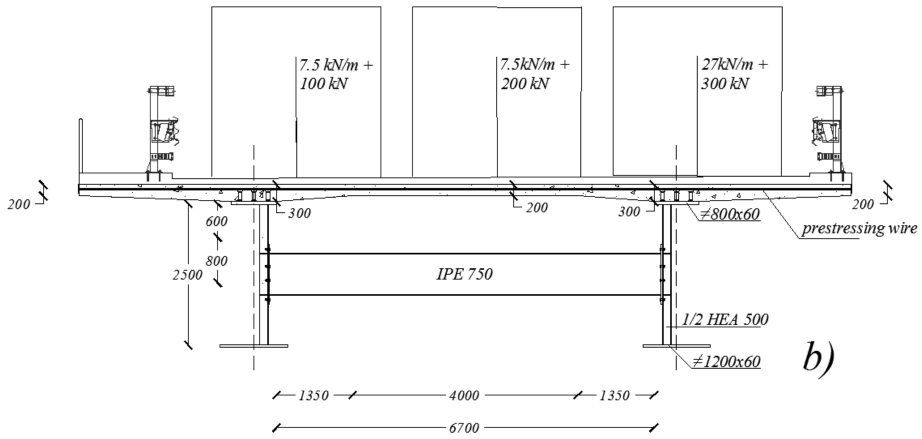

Figure 3. Composite deck with corrugated web girders and variable loads

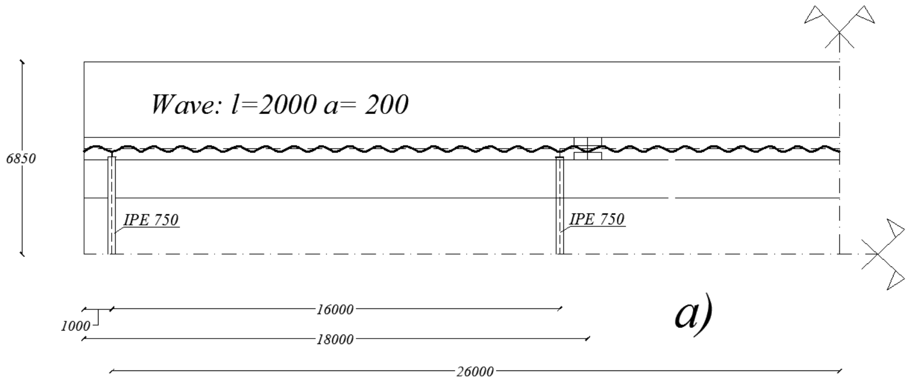

Figure 4. Horizontal section of girder with corrugated web

The Ultimate State Verification for normal stresses refers to buckling resistance, assuming the linear stress distribution with a maximum value of f_{yd} (class 3).
For the flexure verification of the beams with sinusoidal web, according to the EC3 recommendations, the contribution of the web is neglected, and the section consists only of the flanges.

For the shear verification of the web, the shear resistance V_{Rd} must be greater than V_{Sd}, for all load combinations.
The V_{Rd} is expressed by the following relationship:

$$V_{Rd} = \chi_c \frac{f_y}{\sqrt{3} \cdot \gamma_{M1}} h_w t_w \tag{4}$$

h_w and t_w being the height and the thickness of web, f_y the yield strength of the steel, γ_{M1} the safety factor equal to 1.1 for the bridges and χ_c a reduction factor which takes into account the instability of the web panel, assumed as the smallest of the $\chi_{c,l}$ and $\chi_{c,g}$ values, respectively related to local and global instability, given by the following expressions:

$$\chi_{c,l} = \frac{1.15}{0.9+\bar{\lambda}_{c,l}} \leq 1 \qquad \chi_{c,g} = \frac{1.5}{0.5+\bar{\lambda}^2_{c,g}} \leq 1 \tag{5}$$

$$\bar{\lambda}_{c,l} = \sqrt{\frac{f_y}{\tau_{cr,l}\sqrt{3}}} \qquad \bar{\lambda}_{c,g} = \sqrt{\frac{f_y}{\tau_{cr,g}\sqrt{3}}} \tag{6}$$

