Modelling the nodal zone behaviour in a composite frame

Modelling the Nodal Zone Behaviour in a Composite Frame

Claudio BERNUZZI
Research Associate
Univ. of Trento
Trento, Italy

Claudio Bernuzzi, born in 1962, received his engineering degree at the University of Pavia. He has been at the University of Trento since 1987 and his research work is focused on both steel and steel-concrete semi-continuous composite frames.

Shi Lin CHEN
Visiting Research Assoc.
Univ. of Trento
Trento, Italy

Shi Lin Chen, born in 1965, received his doctor degree at the Wuhan University of Hydro-electric Engineering. He has been a faculty member in Tsinghua University since 1991. He is engaged in the research about non-linear behaviour of structures.

Riccardo ZANDONINI
Professor
Univ. of Trento
Trento, Italy

Riccardo Zandonini, born in 1948, received his engineering degree at the Technical University of Milan, where he served as a faculty member from 1972 to 1986. He has been at the Faculty of Engineering in Trento since 1986. His research activity is devoted to the study of steel and steel-concrete composite structures.

Summary

Traditional design approaches for steel-concrete composite frames generally overlook the actual joint response and adopt simplified analysis models. Consequently, more refined design rules based on a complete understanding of the joint behaviour should be used in order to account for the relevant benefits associated with the semi-continuous frame model.
This paper deals with the nodal behaviour in composite frames. Key features of the nodal zone response are outlined, basic requirements for an accurate joint simulation are discussed and, finally, the preliminary results of an extensive numerical study are presented.

1. Introduction

Steel-concrete composite constructions represent very convenient solutions for civil and commercial buildings. Their design, which is generally based on ideal behavioural models (i.e., simple and rigid frame models), neglects the relevant benefits associated with composite joints action. As recently showed by several experimental and numerical studies [1-3], all joints possess flexural stiffness and moment capacity and the actual range of their behaviour is intermediate between the ideal model of simple and rigid joints. Hence, a reasonable use of the degree of continuity associated with the nodal zone improves the overall efficiency as well as the cost effectiveness of composite frames, especially when spans are long.
Despite the semi-continuous frame model is actually included into European Standard for composite structures [4], no specific recommendations are provided for their design, due to lack of fully validated approaches able to predict the semi-rigid behaviour of beam-to-column joints.
A study on joint action in steel-concrete composite systems is currently in progress at the University of Trento. On the basis of tests of composite cruciform joint specimens [5,6] as well as of full-scale sub-frames [7], the key phenomena and the related parameters influencing joint performance were identified. The study is now in the second phase, which is devoted to the development, validation and calibration of finite element (FE) models capable of simulating in an accurate way the joint response in composite frames. The FE modelling technique enables to single out the significant factors which influence the joint response; this is a necessary pre-requisite to the set up of simplified prediction procedures aimed to be used in design practice.

In this paper the key features of the nodal zone response of composite frames are summarised and the requirements for accurate FE models simulation are discussed. Finally, the preliminary results of an on-going numerical study on joints are presented.

2. Joint behaviour

A complete account of the behaviour of beam-to-column composite joints would need to recognize its three dimensional nature. However, the presence in composite framed systems of rather stiff continuous floor slab allows generally out-of-plane and torsional deformations of joint to be neglected. Moreover, with reference to in-plane behaviour, rotational flexibility appears as the most important characteristic affecting the global structural response. As a result, the joint behaviour can be accurately described by its in-plane moment-rotation (M-Φ) curve, for which, in case of joints under hogging moment, three branches can basically be identified: elastic (uncracked and cracked), inelastic (with progressive deterioration of stiffness) and plastic.

A feature peculiar of nodes in composite frames is that partial continuity may be sought between the beams and the column (as in steel frames), depending on the steel connection details as well as on the contact between the concrete slab and the column faces, or just between two adjacent beams, mainly due to the reinforcing bars of the slab across the column. Except that for joints to external columns, the complex problem of beam-to-column interaction, arising in case of unsymmetrically loaded nodes, may be practically neglected if the steel column is totally encased in the concrete slab [6].

