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Influence of viscous phenomena on steel-concrete composite beams with normal or high performance slab

M. Fragiacomo†, C. Amadio‡ and L. Macorini‡†

Department of Civil Engineering, University of Trieste, Piazzale Europa 1, 34127 Trieste, Italy

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Abstract. The aim of the paper is to present some results about the influence of rheological phenomena on steel-concrete composite beams. Both the cases of slab with normal and high performance concrete for one and two-span beams are analysed. A new finite element model that allows taking into account creep, shrinkage and cracking in tensile zones for concrete, along with non-linear behaviour of connection, steel beam and reinforcement, has been used. The main parameters that affect the response of the composite beam under the service load are highlighted. The influence of shrinkage on the slip over the supports is analysed, together with the cracking along the beam. At last, by performing a collapse analysis after a long-term analysis, the influence of rheological phenomena on the ductility demand of connection and reinforcement is analysed.

Key words: composite beams; steel; concrete; high performance concrete; creep; shrinkage; rheological phenomena; long-term behaviour; collapse analysis.

1. Introduction

It is well known how viscous phenomena due to shrinkage and creep of concrete affect the response of steel-concrete composite beams. This influence is significant in terms of both stresses and strains, above all in serviceability conditions. The evaluation of these effects is rather complex because of:

- the non-linear behaviour of the connection system, even for low shear forces;
- the concrete cracking in zones of hogging bending moment and, if the neutral axis is into the slab cross section, even in zones of sagging bending moment.

The compressive strength class of the concrete can play a very important role on the structural response since a strength increment generally raises the stiffness and drops the connection ductility (Bullo and Di Marco 1995). Besides, an increment of strength involves an increase of the autogenous shrinkage, especially during the first days after casting, an increase of the tensile strength and a decrease of the creep effects (Hilsdorf and Müller 1999).

It may then be important to evaluate how these different aspects affect the response of the composite beam. The aim of this paper is to find out possible limits in current codes. In fact prediction models for creep and shrinkage of high performance concrete have just recently been proposed (Hilsdorf and Müller 1999). Because of the many parameters that influence the problem, some preliminary numerical

†PhD Researcher
‡Associate Professor
‡†PhD Student

analyses have been performed. They may be useful to correctly address possible experimental tests, which are essential to validate theoretical results.

In this paper the results of an analysis performed on two composite beams are reported. The first is a one-span simple supported beam, which is typical of bridge structures. The second one is a two-span continuous beam, which is typical of buildings. To highlight the effects of the concrete strength class on the structural behaviour, both beams are analysed assuming that the slab is built with normal (NC) or high performance concrete (HPC).

For both kinds of concrete, the analysis is carried out using a finite element program that can take into account all phenomena affecting the long-term behaviour, like creep, shrinkage and cracking of concrete. To better understand limits and at the same time the significance of the analysis, the basic hypotheses assumed in the program to model the material behaviour are presented.

For normal concrete, the creep and shrinkage prediction models proposed by CEB-FIP M.C. 90 (C.E.N. 1993) and by a recent enhancement proposal (Hilsdorf and Müller 1999) are adopted. For high performance concrete, only the latter is adopted. It represents an extension of the CEB-FIP M.C. 90 based on experimental data of the Rilem data bank. Tension stiffening phenomenon is modelled by means of a softening law of concrete in tension after cracking (Stevens *et al*. 1991).

After having pointed out the reliability of the composite beam modelling, a series of comparisons varying the softening law and environmental conditions is carried out. It is underlined how shrinkage effects are meaningful for correctly assessing the shear force in the connection and the cracking of the slab along the beam. The effect of the connection deformability on the structural response under the serviceability load is presented as well.

Finally a collapse non-linear analysis is performed at short and long-term, i.e. before the beginning and after that viscous phenomena have fully developed, with the aim to show possible differences in behaviour of the composite beam. A significant influence of rheological phenomena on the ductility demand of reinforcement and on the ultimate slip demand of connection is observed.

2. The adopted numerical model

The composite beam adopted in this analysis is schematised in Fig. 1. It is constituted by two parallel beams: an upper one, which represents the concrete slab, and a lower one, which represents the steel beam. They are connected by a continuous non-linear spring system, which represents the connection, usually constituted by Nelson studs, hypothesised smeared over the element length.

To properly model the material behaviour in all its phases, the cross section of each component beam has been divided into a finite number of fibres (Fig. 1). The assumed kinematic hypotheses are similar to those adopted in the model of Newmark *et al*. (1951), which are:

1) negligibility of the shear strains;
2) equal vertical displacements $v_c = v_s = v$;
3) preservation of the plain sections for the single component beams (slab and steel);
4) perfect bond between concrete and reinforcement.

The hypotheses on material behaviour to evaluate long-term solutions under the service load are:

1) concrete is regarded as linear-viscoelastic in compression and in tension before cracking. Tension stiffening effect due to reinforcement is taken into account by the non-linear softening law proposed by Stevens *et al*. (1991), as it was demonstrated to be suitable for studying steel-concrete composite beams

