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Analysis of rigid and semi-rigid steel-concrete composite joints under monotonic loading Part II: Parametric study and comparison with the Eurocode 4 proposal

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Abstract. This paper analyses the response of rigid and semi-rigid steel-concrete composite joints under monotonic loading. The influence of some important parameters, such as the presence of column web stiffening and the mechanical properties of component materials, is investigated by using a three-dimensional finite element modelling based on the Abaqus code. Numerical and experimental responses of different types of composite joints are also compared with the analytical results obtained using the component approach proposed by Eurocode 4. The results obtained with this approach generally fit well with the numerical and experimental values in terms of strength. Conversely, some significant limits arise when evaluating initial stiffness and non-linear behaviour of the composite joint.

Key words: Abaqus code; beam-to-column connection; Eurocode 4; semi-rigid joints; steel-concrete composite joints.

1. Introduction

The real behaviour of steel joints has been thoroughly investigated to date. Careful consideration was used to determine the moment-rotation law for the joint, which significantly affects the global response of frame structures under both monotonic and cyclic loading. Together with the other structural components (columns and beams), the joints also have to be modelled when analysing the frame. The cases of pinned and rigid joints represent only two limit cases employed in simplified analyses. The opportunity to achieve more detailed calculations and, most significantly, the possibility to reduce structural costs by using simple beam-to-column connection details have led to model the joint as a semi-rigid connection.

Originally, this type of study was developed for steel structures. Recently, however, research in this area has focused mainly on steel-concrete composite structures, for which the use of semi-rigid joints has been demonstrated to be particularly appropriate. The use of simple details in steel beam-to-column connections together with the presence of reinforcement in the concrete slab reduces costs and at the same time improves the joint behaviour. For braced frames, the presence of a reinforced concrete slab

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in the zones of hogging bending moment raises both stiffness and strength of the joint. A better behaviour in terms of both maximum deflections and vibrations at the serviceability limit state is also obtained. In addition, improvement of the joint behaviour allows the frame to resist horizontal actions without the need for bracings, according to a semi-continuous scheme. A multi-storey frame with semi-rigid composite joints may then represent a very attractive technique for both domestic and commercial buildings in order to reduce the duration of construction and to improve the cost-to-benefit ratio.

Different approaches can be employed in order to evaluate the moment-rotation law $M-\theta$ of a semi-rigid joint (Nethercot and Zandonini 1989, Zandonini 1989, Mazzolani and Piluso 1996):

- *analytical models*, based on mathematical formulations where the parameters of the $M-\theta$ curve are expressed as a function of mechanical and geometric properties of the composite joint (Nethercot and Zandonini 1989, Li *et al*. 1996b, Xiao *et al*. 1996, Wong *et al*. 1996, Faella *et al*. 2000);
- *mechanical models*, also called "spring models" or "component models", based on the use of both rigid and flexible elements appropriately linked to each other (Anderson and Najafi 1994, Tschemmernegg and Queiroz 1995, Ren *et al*. 1996, Tschemmernegg 1998, Dissanayake *et al*. 2000, Kattner and Crisinel 2000, Faella *et al*. 2000, Amadio *et al*. 1993, 2001);
- *finite element models*, mainly used to investigate the real behaviour of the joint and to calibrate the different components employed in mechanical models (Amadio and Piva 1995, Bursi and Ballerini 1997, Bursi and Gramola 1997, Amadio and Fragiacomo, part one of this paper).

The modern trend for designing composite joints is the use of mechanical models, such as the one proposed by Annex J of Eurocode 3 (CEN 1992) and 4 (CEN 1996). In the case of steel connections, this type of approach has been extensively investigated by numerous authors (Faella *et al*. 2000) and it is considered to be quite reliable. Steel-concrete composite joints have also been actively investigated (Leon and Zandonini 1992, Benussi *et al*. 1997, Huber and Tschemmernegg 1998, Nethercot 1998, Tschemmernegg *et al*. 1998, Faella *et al*. 2000, Amadio *et al*. 2001); however some issues, such as modelling of the concrete slab and interactions with the steel structure, have yet to be fully resolved.

