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Experimental analysis of semi-rigid composite frames

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Summary

Beam-to-column joints in steel-concrete composite frames generally provide a non negligible degree of flexural continuity, which substantially improves the overall performance of the structural system. The traditional design approaches based on simple frame models thus result inadequate for an "optimal" design of the composite frames. More refined rules should be defined in order to account for the relevant benefits associated with the joint action. This paper summarises an experimental study carried out at both Universities of Trento and Trieste, and presents the first results of the full scale tests on two different steel-concrete composite sub-frames under monotonic loading.

1. Introduction

No sway steel-concrete composite frames are usually designed with reference to the simple frame model, i.e. the composite beams are considered simply supported and the columns resist to the vertical loads and to the bending moments associated with the eccentricity of the beam reactions. This design philosophy neglects the relevant benefits provided by the action of the composite joints, as it is shown by the several experimental and theoretical studies carried out in the past [1]. Also in the case of low amount of longitudinal reinforcement bars in the slab, which in the current practice is used to limit the cracking of the concrete, the composite joints are stiff enough to decrease remarkably the over stressing or the excessive deflections in the beams under working loads. Therefore, significant improvements of the structural behaviour can be obtained by a complete understanding of the nature of the joint action and consequently by an efficient use of the semi-continuity of the frame.
Two different types of flexural continuity are associated with a composite node [2]: (1) the beam-to-beam continuity, due to reinforcing bars, and (2) the beam-to-column continuity, mainly provided by both the steel connection details and the contact between the slab and the column faces. In the past extensive investigations were devoted to the former through a great number of tests on composite joints to internal columns under symmetrical loading conditions, while a very limited series of data on the possible degree of continuity provided by the beam-to-column interaction is presently available. As a consequence, the state of the knowledge does not allow a full understanding of the interaction mechanism between all structural components

in the nodal zone under a general loading condition (i.e., different values of the bending moment in the node due to the presence of composite beams).
A joint study between the Universities of Trento (I), Trieste (I) and Nottingham (UK) was focused on the study of joint action in steel-concrete composite frames [3]. In the framework of this general research project two series of full-scale tests both on composite frames and on composite sub-frames were planned and carried out for obtaining an important basis of knowledge for the complete understanding of the performance of composite connections tested in a frame environment.
In this paper the part of the experimental phase of the research developed by the Italian partnerships is outlined, and the main features of two full-scale tests on steel-concrete composite sub-frames under monotonic loading are presented. A report on the very preliminary findings related to the data analysis phase, which is currently under development, is also presented.

2. The experimental analysis

Two one storey, two bays steel-concrete composite sub-frames were designed, assembled and tested (fig. 1). Beam spans, member sizes and connection detailing were selected in order to satisfy the prime requirement of consistency among the different activities of the general research project [3], i.e. to achieve conditions as close as possible to the frames and limited frames [4] tested at the Building Research Establishment (BRE), also with reference to the main features of the expected response, within the restraints imposed by the testing rig and by the use of European sections.