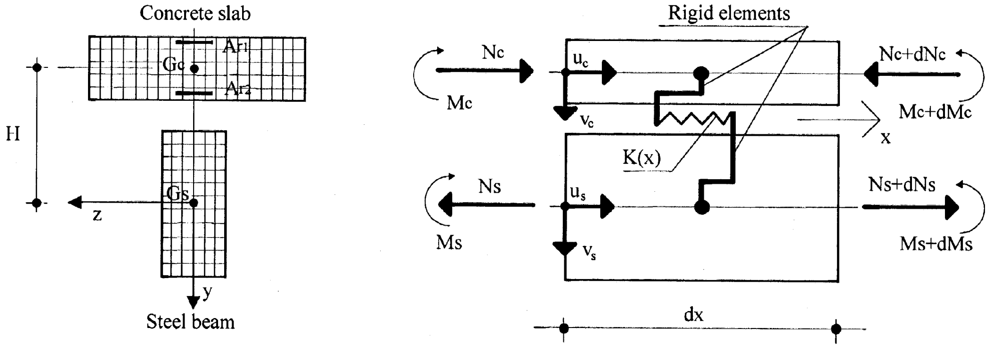

Fig. 1 The used finite element

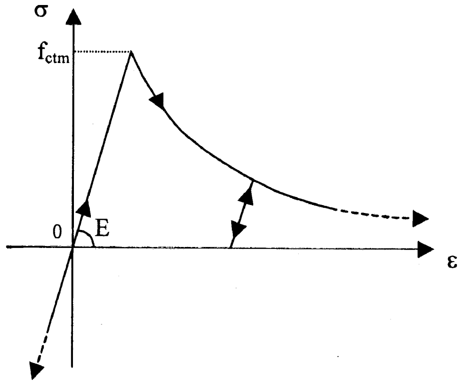

Fig. 2 Assumed stress-strain law for concrete in tension

(Amadio and Fragiacomo 1999). In case of strain reduction after cracking, the stiffness is assumed to be equal to the elastic one (Fig. 2). In the cracked phase, creep is considered as tied only to the elastic part of the total strain. The adopted creep laws for NC and HPC are compared in Fig. 3a for an average environmental relative humidity $RH = 75\%$, a notational size of member $h = 20$ cm and a mean compressive cylindrical strength f_{cm} = 34 MPa for NC and f_{cm} = 80 MPa for HPC. The notational size is given by the formula $h = 2A_c / \bar{u}$, where A_c and $\bar{u}$ are the area and perimeter of the cross section exposed to the atmosphere, respectively. It can be observed that the two prediction models are almost coincident for NC, while they present considerable differences for HPC. To evaluate the importance of the tension stiffening effects, the case of elastic-brittle material in tension will also be considered;

2) reinforcement and steel are assumed to be elastic-plastic with a final hardening branch;

3) for connection, the non-linear law proposed by Ollgard *et al.* (1971) is considered for the loading branch, and the experimental law proposed by Gattesco (1997) is assumed for the unloading branch;

4) shrinkage is regarded as an inelastic strain constant over the cross section with the same value in cracked and uncracked zones. The prediction model proposed by Hilsdorf and Müller (1999) is assumed for both NC and HPC. According to this model, the total shrinkage is given by the sum of autogenous and drying components, where the former is important especially for young concrete. The adopted laws for NC and HPC are compared in Fig. 3b using the values of *RH*, *h* and f_{cm} already employed for the comparison in terms of creep laws. It may be noted as the autogenous component is more significant for HPC. However, after a long period of time, NC shows the largest total shrinkage strain;

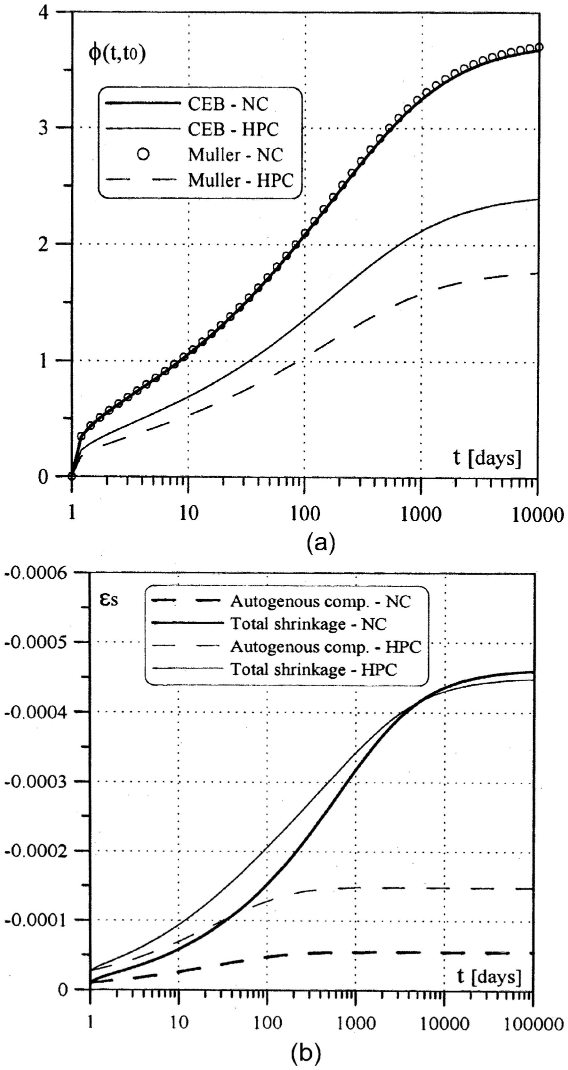

Fig. 3 (a) Trend of the creep coefficient in time, (b) Trend of the shrinkage strain in time

5) tensile and compressive strength of concrete are considered as constant or variable in time according to the laws proposed by CEB-FIP M.C. 90 (CEN 1993).

The hypotheses on material behaviour in order to evaluate the short-term (after 28 days since the concrete casting) or the long-term collapse solution (after 30000 days since the concrete casting) are:

1) for concrete in compression, the laws of Mander *et al.* (1988) and Razvi and Saatcioglu (1999) are adopted in case of NC and HPC respectively. Both laws are characterized by an elastic behaviour up to 40% of the maximum strength, and by an elastic-plastic behaviour with a final softening branch beyond the elastic limit;

2) for concrete in tension, reinforcement, steel beam and connection, the same laws adopted for the

long-term solution under the service load are used.