The aim of this paper is to assess the reliability of the mechanical approach proposed by Annex J of Eurocode 4 (CEN 1996) for steel-concrete composite joints. Solutions obtained by this approach are compared with experimental results for different types of rigid and semi-rigid joints tested at the University of Trieste (Benussi *et al*. 1989, Puhali *et al*. 1990). Numerical results evaluated through an accurate three-dimensional finite element modelling based on the use of the Abaqus code (Hibbit *et al*. 1997), as proposed in part one of this paper, are also reported for some types of joints. These analyses highlight that the EC4 mechanical approach generally allows a correct evaluation of the ultimate moment, whereas results obtained in terms of stiffness and non-linear behaviour of the composite joint are not always accurate. Lastly, the influences of the most important parameters on the joint behaviour are investigated through the finite element modelling.

2. Comparison between experimental and EC4 response

In this section some comparisons between experimental and analytical responses of rigid and semi-rigid composite joints are presented. The analysed composite joints can be divided into two groups:

- First Group: semi-rigid joints denoted as SJA10, SJA14, SJB10, SJB14, tested by Benussi *et al*. (1989), and a rigid joint denoted as RJ14, tested by Puhali *et al*. (1990), the characteristics of which are reported in part one of this paper;
- Second Group: semi-rigid joints denoted as CT1C and CT2C, tested by Benussi *et al*. (1991). The

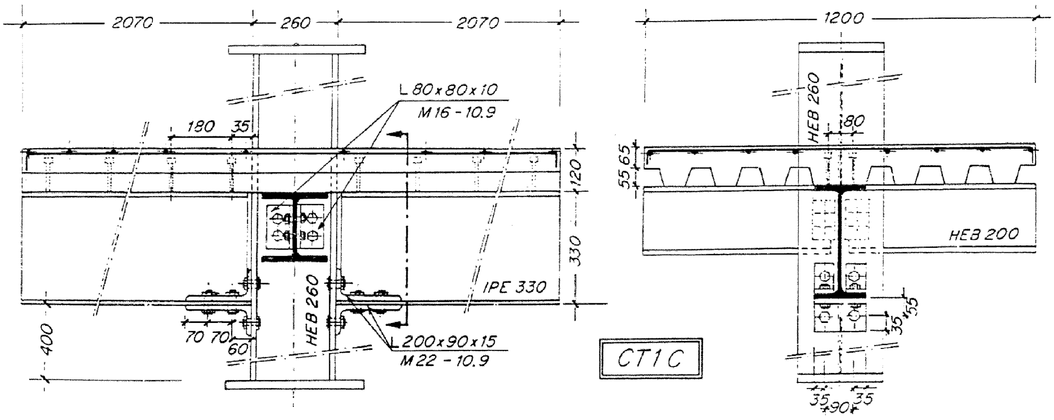

Fig. 1 Geometry of the CT1C joint (measures in mm)

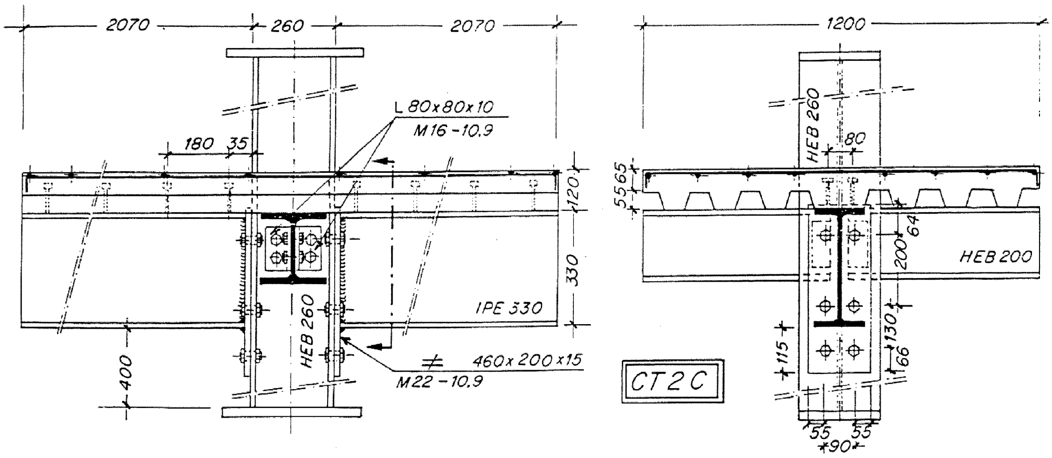

Fig. 2 Geometry of the CT2C joint (measures in mm)

steel beam-to-column connection is obtained through a bolted double bottom angle in the CT1C joint (Fig. 1) and through an extended endplate, bolted to the column and welded to the beam in the CT2C joint (Fig. 2).