The evaluation of τ_{cr} is carried out in according to EC3-part 1-5 (annex D), considering sinusoidal corrugated steel web like an orthotropic plate. The flexure stiffness along the longitudinal direction D_y and transversal direction D_x are:

$$D_x = \frac{Et^3 l}{12(1-\nu^2)s} \qquad D_y = \frac{EI_z}{l} \tag{7}$$

where l is the length of the projection of the wave, s is the effective length and I_z is the moment of inertia of the wave with respect to longitudinal axis.
Using the stiffness above, it is possible to define $\tau_{cr,g}$ and $\tau_{cr,l}$ as:

$$\tau_{cr,g} = \frac{32.4}{t_w h_w^2}\sqrt[4]{D_x D_y^3} \qquad \tau_{cr,l} = (5.34+\frac{as/2}{2h_w t_w})\frac{\pi^2 E}{12(1-\nu^2)}\frac{2t_w}{s/2} \tag{8}$$

where the effective length *s* is:

$$s = l(1+\frac{\pi^2 a^2}{16l^2}) \tag{9}$$

3 NUMERICAL ANALYSES OF THE BEAMS

Numerical simulations were carried out by means of finite element (FE) analyses, with the code SAP2000 v.15. In particular, models were aimed at studying the behavior of the steel beams subjected only to dead loads of the beams and of the concrete deck. This condition was considered to simulate the first construction stage of the bridge. Three different beams were considered: corrugated web beam with a=100 mm (C100 model), corrugated web beam with a=200 mm (C200 model) and straight web beam (S model).

The beam is modeled with 3D solid elements. The transverse cross section was subdivided into 16 elements for each flange, while 4 elements were considered for the web. The beam is divided into vertical strips 100 mm in length along its longitudinal axis. Overall, 11359 joints and 5296 solid elements describe the complete geometry of the corrugated beams.

Each solid element was made up of linear elastic isotropic material having E = 210 GPa, ν = 0.3 MPa, γ = 76.97 kN/m^3.
Two conditions of restraint are considered:

a) Isolated beam with supports on the lower flange;
b) Connected beam also with cross-beams.

Joint restraints were considered at the beam's extremities, only in correspondence to the base joints. Displacements were restrained in each direction (X,Y,Z) for the left extremity, while axial displacements (X displacements) were allowed for the right extremity of the beam.

The transversal beams are arranged at intervals of 16 m and are modelled with a frame element (IPE 750) connected to the central node of the core. In relation to the structural and load symmetry, the secondary crossbeam was considered half, restrained at the end with a bi-pendulum (figure 6).

The analyses were performed in one step, and the following maximum mid-span deflections were obtained for the isolated beams:

- C200 model: f=27.94 mm
- C100 model: f=27.82 mm
- S model: f=27.19 mm

Applying the well-known expression of the maximum deflection in a simply supported beam the following values of the displacement f are obtained:

- for the corrugated web (models C200 and C100), adopting the same weight of 11,78 kN/m and the same moment of inertia J=0.1888 m^4, f=28.27 mm;
- plane web beams (S model) adopting the mean value of the moment of inertia J_m of the two segments: J_{est} = 0.1770 m^4 , J_{int}=0.2071, J_m = 0.1920 and the mean value of the weight (11.42 kN/m), f=26.96 mm.

These values were calculated assuming self weight as a distributed load for unit length and a free span of 52 m.

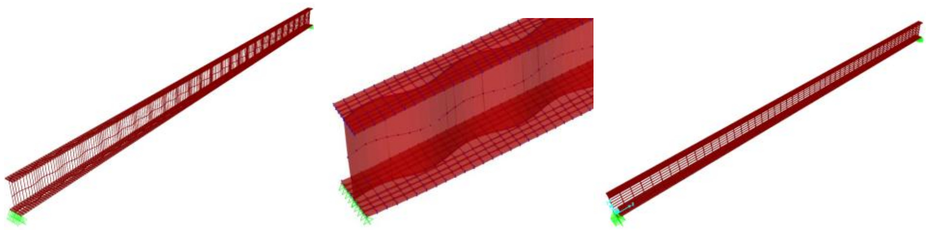

Figure 5. Numerical FE Models: corrugated web beam (C200) and plane web beam (S)

The calculation of the moment of inertia was made with reference to the effective section for the S model, while an idealized section, assumed neglecting the web, was considered for corrugated web beams (J=0.1888 m^4), according to the provisions of the code.