Because of the very general hypotheses, the complexity of both viscous and collapse analyses is evident. The integration in time of the viscous problem may encounter convergence problems due, above all, to the presence of the softening branch for concrete. To overcome these problems, a new iterative procedure based on an incremental method of the secant stiffness was developed. Using this method, good results in terms of both convergence and computational time can be obtained. More detailed information on the numerical procedure and validity of hypotheses assumed for materials can be found in previous papers (Amadio and Fragiacomo 1997, 1999, Amadio *et al.* 2000), where a series of comparisons at short and long-term between experimental and numerical solutions were performed.

3. Numerical analyses

The aim of this study is to point out effects on steel-concrete composite beams due to creep and shrinkage in case of a slab of normal (NC) or high performance concrete (HPC). To obtain general results, two types of beam are analysed:

1) a one-span simply-supported beam, typical of bridges, that has already been analysed numerically for short-term loading with NC (Aribert 1988) and HPC slabs (Bullo and Di Marco 1988);

2) a two-span continuous beam, simply-supported, typical of buildings, that has already been analysed experimentally for short-term loading (Ansourian 1982) and also numerically for long-term loading (Amadio and Fragiacomo 1999, Amadio *et al.* 2000) in case of a NC slab.

Both beams have full connection, according to Eurocode 4 (CEN 1992).

3.1. One-span beam

3.1.1. Geometrical and mechanical properties

The analysed beam (Aribert 1988) is displayed in Fig. 4, together with the geometrical properties. A notational size of the slab h = 13.3 cm and an average environmental relative humidity RH = 75% are assumed. The normal concrete has a mean compressive cylindrical strength after 28 days since the casting f_{cm} = 35 MPa and a mean tensile strength f_{ctm} = 3.19 MPa. For high performance concrete the

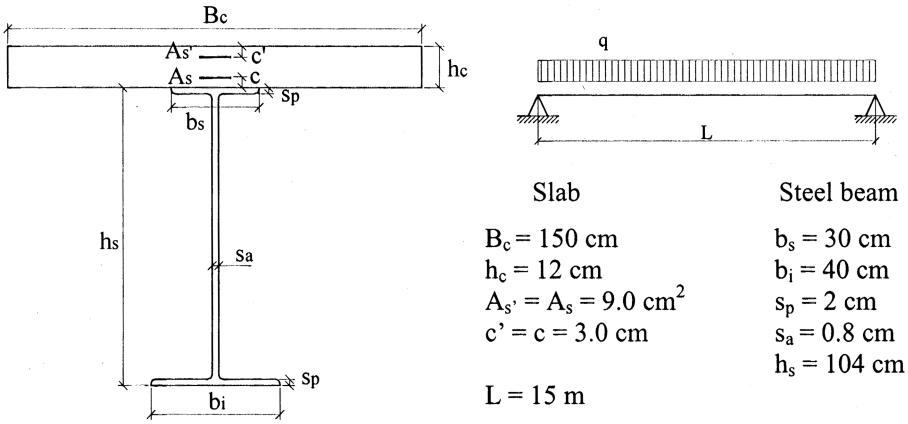

Fig. 4 Geometrical characteristics of the one-span beam

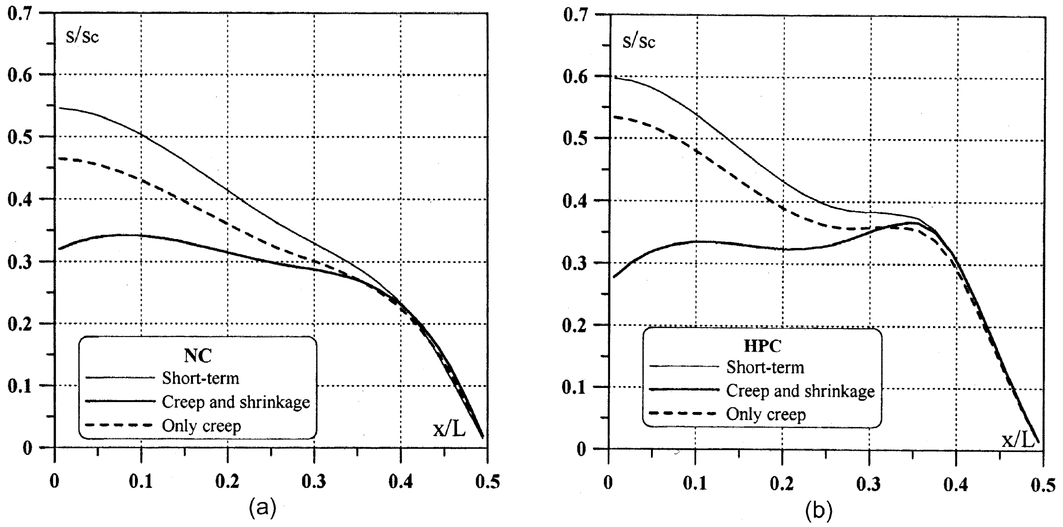

Fig. 5 Dimensionless slips along the beam, (a) (NC), (b) (HPC)