The analytical responses have been obtained according to the approach proposed by Annex J of Eurocode 4 (1996). This approach is based on the mechanical component model developed by Tschemmernegg *et al*. (1998), which was simplified in order to make it suitable for direct design applications (Aribert 1995). The moment-rotation curve for the composite joint is determined by providing three different laws for:

- the elastic phase, up to two-thirds of the design resisting moment of the joint;
- the non-linear phase, characterised by a transition branch between the elastic limit and the beginning of plastic branch;
- the collapse phase, characterised by a plastic plateau extending until the ultimate rotation of the joint is reached.

Comparisons between experimental and analytical results are plotted in Figs. 3, 4, 5 for the First Group and in Fig. 6 for the Second Group of joints in terms of moment vs. rotation curve. The moments

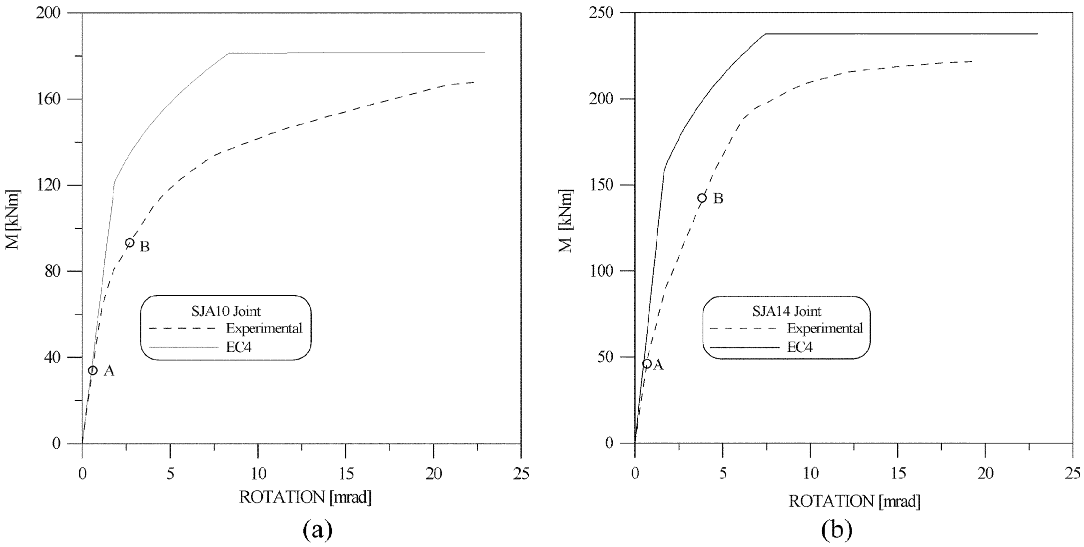

Fig. 3 Comparison between experimental result and EC4 solution for the SJA10 (a) and SJA14 (b) joint in terms of moment vs. rotation curve