As reported in [1], a significant number of variables play a substantial role in the development of joint action and hence affect the M-Φ curve. This relationship, which is the end product of a complex interaction in the nodal zone, depends on the key joint components and, in particular, on:

- the concrete slab: its axial stiffness in tension governs remarkably joint response in elastic uncracked phase. After cracks, slab merely serves to transfer tensile force to reinforcement with the aid of shear studs;
- the slab reinforcement: the amount of longitudinal rebars, which carry tensile force after attainment of tensile concrete strength, is the most important parameter affecting strength, rotational capacity and to some extent stiffness of the joint. Moreover, a proper design of transverse reinforcement is essential in order to active the strut mechanism involved in the horizontal shear transfer;
- the connection system between concrete slab and steel beam: stud distribution affects the cracking pattern whilst the degree of steel-concrete interaction influences significantly the joint response in its latest nonlinear phases, where slip and uplift of the slab can occur;
- the steel beam-to-column connection: non-negligible moment capacity (of the order of the negative plastic moment of the composite beam) may be achieved while maintaining simple details in the steel work, which transfer the compressive force from beam to column. Stronger connection typologies, such as end plate connections, improves remarkably the joint behaviour in the post-elastic phases, due to the transferring of tensile force also by means of the upper row of bolts. Non-linearities of this component, which can be caused by slippage, in case of cleated connection, as well as by changing of the contact zone of the compressive stresses, affect reasonably the M-Φ curve;
- the steel beam: bottom flange together with web transfer the compressive force to the column through the connection. Failure due to local buckling of the beam bottom flange does not lead to an immediate loss of resistance in semi-rigid joint as in rigid joint.
- the column: with reference to most common cases of joints framing into the column major axis, column web failure in shear as well as in compression, which affect substantially joint moment

resistance, can be prevented by means of web stiffener in case of H bare sections or of concrete encasement for composite columns.

The action of these key components on composite joints can be singled out from experimental analysis, which results nevertheless a costly approach and is essential to establish the fundamental background for the validation of all theoretical approaches. However, the experimental analysis has by its very nature a limited scope. Hence, the parametric investigations appear possible only by means of FE simulations, which enable for an exhaustive understanding of the joint behaviour and of the transfer force mechanisms between frame members and joints over a sufficiently extensive range of both mechanical and geometrical parameters.

3. Joint modelling

Although FE method has been successfully used to model steel beam-to-column joints [9], only a very limited number of studies [6,10-12] was focused on the FE analyses of composite nodes.

Despite an accurate simulation of the response of composite joints should require a three-dimensional (3D) analysis, two-dimensional (2D) models can be adopted in order to reduce the computation difficulties associated with large 3D meshes. In the case of a 2D representation, the contribution of the uncracked slab generally requires a preliminary 3D elastic analysis, which allows the relevant slab effective width to be defined[12,13].

Due to the complex interaction between the main nodal components as well as the key features of each of them, FE joint models should consider both geometrical and material non-linearity. As far as the material laws for steel components (beam, column, steel connection details, studs and rebars) are concerned, a good agreement with the actual behaviour is usually provided by the sole uniaxial multilinear stress-strain relationship, which can be correlated to a more complex and representative state of loading, via the selection of suitable yielding criterion (von Mises, Drucker-Prager, etc.). For the slab modelling, concrete constitutive laws provided by general purpose FE packages are based on a smeared-cracked approach, which assumes an equivalent isotropic continuum with smeared cracks for the simulation of the slab after the attainment of the concrete tensile resistance[14,15]. Due to the presence of longitudinal bars in the concrete slab, two modelling techniques can be adopted for the simulation of the slab reinforcements:

- a discrete rebar approach: rebars are modelled using truss or beam non-linear elements, which satisfy the displacement compatibility with the concrete elements;
- a smeared rebar approach, in which rebar-concrete interaction in tension can be modelled by appropriate modifications of the concrete constitutive relationship [15,20].

Moreover, an accurate simulation of the interaction (contact/separation) between concrete slab and steel beam as well as steel connection and members (beams and column) requires the use of interface and/or non-linear spring elements, the constitutive non-linear laws of which can be defined in accordance with proposals available in literature [16,17].

4. Numerical analysis

The on-going numerical study was developed by means of the general purpose non-linear FE package ABAQUS [17], which is characterized by models as well as by material laws capable of modelling composite joints adequately. As model validation should be verified by the existing test data, in this initial phase attention was paid to the simulation of the nodal response of cruciform symmetrical specimens SJA10 and SJA14 (fig. 1a), which were tested under hogging moment [5]. The steel connection consists of a partial depth end plate welded to the beam and bolted to the column (see fig. 1b) and the difference in the two specimens consists in the amount of the top longitudinal rebars: 8ø10 bars for SJA10 and 8ø14 bars for SJA14 specimen. The loads, monotonically increased up to collapse, were located at a slightly different distance from the column in order to preselect in which of the two joints collapse would occur.