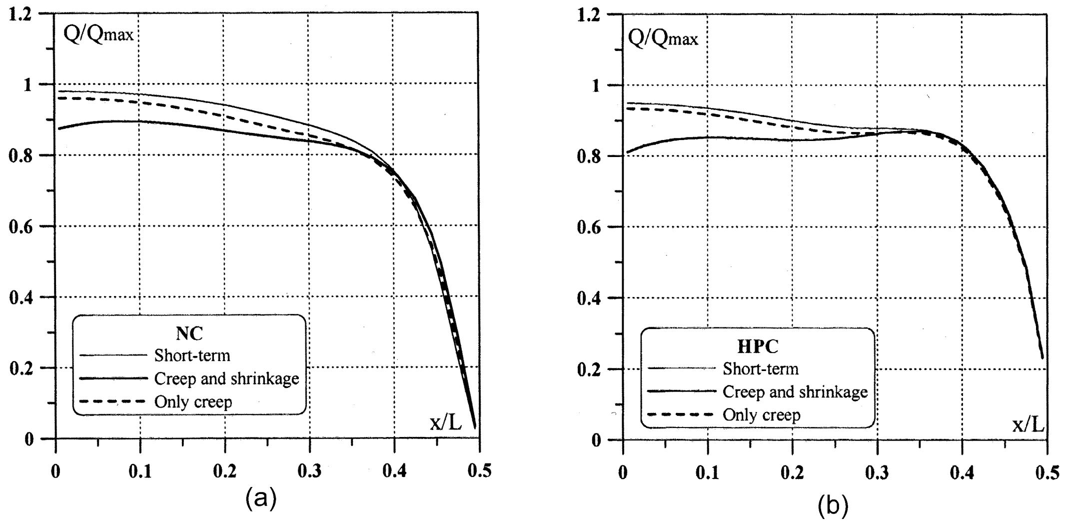

Fig. 6 Dimensionless stud shear forces along the beam, (a) (NC), (b) (HPC)

corresponding values are $f_{cm} = 80$ MPa and $f_{ctm} = 4.66$ MPa. Steel beams and bars have a Young's modulus $E_s = 210000$ MPa and a yield stress $f_y = 360$ MPa. Steel has a hardening modulus $E_{sh} = 100$ MPa, whereas for reinforcement an elastic-perfectly plastic behaviour is assumed. To model the connection system, the law of Ollgard *et al.* (1971), $Q = Q_{\max} \cdot (1 - e^{-\beta s})^{\alpha}$, is used. In this equation Q is the shear force on the stud, $Q_{\max}$ is the collapse value, s is the slip, α and β are constant parameters. They assume different values for the two types of concrete (Bullo and Di Marco 1998): for NC $\alpha = 1.17$, $\beta = 1.15$ mm^{-1} and $Q_{\max} = 110$ kN, for HPC $\alpha = 0.5$, $\beta = 1.10$ mm^{-1} and $Q_{\max} = 190$ kN. Ultimate slips of studs are also different, due to the diverse ductility of NC and HPC: the values $s_c = 0.7$ cm and $s_c = 0.35$ cm are, respectively, adopted (Bullo and Di Marco 1995, 1998).

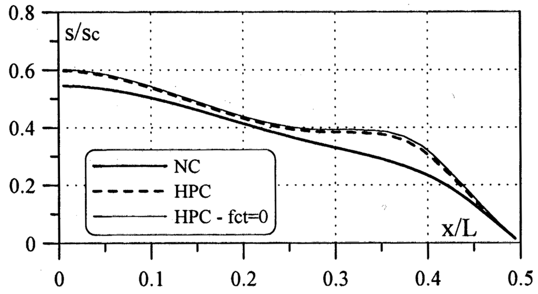

Fig. 7 Dimensionless slips along the beam for the collapse load in a short-term analysis

3.1.2. Numerical results

In Figs. 5(a), (b) the trends of dimensionless slips along the beam axis are plotted for NC and HPC slab respectively. Three kinds of analyses are performed:

1) step by step analysis up to the collapse, performed at the instant t_i = 28 days since the concrete casting, where the shrinkage effect before t_i is neglected;

2) step by step analysis up to the collapse, performed at the instant t_f = 30000 days since the concrete casting, after a viscous analysis. It is performed applying a service load equal to 40% of the collapse load P_u evaluated by a plastic analysis during the period between t_i and t_f, and neglecting the shrinkage effect;

3) like the previous analysis, but considering the shrinkage effect.

In Figs. 6(a), (b) the trends of dimensionless stud shear forces along the beam axis are plotted for NC and HPC slab respectively, considering the same types of analysis above seen. The beams qualitatively show a similar trend for NC and HPC. The concrete shrinkage produces a favourable effect on connection that is more important for HPC because of the greater connection stiffness, however

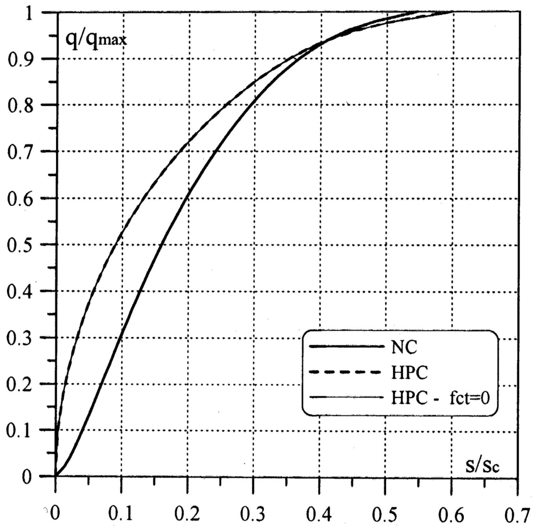

Fig. 8 Dimensionless slips over the support versus the load

inelastic strains due to shrinkage are larger for NC compared to HPC. Thus the ductility demand of connection may be assessed on the basis of a short-term collapse analysis.