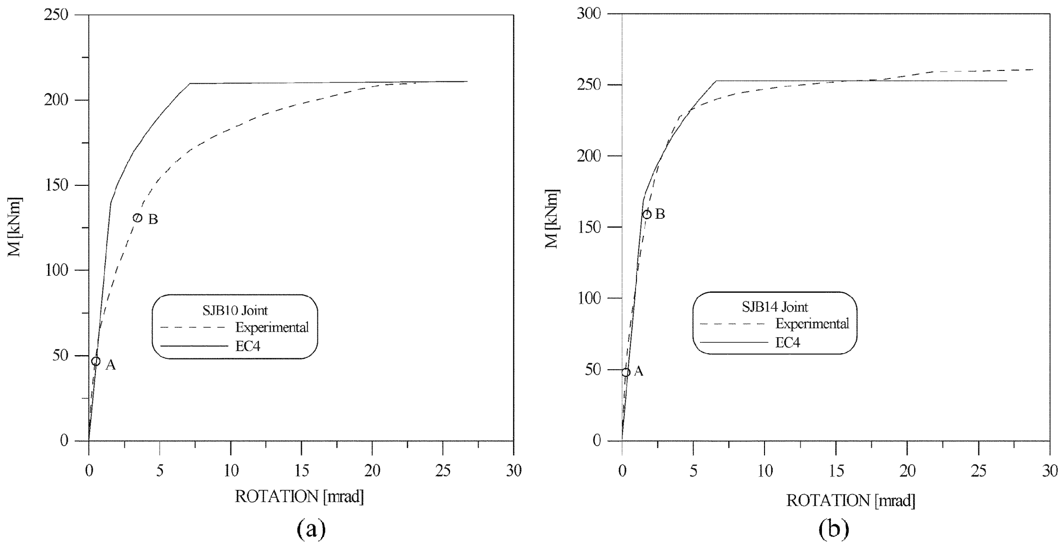

Fig. 4 Comparison between experimental result and EC4 solution for the SJB10 (a) and SJB14 (b) joint in terms of moment vs. rotation curve

are evaluated on the external surface of the column flange and the rotation in the beam cross-section 290 mm from the column flange. The joints were loaded in such a way as to produce a hogging bending moment. The points A and B represent the beginning of cracking in the concrete slab and the beginning of yielding in the steel parts of the joint, respectively.

2.1. Evaluation of joint strength

For the evaluation of the joint strength, the following observations are noted:

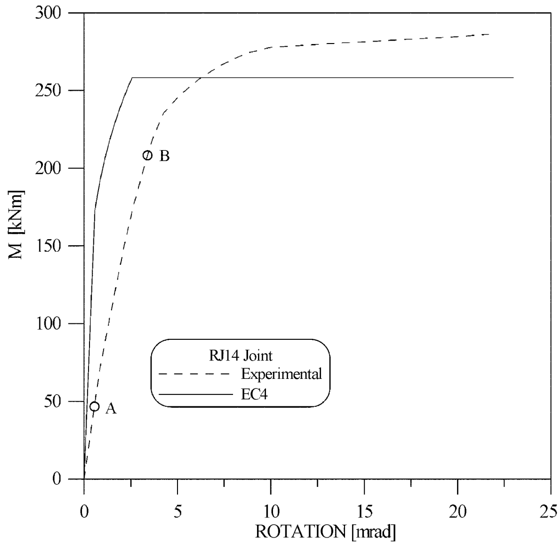

Fig. 5 Comparison between experimental result and EC4 solution for the RJ14 joint in terms of moment vs. rotation curve

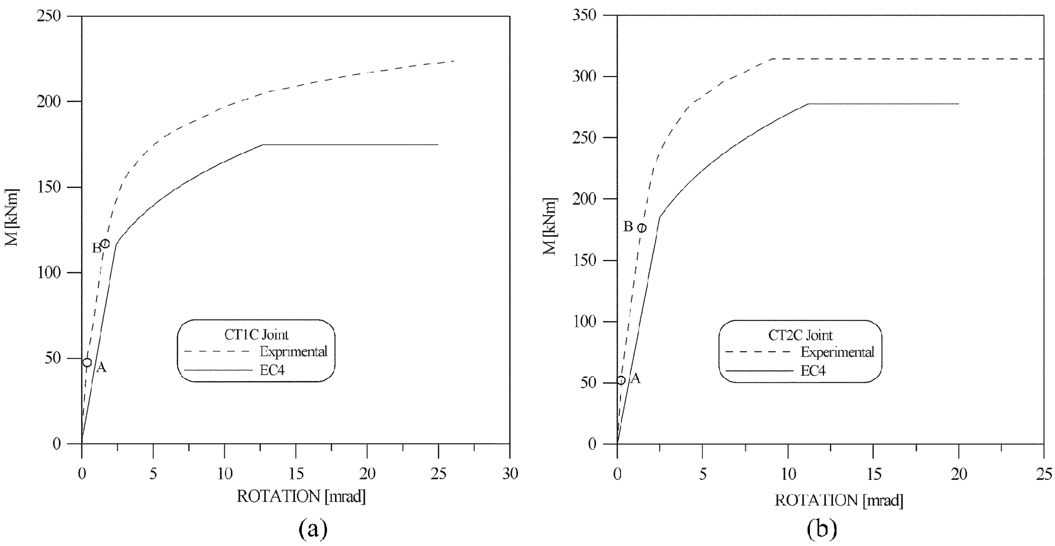

Fig. 6 Comparison between experimental result and EC4 solution for the CT1C (a) and CT2C (b) joint in terms of moment vs. rotation curve