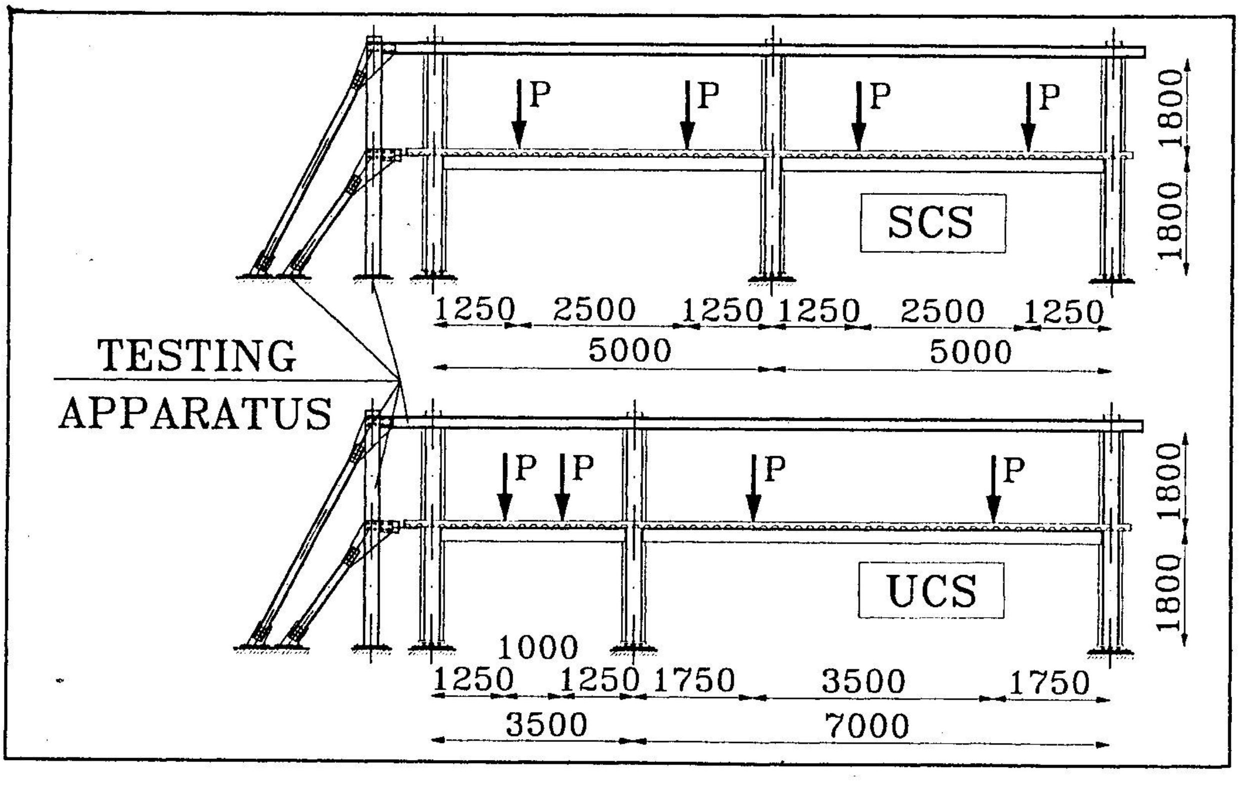

Fig. 1. Composite sub-frame specimens

The design phases of the two sub-frames were carried out according to the rules provided by both Eurocode 3 [5] and Eurocode 4 [6]. The geometrical configuration and the loading pattern of the specimens are presented in fig. 1. The first specimen is characterized by equal 5.0 meters long beam spans (SCS), while in the second one (UCS) the beam span lengths are 3.5 and 7.0 meters respectively. By comparing tests on specimens with symmetrical and unsymmetrical beam spans the effects of the beam-to-beam and beam-to-column continuities provided by composite joints are investigated. For the columns and the steel part of the beams HEB 260 and IPE 240 profiles respectively were selected. The steel beam-to-column connections are flush end plates welded to the steel beams and bolted to the column with 4 M20 bolts grade 8.8 pre-tightened according to the Eurocode 3 criteria (fig. 2).