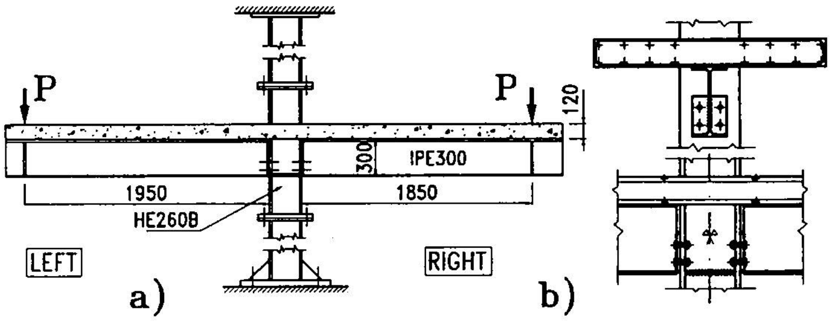

Fig. 1 The specimen (a) and the composite joint (b)

Attention was focused on both 2D and 3D models. Before 2D models were developed, a preliminary 3D elastic analysis on a quarter of the specimen, making use of the geometrical symmetry about both the web of steel beams and the column, as to reduce the problem size, permitted the effective width (fig. 2) for the definition of equivalent slab geometry to be assessed. Two-dimensional models (fig. 3) were built up with regard to complete or half specimen (FS and HS, respectively). Longitudinal rebars and bolts were modelled via truss elements and the action of the stud connectors, which provided full interaction in the considered specimens, was simulated via non-linear spring, the constitutive law of which was based on ref. [18]. Plane stress four node elements were used for the slab as well as for the other steel components (beam, column and connection plate). As to the material properties, an elastic-plastic law with strain hardening associated with the von Mises yield surface was selected for the steel components. For concrete, in addition to the concrete material model of ABAQUS (cma), which has been found in some cases not very efficient [11], a model based on von Mises yield criterion to deal with concrete cracking under tensile stresses (cmv) was also considered and the bond behaviour of rebars was simulated separately, in accordance with the results of ref. [19].

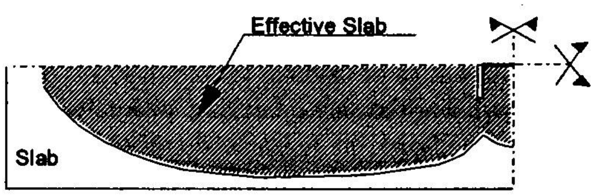

Fig. 2 Effective width of slab

As to 3D models, reference was made to a quarter of the specimen (3D HS in fig. 4). Eight node shell elements were selected for concrete slab, steel members and steel connection, while beam elements modelled the bolts. The same material law as in 2D simulations was considered for steel components while a smeared reinforcement was adopted for the concrete slab, for which the von Mises yielding criterion was adopted.

Both for 2D and 3D simulations, tension stiffening of concrete was considered in all the concrete models using the criterion proposed by Stevens [20], and unidirectional gap elements modelled separation/contact between steel connection and column flange as well as between concrete slab and top beam flange.

Figs. 5 and 6 present some of the numerical results, in terms of M-Φ curves, compared with the corresponding experimental responses. It appears that all the models can reproduce accurately the joint response in the elastic uncracked phases. With reference to 2D models, differences in the other phases are due to the concrete material laws adopted (i.e., cma and cmv) as well as to the simulation of the explicit bond slippage of rebar in cmv model. The bond behaviour provides a more flexible response mainly in the elastic cracked branch.

A comparison between the 2D responses of half and full specimen, HS and FS, respectively, shows a limited influence of beam-to-column interaction, due to the presence of a modest unbalanced moment on the node. As to the 3D HS simulations, the degree of accuracy is slightly greater than the corresponding 2D HS ones mainly in the post-elastic phases, despite the 3D numerical curves are stiffer than the experimental M-Φ relationships.

Therefore, the predicted joint response reflects a trend generally in a good agreement with the test data and the cracking pattern is similar to the experimental one. The predicted collapse mode, due to plasticity of rebars, and consequently excessive joint deformation, as in the tests, was associate with ultimate moments in all the models very close to the actual joint moment capacity (differences lower than 5%).