In Fig. 7 the slips along the beam axis are compared, and in Fig. 8 the dimensionless load-slip curves are plotted, for NC and HPC in the long-term collapse analysis. It may be noted that the ductility request for HPC is just lightly higher with respect to the one for NC, however the final values are reached following two different paths in terms of load-slip curve. These results are in a good agreement with the ones obtained by Bullo and Di Marco (1998), where the concrete tensile strength was neglected. The thin solid line in Fig. 8 represents this kind of solution: it may be concluded that the concrete tensile strength does not affect significantly the solution.

In Figs. 9(a), (b) the ratio between the mid-span deflection δ and the elastic one evaluated in hypotheses of rigid connection δ_e is plotted under the service load in a long-term viscous analysis for NC and HPC. The increment of deflection is higher for NC compared to HPC due to the different creep and shrinkage laws. The hypothesis of rigid connection is more appropriate for HPC than for NC. The environmental relative humidity affects in an important way the long-term response. Finally it must be underlined that, if the change of concrete strength in time is considered, the only shrinkage effect without any other load does not produce cracking into the slab in terms of medium values, despite of the higher autogenous component in case of HPC, even for completely propped beam.

3.2. Two-span continuous beam

3.2.1 Geometrical and mechanical properties

The analysed beam (Ansourian 1982) is displayed in Fig. 10, together with the geometrical properties. A notational size of slab h = 11.43 cm and an average environmental relative humidity RH = 0.5 are assumed. The normal concrete has a mean compressive cylindrical strength after 28 days since the casting f_{cm} = 34 MPa and a mean tensile strength f_{ctm} = 3.14 MPa. For the high performance concrete the

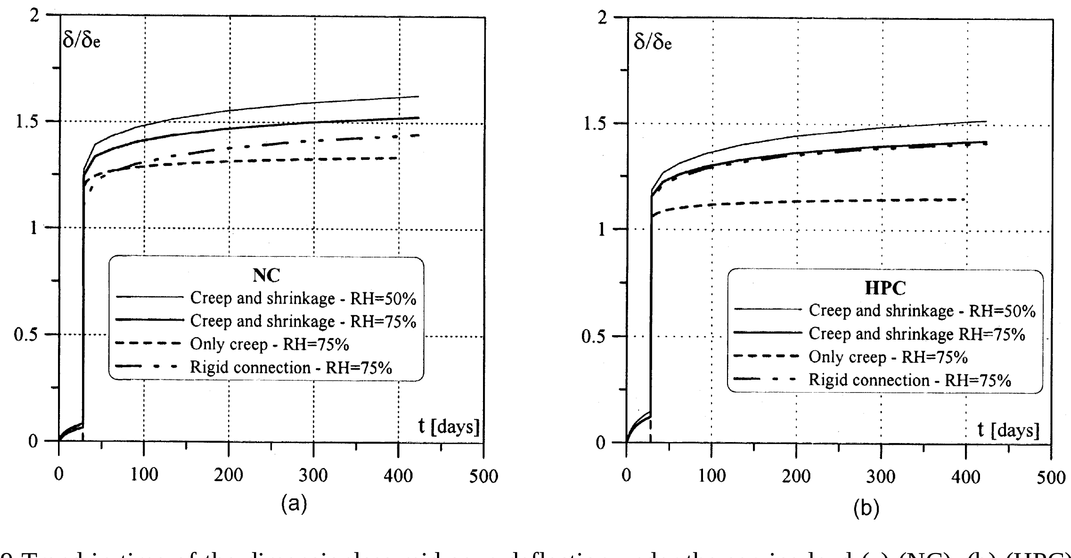

Fig. 9 Trend in time of the dimensionless mid-span deflection under the service load (a) (NC), (b) (HPC)

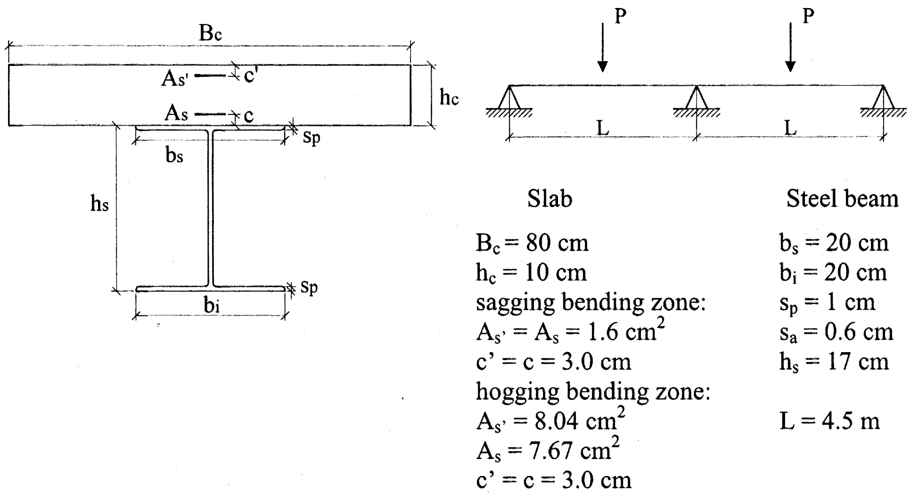

Fig. 10 Geometrical characteristics of the two-span beam

corresponding values are f_{cm} =80 MPa and f_{ctm} = 4.66 MPa. The steel has a Young's modulus E_s = 200000 MPa, a yield stress f_y = 237 MPa and an ultimate strength f_t = 397 MPa. The reinforcement has a Young's modulus E_s = 200000 MPa, a yield stress f_y = 430 MPa and an ultimate strength f_t = 533 MPa. For both materials an elastic-plastic with hardening branch law is assumed. The degree of shear connection, evaluated according to Eurocode 4 (CEN 1992), is equal to 1.3 in the zone of sagging bending, and equal to 1.5 in the zone of hogging bending. The parameters adopted in the Ollgard's law are: for NC $\alpha = 0.8$, $\beta = 0.7\ \text{mm}^{-1}$ and $Q_{\max}$ = 106 kN, for HPC $\alpha = 0.5$, $\beta = 1.10\ \text{mm}^{-1}$ e $Q_{\max}$ = 190 kN. The assumed ultimate slips of studs are s_c = 0.7 cm and s_c = 0.35 cm for NC and HPC respectively.