- The first yielding moment (B point in Figs. 3 to 6) is generally well fitted. However, being determined simply as two-thirds of the design plastic moment, it is not affected by the behaviour of individual components of the joint.
- The ultimate resistant moment is generally assessed with good accuracy for all the analysed joints. For the CT1C and CT2C joints (Fig. 6), this value is rather low compared to the experimental one (176 kNm compared to 229 kNm for the CT1C and 278 kNm compared to 314 kNm for the CT2C joint). The main reason for this is that the analytical model hypothesises an elastic-plastic behaviour

for the component materials, whereas the experimental stress-strain law of reinforcement is characterised by a large hardening branch. This difference is smaller for the CT2C joint, since the resistant mechanism depends on the interaction among several components, and the mechanical model can better approximate the global response of the joint.

- The ultimate resistant moment is overestimated for the SJA10 and SJA14 joints (Figs. 3 and 4), the more flexible types, and the analytical solution is not conservative. The main reason for this is the behaviour of the compressed zone, which is only approximately modelled by the analytical solution. The compressive centre should be more correctly located slightly above the bottom of the endplate rather than in the geometric centre of the bottom flange. A significant improvement in the solution could be obtained by analytically evaluating the correct position of the compressive centre (Amadio *et al.* 2001).

2.2. Evaluation of joint stiffness

The following comments are made in regard to the evaluation of the joint stiffness:

- The accuracy in evaluating the elastic rotational stiffness depends on the type of joint. For the SJA joints (Fig. 3), the most flexible types, the EC4 approach provides an adequate initial stiffness, whereas the response in the plastic phase is much more rigid. Conversely, the response of the SJB joints (Fig. 4) is adequate in terms of both initial stiffness and behaviour in the plastic phase. The initial stiffness of the rigid joint RJ (Fig. 5) is largely overestimated by the EC4 approach because of the column web stiffening, which is hypothesised as fully rigid. The initial stiffness of the CT1C and CT2C joints (Fig. 6) is instead underestimated, mainly due to the assumption of neglecting the concrete stiffness in non-cracked phase and the tension stiffening effect in the cracked phase. Concerning this, an improvement is reported in Amadio *et al.* (2001), where the tension stiffening effect is considered by modelling the concrete through a series of springs characterised by an elastic law with a linear softening branch in tension.
- The EC4 mechanical model is, in general, almost insensitive to detail variations of the steel beam-to-column connection, particularly in the case of the endplate connections. In fact, the contribution provided by the reinforcement is assigned with an overly large weight.
- The hypothesis that the column web stiffening is regarded as fully rigid enhances this trend (see the RJ joint for example), considerably enlarging the contribution on the global stiffness from the most external mechanical components. Thus, the web stiffening should more correctly be modelled as flexible.
- The behaviour of the composite joint in the non-linear phase, described by the EC4 formulation in a simplified form, is generally not adequate to describe the complex plastic phenomena that arise in the steel parts of the joint.

3. Parametric analysis

As described in part one of this paper, the response of rigid or semi-rigid steel-concrete composite joints is influenced by several parameters. Hence it may be important to investigate in detail the influence of such parameters on the global behaviour of the joint. This study has been carried out by using a three-dimensional finite element modelling based on the use of the Abaqus code, which has been demonstrated in part one of this paper to be reliable and to fit adequately with the experimental results. The parametric analysis has been performed for joints with the same geometric characteristics as the RJ14, SJA14 and SJB14 specimens of the First Group (section 2). The results are reported in terms of moment vs. rotation law measured on the edge of the column flange. In some significant cases, the analytical results obtained using the Eurocode 4 formulation are also reported, in order to provide additional information on the attainable accuracy by means of this analytical approach. It should be emphasized that the finite element method is the only approach that allows a reliable comparison among the joint responses with characteristics of materials established a priori. In a series of experimental tests it is practically impossible to fix the material properties because of the uncertainty that affects these quantities.