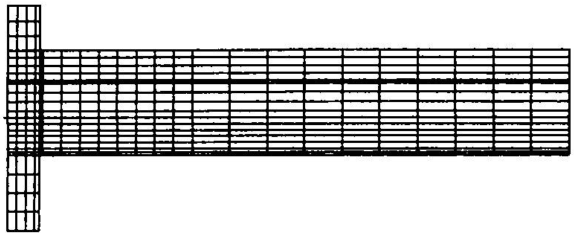

Fig. 3 Two-dimensional (2D) model

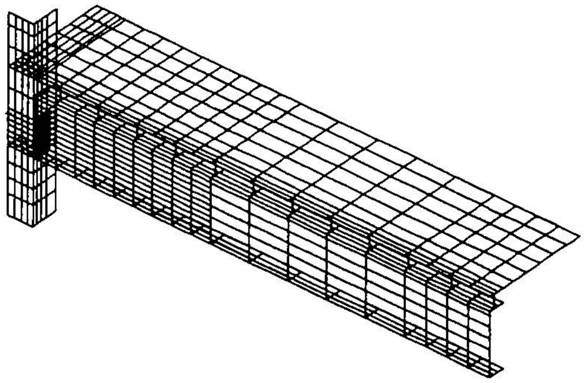

Fig. 4 Three-dimensional (3D) model

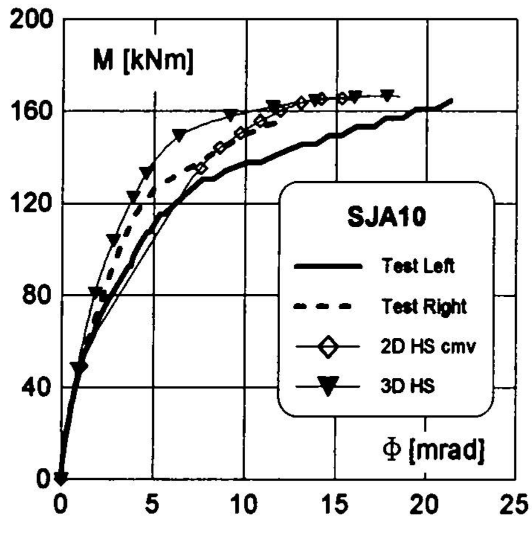

Fig. 5 Comparison of M-Φ curves for SJA10

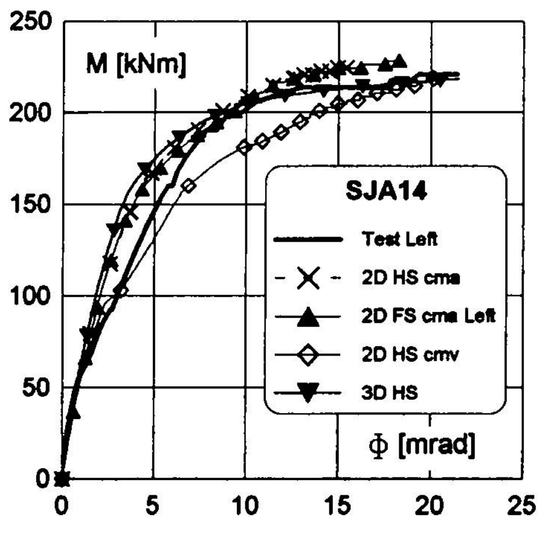

Fig. 6 Comparison of M-Φ curves for SJA14

5. Conclusions

This paper briefly reports an on-going study on the joint action simulation in steel-concrete composite systems. Key features of the nodal zone response are summarized and the general requirements of FE models, which can reproduce the main aspects of the physical behaviour of composite joints, are discussed.

Numerical simulations, carried out with reference to both 2D and 3D models, seem to be in a good correlation with test results and differences can be detected mainly in the post-uncracked phases of the M-Φ responses. The joint ultimate moment is assessed with a satisfactory degree of accuracy by all the models. Despite the 3D simulation is associated with better appraisal of the nodal behaviour, 2D model seems sufficiently accurate to estimate the joint response, if the key features of concrete slab are taken into account and modelled by means of suitable elements and material laws. As to future work, a complete analysis of the numerical results related to these as well as additional specimens would make possible an exhaustive understanding of the complex interactions between the components of the nodal zone.

Acknowledgements
The research project is supported by the National Research Council (C.N.R.) and by the Italian Ministry of the University and Scientific and Technological Research (M.U.R.S.T.).