As expected, good accordance is observed between the closed form predictions and the FE results with slight overestimations for the corrugated web beams and underestimation of the deflection for the straight web beam.

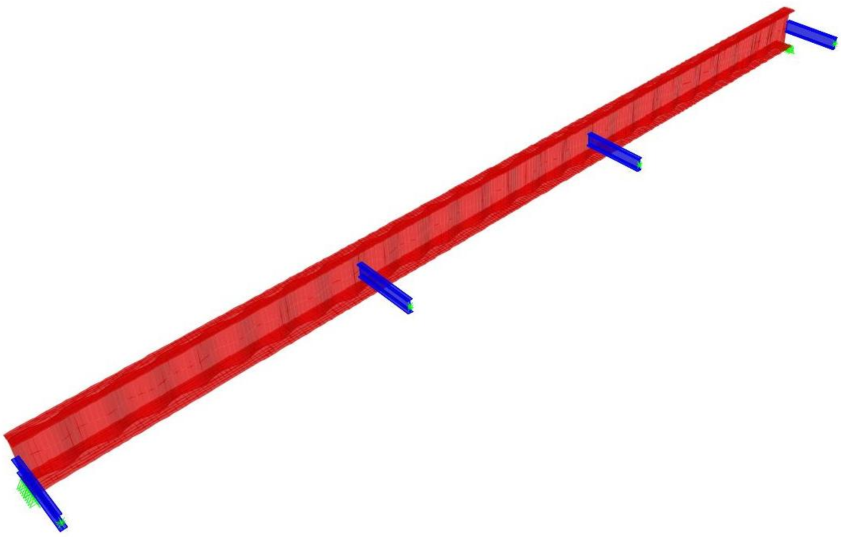

Figure 6. Numerical FE Models: corrugated web girder (C200) with transversal beams

However, despite this expected result, deformed shapes of corrugated web beams obtained numerically have also shown an out-of-plane deflection (fig. 7). The transversal displacements are different for the single beam and the beam restrained by the transversal beams:

a) For the single beam the transversal displacement of the upper flange at the ends has a value of 5.07 mm for C200 model and of 3.2 mm for the C100 model.
b) In the model with transversal beams the value of transversal displacement at the same tip is 2.61 mm for C200 model and 1.8 mm for the C100 model.

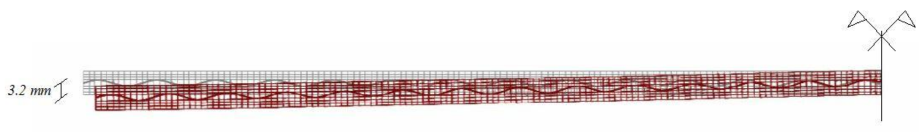

Figure 7. Out-of-plane deflections in corrugated web beams (C100 model)

This effect is well documented in the literature [1, 2, 3], and it is induced by a transverse bending moment due to the sinusoidal shape of the web. The plot of principal stresses shows that the web corrugation induces a non uniformity of principal stresses in the flanges. A stress concentration was observed in the flanges in correspondence to the maximum amplitude of the web corrugation the web, even the average stress values were similar to those recorded in straight beam.

The effect of this warping deflection was also more marked when observing the color plot of principal stresses at the beam's extremities. It was observed that stress distribution in corrugated beams approached an irregular trend which induced stress concentration and variation of the stress along the flanges (Figure 8a - 8b). On the other hand, the trend of principal stresses was more regular in straight beams (Figure 8c - 8d).

The values of V_{Rd} and the instability factors of the web in according to EC3 are shown in Tables 2 and 3.

Table 2. Geometric characteristics of girder with corrugated web

Type	t_w [mm]	a [mm]	l [mm]	web weight [kN/m]
C100	12	100	2000	2.359
C200	12	200	2000	2.370

The fig. 8a shows the minimum principal stress (C200 model); the fig. 8b shows the maximum principal stress (C200 model); the fig. 8c shows the minimum principal stress (S model) and the fig. 8d shows the maximum principal stress (S model).