3.1. Influence of column web stiffening

As highlighted in section 2, the stiffening of the column web considerably affects the response of the composite joint. A numerical comparison for the RJ14 rigid joint with and without column web stiffening is presented in Fig. 7. Mechanical and geometric properties are those of the specimen tested by Puhali *et al.* (1990) and already tabled in part one of this paper. The figure also contains the initial stiffness for a joint with column web stiffening and a rigid connection between the concrete slab and steel beam, which represents an upper limit for the joint. A remarkable reduction in both initial stiffness and ultimate strength can be noted for the joint without web stiffening. Due to the lack of horizontal steel plates at the level of the bottom flange, the joint begins to yield for a bending moment slightly larger than 50% of the ultimate value. The finite element analyses revealed that the lower part of the steel beam near the column and even the column web are widely yielded. A significant increase in the initial flexibility of the composite joint can be noted when the actual constitutive law for the studs is considered, even if the connection between the slab and steel beam is full according to Eurocode 4 (CEN 1992).

From this first numerical comparison, it may be concluded that both the slab-to-beam connection deformability and the presence or absence of column web stiffening should be adequately considered in a correct evaluation of the global joint behaviour.

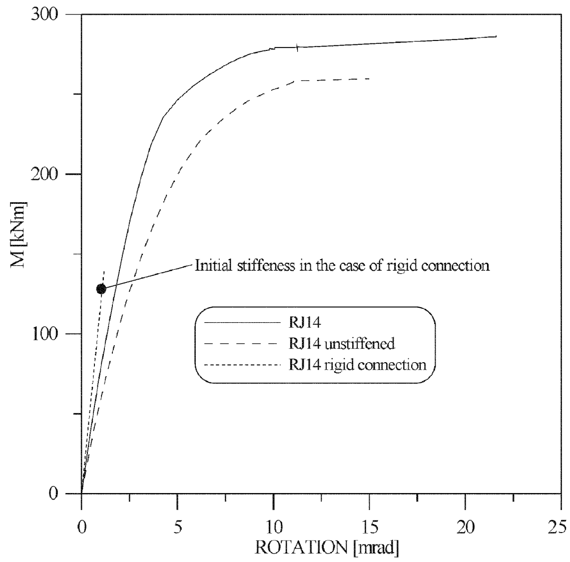

Fig. 7 Response of the RJ14 joint with and without column web stiffening in terms of moment vs. rotation curve

3.2. Comparison among the RJ14, SJA14 and SJB14 joints

In this section, the results of a parametric analysis performed on the RJ14, SJA14 and SJB14 joints with different mechanical properties of the component materials (concrete, reinforcement and profile steel) are presented. Two combinations of material properties are considered:

- the first combination (Table 1), characterised by good quality concrete and medium quality steel;
- the second combination (Table 2), characterised by materials with inferior qualities (concrete with 28% less strength and a steel profile with 8% less strength).

These differences are consistent with a possible scattering of the steel and concrete strengths with respect to the hypothesized design values. For each type of joint and combination of material properties, a joint with and without column web stiffening, respectively, has been considered.

Comparisons in terms of moment vs. rotation curve among the three types of joint with and without web stiffening are presented in Fig. 8 for the first combination of material properties. This analysis reveals that the initial stiffness of the SJB14 joints is almost the same as the stiffness of the rigid joint RJ14, whereas the strength is intermediate between that of the RJ14 and SJA14 joints. Furthermore, a nearly constant ratio between the responses with and without web stiffening may be observed for all types of joint. The SJA14 joint, although characterised by a simple beam-to-column connection, demonstrates behaviour rather close to that of the other joints, which are characterised by more complex and, therefore, more expensive details.

Fig. 9 shows the responses of the SJA14 joint for different combinations of material properties. The differences between the cases with and without web stiffening are quite close by varying the combinations of material properties and are similar to those referred to in section 3.1. A remarkable reduction in both initial stiffness and ultimate strength can be noted for the joint without web stiffening. The strength decrease near the collapse ranges between 10% and 12% by varying the properties of materials, whereas the initial stiffness is nearly the same. On the whole, differences in the mechanical properties of materials affect the joint response to a limited degree, and definitely less than the presence or absence of the column web stiffening.