3.2.2. Numerical results

The same three kinds of analyses already seen in Section 3.1.2 are performed also for the continuous beam. The only difference concerns the service load, which is assumed equal to 50% of the collapse load P_u evaluated by a plastic analysis. In Fig. 11a,b the load versus mid-span deflection curves are plotted for NC and HPC respectively. The cases of f_{cm} constant in time, elastic-brittle concrete in tension and rigid connection are considered as well. By comparing the beam responses for NC and HPC, a significant increase of the collapse load may be observed for HPC. The hypothesis of rigid connection is adequate for HPC, whereas it overestimates both stiffness and strength in case of NC. The tension stiffening effect produces only small differences with respect to the case with elastic-brittle concrete.

Creep and shrinkage effects do not affect very much the collapse load, even if the concrete compressive strength is supposed to be constant in time. However, the numerical collapse load is higher compared to the one determined by means of the plastic analysis P_u. The ductility demand of the reinforcement near the intermediate support is instead significantly changed compared to a short-term analysis (Figs. 12(a), (b)). The shrinkage effect may increase the bar strains of 25 to 30%. The ductility demand is in any case much lower with respect to the available values for steels commonly used in reinforced concrete structures.

The trend in time of the mid-span deflection under the service load (Figs. 13(a), (b)) is similar to that

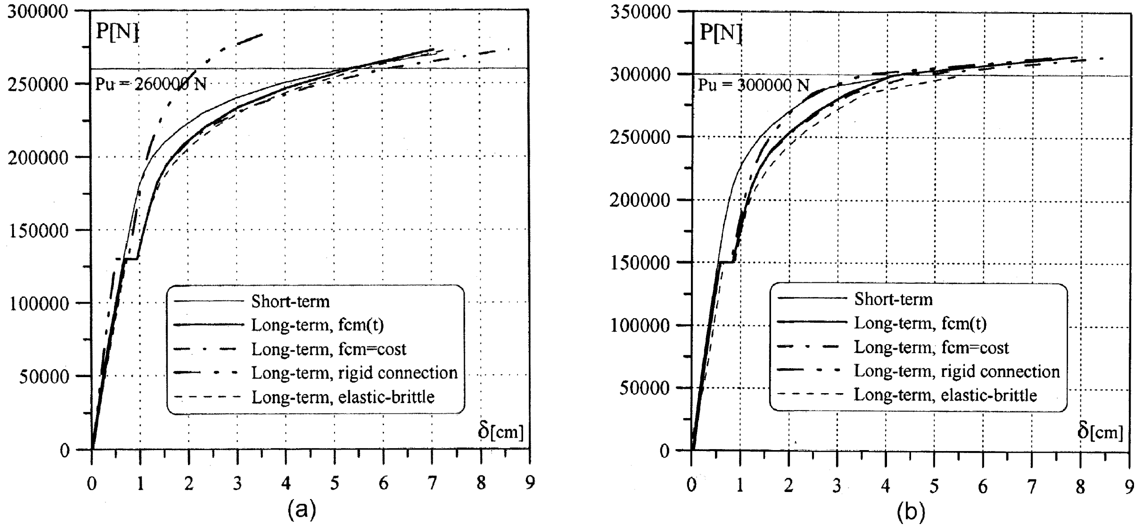

Fig. 11 Load versus mid-span deflection in a short and long-term analysis, (a) (NC), (b) (HPC)

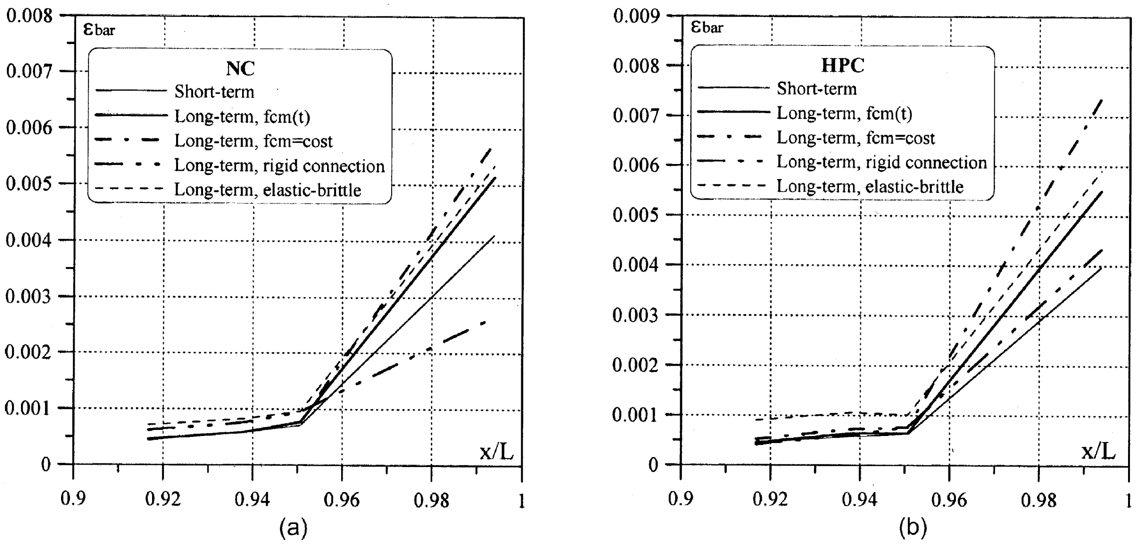

Fig. 12 Strain in the upper bars over the middle support, (a) (NC), (b) (HPC)