Table 3: Stability factors of the web and V_{Rd}

Type	$\chi_{c,g}$	$\chi_{c,l}$	χ_c	V_{Rd} [kN]
C100	2.999443	1.08	1	5856
C200	2.999444	1.13	1	5856

The Tab. 3 values show that the amplitude of the sine wave of 100 mm is sufficient to ensure the stability of the web. A well designed shape corrugation should ensure a global stability factor close to 1.

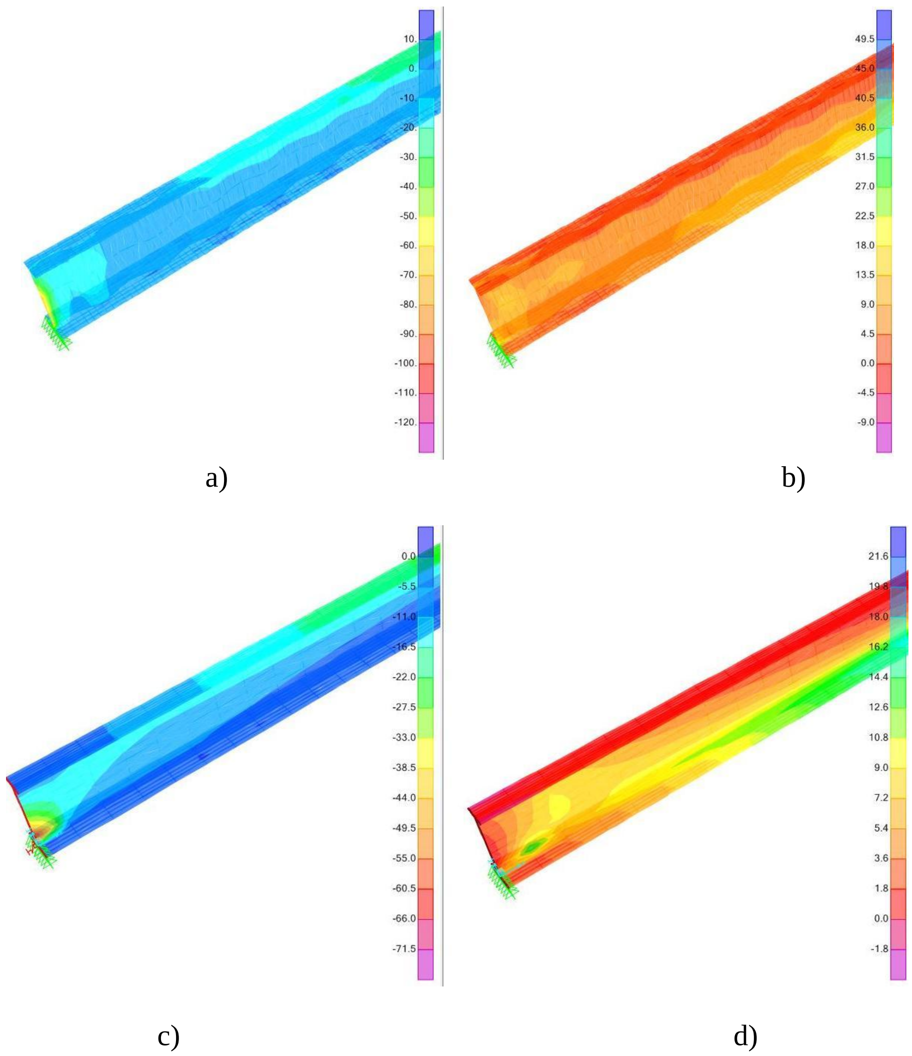

Figure 8. Principal stresses in the extremity zone of the beam (MPa);

CONCLUSIONS

The comparison between the two types of bridge girders with plain and stiffened webs and with corrugated webs has highlighted some peculiarities of the behavior.

It is observed a transversal distribution of stresses dues at the corrugated shape of the web. With reference at the live load of the bridge these incremental stresses are absorbed from the reinforced o pre-stressed plate. That solution allows us to reduce the weight of the web girder. Further developments will be reported in other papers.

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