Table 1 Mechanical properties of the concrete assumed in the two combinations of material properties

Medium compressive cylindrical strength f_{cm} (N/mm^2)		Medium tensile cylindrical strength f_{ctm} (N/mm^2)		Medium elastic modulus E_{cm} (N/mm^2)	
1st comb.	2nd comb.	1st comb.	2nd comb.	1st comb.	2nd comb.
36.0	28.0	3.4	2.7	32000	30000

Table 2 Mechanical properties of the steel assumed in the two combinations of material properties

Type of steel	Yield stress f_y (N/mm^2)		Tensile strength f_u, f_t (N/mm^2)		Elastic modulus E (N/mm^2)
	1st comb.	2nd comb.	1st comb.	2nd comb.	All combinations
IPE 300	340	320	510	450	206000
HEB 260	330	320	480	480	206000
14 mm bars	460	430	670	640	206000
20 mm bolts	640	640	800	800	206000

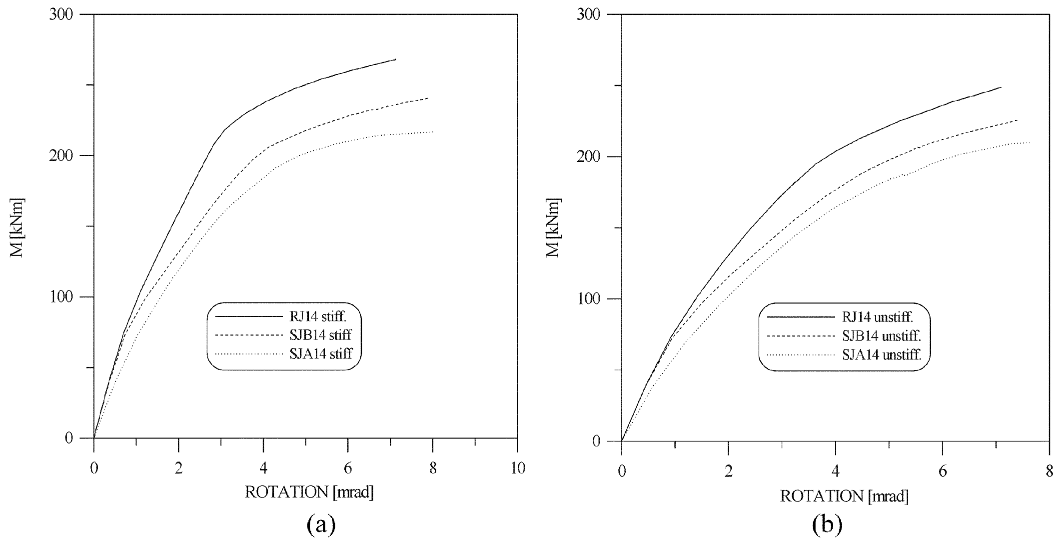

Fig. 8 Comparison between RJ14, SJA14 and SJB14 joints with (a) and without (b) column web stiffening in terms of moment vs. rotation curve for the first combination of material properties

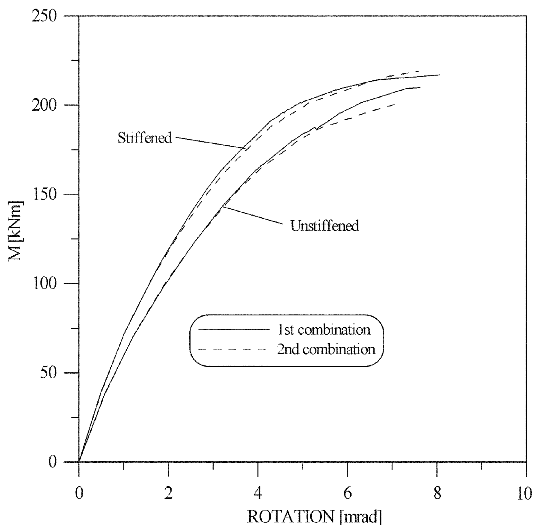

Fig. 9 Response of the SJA14 joint with and without column web stiffening in terms of moment vs. rotation curve for different combinations of material properties

Fig. 10 presents a comparison between the numerical responses obtained by using the finite element modelling and the EC4 approach for the rigid joint RJ14 with and without web stiffening for the first combination of material properties. The EC4 solution remarkably overestimates the initial stiffness for the joint with web stiffening because of the assumption of a fully rigid panel, whereas it is adequate in terms of both stiffness and strength for the joint without web stiffening.