References

[1] Zandonini R., 1989, "Semi-Rigid Composite Joints", in *'Structural Connection-Stability and Strength series: Vol. 8'*, Narayanan R. ed., Elsevier Applied Science ed., 63-120.
[2] Leon R.T. and Zandonini R., 1992, "Composite joints" in *'Constructional Steel Design: An International Guide'*, Harding J. et al. eds., Elsevier Applied Science, 1992.
[3] Zandonini R., Nethercot D.A., 1994, "Recent Studies on the Behaviour of Semi-Rigid Composite Connections", proc. of the ASCE Structural Conference, Atlanta, 1143-1148.
[4] Commission of the European Communities, 1994, "Eurocode 4-Design of Composite Steel and Concrete Composite Frames-Part 1.1 General Rules and Rules for Buildings".
[5] Benussi F., Puhali R., Zandonini R., 1989, "Semi-rigid Joints in Steel-Concrete Composite Frames", *Costruzioni Metalliche*, No. 5, 237-264.
[6] Puhali R., Smotlak I., Zandonini R., 1990, "Semi-rigid Composite Action: Experimental Analysis and a Suitable Model", *Journal of Constructional Steel Research*, Special Issue on Composite Construction, R. Zandonini ed., Vol. 15, Nos 1&2, 121-151.
[7] Benussi F, Bernuzzi C., Noè S, Zandonini R., 1996, "Experimental Analysis of Semi-Rigid Composite Frames", proc of the IABSE Colloquium: Semi-Rigid Structural Connection, Istanbul 1996, 105-113.
[8] Benussi F., Nethercot D.A., Zandonini R., 1995, "Experimental Behaviour of Semi-Rigid Connections in Frames", in *'Connections in Steel Structures III'*, R. Bjorhovde et al. eds., Elsevier Applied Science, 57-66.
[9] Nethercot D.A., Zandonini R., 1989, "Methods of Prediction of joint Behaviour: beam-to-column connections", in *'Structural Connection-Stability and Strength series: Vol. 8'*, R. Narayanan ed, Elsevier Appl. Science 23-62.
[10] Leon R., Lin J, 1986, "Towards the Development of an Analytical Model for Composite Semi-Rigid Connections", Report to AISC, Struct. Eng. Rep. No. 86-06, Univ. of Minnesota, Minneapolis, USA., p. 83.
[11] Ahmed B, Nethercot D.A., 1995, "Numerical modelling of Composite Flush End Plate Connections", *Steel Structures-Journal of Singapore Steel Society*, Vol. 6, No. 1, 87-102.
[12] Bursi O., Gramola G., 1997, "Smeared crack analysis of steel-concrete composite substructures", Stessa'97 Conference, Kyoto.
[13] Lee S.J. and Lu L.W., 1991, "Cyclic Load Analysis of Composite Connection Subassemblages", , in *'Connections in Steel Structures II'*, R. Bjorhovde et al. eds., American Institute of Steel Construction, 209-216.
[14] Kotsovos M.D., Pavlovic M.N., 1995, "Structural Concrete - Finite Element Analysis for Limit State Design', Thomas Teldfort Pub., p. 550.
[15] Lofti H.R., 1992, "Finite Element Analysis of Concrete and Masonry Structures", Ph.D. Thesis, University of Colorado, p. 148.
[16] Link R.A., Elwi A.E., 1995, "Composite Concrete-Steel Plate Walls: Analysis and Behaviour", *Journal of Structural Engineering*, Vol. 121, No. 2, 260-271.
[17] Hibbit, Karlsson & Sorensen Inc., 1996, "ABAQUS - User's manual, version 5.5", Vol. 1&2.
[18] Aribert J.M., 1988, "Critical Numerical Analysis of Methods Proposed by Eurocode for Dimensioning of Steel-Concrete Composite Beams with Partial Connection" (in France), *Construction Metallique*, Vol. 25(1)
[19] Eligehausen R., Popov E.P., Bertero V.V., 1983, "Local bond stress strain relationships of deformed bars under generalised excitation", Report N. UCB/EERC-83/23, University of California.
[20] Stevens, N.J., Uzumeri, S.M., Collins, M.P., and Will, G.T., 1991, "Constitutive Model for Reinforced Concrete Finite Element Analysis", *ACI Structural Journal*, V.88, No.1, 49-59.