above seen for the one-span beam. In this case the effect of the connection deformability is more evident. The variation of environmental relative humidity affects significantly the beam behaviour. In Figs. 14(a), (b) and 15(a), (b) the trends of dimensionless stud shear forces and slips along the beam axis are plotted for NC and HPC slab respectively. Some significant differences between long and short-term solutions may be noted near to the lateral supports and the concentrated loads. The shrinkage effect modifies the connection response near the lateral supports especially for HPC, where an inversion of shear forces can even appear (Fig. 14b).

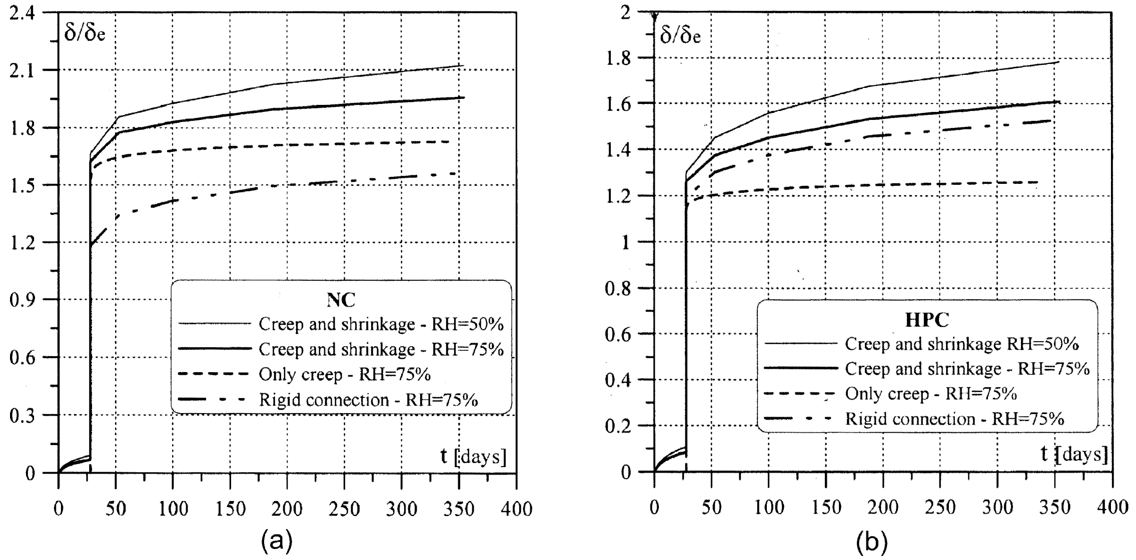

Fig. 13 Trend in time of the dimensionless mid-span deflections under the service load, (a) (NC), (b) (HPC)

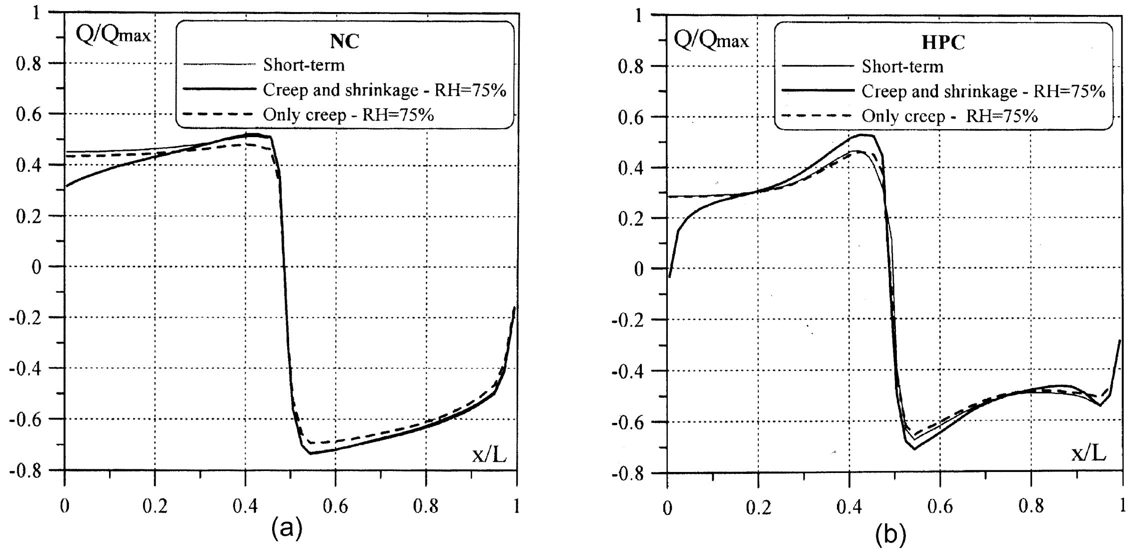

Fig. 14 Trend of the dimensionless connection shear force along the beam under the collapse load, (a) (NC), (b) (HPC)

In Figs. 16(a), (b) the crack pattern is displayed. The effects of creep and shrinkage are more important for NC, because of its prediction laws (Figs. 3a, b) compared to HPC. Cracks develop in the middle span and over the intermediate support. The better mechanical and viscous properties of HPC with respect to NC seem to produce therefore a more favourable behaviour even in terms of cracking and durability.