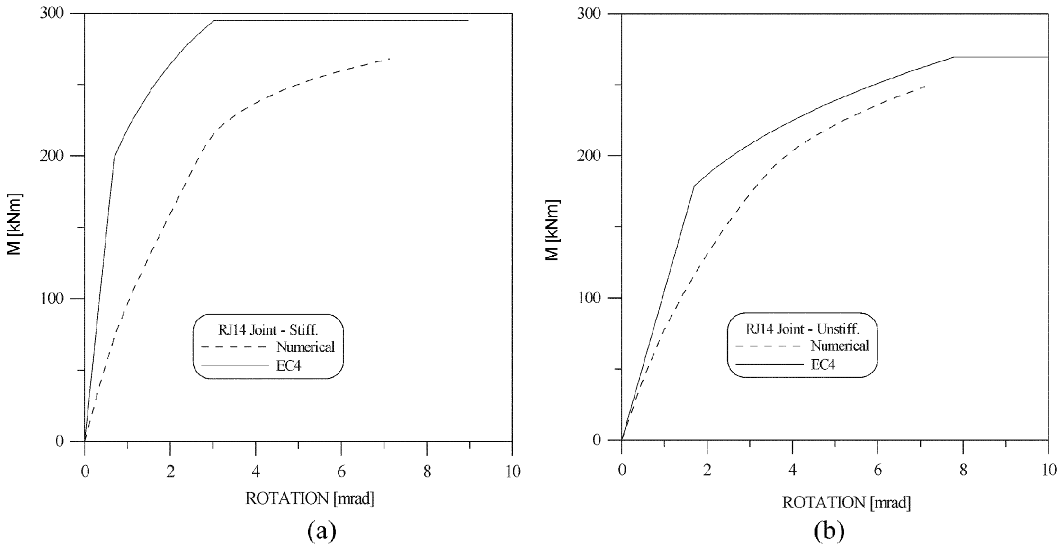

Fig. 10 Response of the RJ14 joint with (a) and without (b) column web stiffening in terms of moment vs. rotation curve for the first combination of material properties

4. Conclusions

In this paper some results of a series of comparisons performed on rigid and semi-rigid steel-concrete composite joints are presented. Two types of solutions are considered:

- the simplified analytical approach proposed by Annex J of Eurocode 4;
- an accurate three-dimensional finite element modelling based on the use of Abaqus code, which is the only means to validate simplified analytical or mechanical approaches by choosing a priori geometric characteristics of the joint and mechanical properties of the component materials.

The simplified solutions are also compared for some cases with experimental results. The comparisons highlight that the EC4 modelling is generally adequate in terms of strength, but demonstrates significant shortcomings in terms of initial stiffness and non-linear response. Important improvements could be obtained:

- by adequately modelling the concrete in the cracked phase, through a suitable stress-strain law in tension in order to take into account the tension stiffening effect;
- by regarding the column web stiffening as flexible;
- by evaluating the correct position of the compressive centre for endplate joints, as in many cases this does not coincide with the geometric centre of the beam bottom flange.

The parametric analysis performed using the Abaqus code on rigid and semi-rigid composite joints has revealed that:

- the presence of column web stiffening markedly affects the joint response in all phases;
- the use of semi-rigid composite joints characterised by simple steel beam-to-column connections, such as partial depth endplate connections (e.g. SJA joints), together with an adequate continuity reinforcement in the concrete slab, provides the best compromise between cost and joint behaviour in terms of both strength and stiffness;
- the use of semi-rigid composite joints with flush endplate connections, such as the SJB type, even if

characterised by simpler details compared to rigid joints, leads to values of initial stiffness comparable with those of rigid joints. The strength is, in this case, only slightly lower (10% less);
- the semi-rigid composite joint is almost insensitive to the scattering of mechanical properties that arises in situ.

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