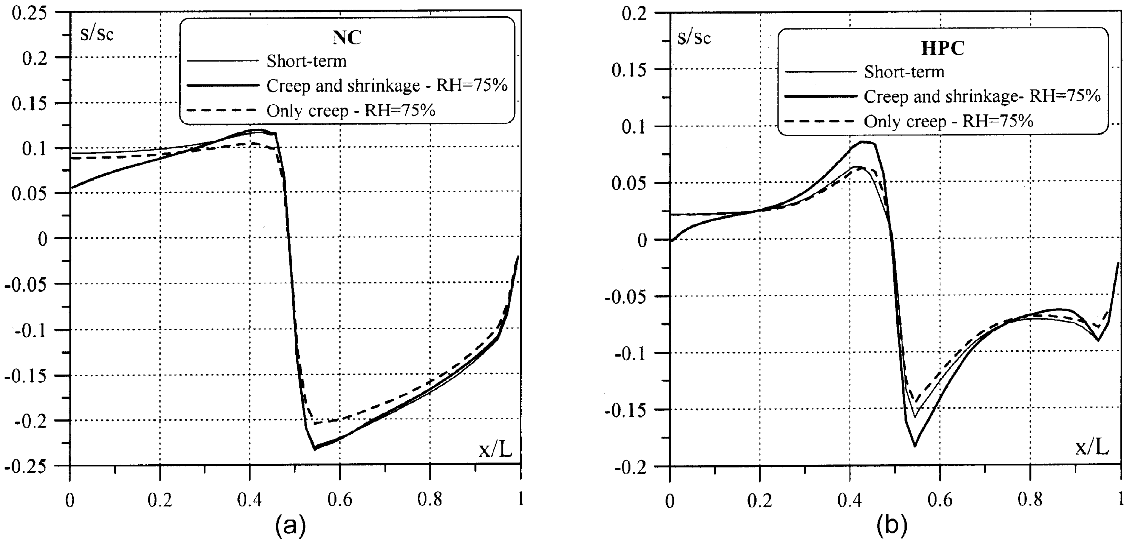

Fig. 15 Trend of the dimensionless slip along the beam under the collapse load, (a) (NC), (b) (HPC)

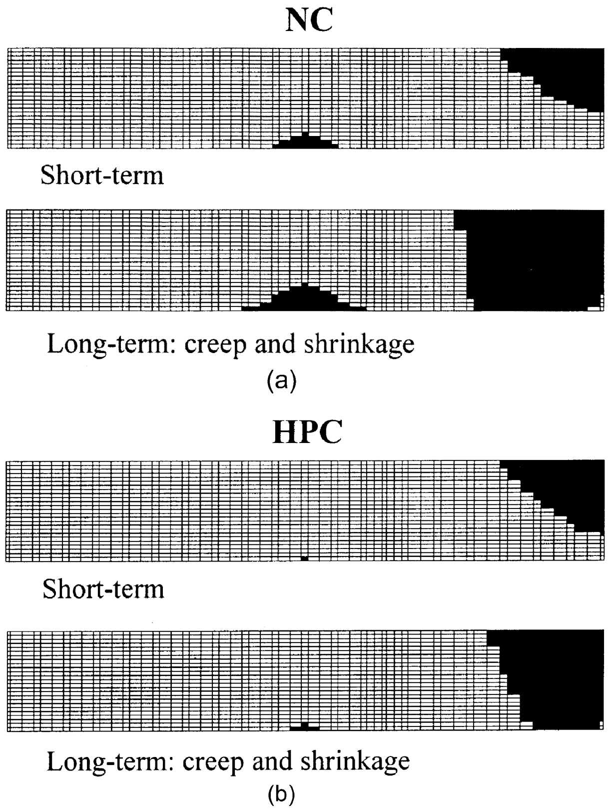

Fig. 16 Cracking pattern of the slab under the service load, in a short and long-term analysis, for the left span, (a) (NC), (b) (HPC)

4. Conclusions

In this work, the responses of two kinds of beams are analysed by means of a finite element program developed to study accurately the short and long-term behaviour of steel-concrete composite beams. The first is a one-span simply-supported beam, typical of bridge structures, and the second one is a two-span continuous beam typical of buildings. They are studied considering a slab built using normal (NC) or high performance concrete (HPC).

From these comparisons, the main remarks are:

- the ratio between required and available ductility of connection is very similar in both cases of NC and HPC;
- creep and shrinkage produce only limited increase of connection shear forces in the zones near concentrated loads. Near the lateral supports, the shrinkage effects are significant but generally on the safe side since they produce a reduction of shear force and slip;
- these effects lead to an increase of ductility demand for reinforcement, near to the collapse, of about 30% of the short-term value. However, this value is much lower than the available ductility of conventional steel;
- in terms of deformability under the service load, no considerable difference is observed between NC and HPC. Only a higher influence of the viscous phenomena may be noted for NC;
- due to the higher stiffness of connection for HPC, in case of full connection its deformability may be neglected for the evaluation of short and long-term deflections;
- better mechanical and rheological characteristics of HPC imply a more favourable behaviour with respect to NC also in terms of crack pattern and durability of the structures.

From these preliminary analyses it is possible to remark that HPC slabs improve the behaviour of the composite beam in terms of both strength and deflection with respect to NC. In particular, the viscous phenomena are less important for HPC slab, which therefore represents a good combination with the steel beam.

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