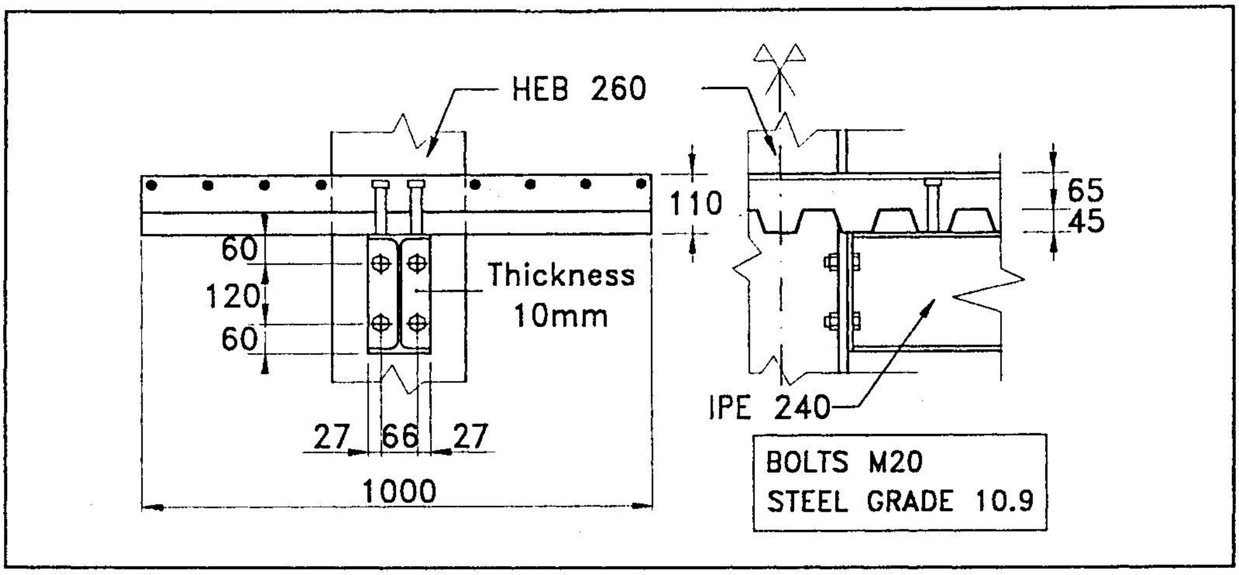

Fig. 2. Composite joint

The composite cross-sections of the beams was designed assuming full interaction between the steel beam and the concrete slab on steel decking with ribs perpendicular to the beam. The slab reinforcing ratio equal to 1.0 % (8ϕ12mm bars) was selected with reference both to the joint hogging flexural capacity and to the requirements of satisfactory rotational capacity provided through a joint collapse due to the yielding of the rebars. For the external joints, where the problems of anchorage of the longitudinal rebars play a fairly important role, additional trimming bars (2ϕ16mm) were placed in the slab for increasing the structural performance of the node, according to previous studies [7]. The layout of the longitudinal and transverse reinforcing bars is reported in fig. 3. As to the material properties, the mean yield strength values determined through tensile tests were 333 MPa for the steel beam, 292 MPa for the steel column, 463 MPa for the longitudinal rebars and 546 MPa for the additional trimming bars. The concrete of the slab was characterised for the SCS and the UCS sub-frames by a mean value of the cylindrical compressive strength of 51 MPa and 34 MPa respectively. The values of the tensile concrete strength, determined via split-cylinder tests, were 4MPa and 3MPa.

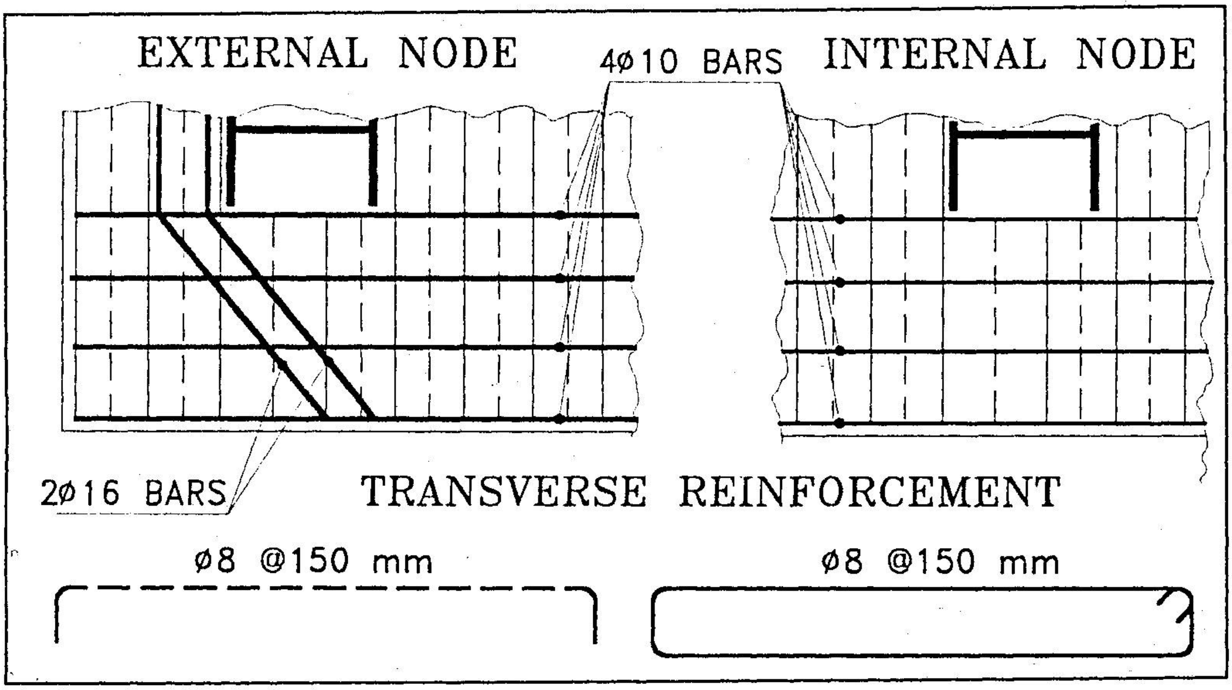

Fig. 3. Slab reinforcement

The measuring system [8] was designed in order to allow the monitoring of both the global response of the tested sub-frames and of the local behaviour of the nodal zones (fig. 4 and fig. 5): inductive transducers (LVDT), electrical strain gages, inclinometers and load cells were used for a total of about 220 measuring points.

The instrumentation system allowed the evaluation of:

- the vertical deflection of the composite beams at different cross sections (LVDTs A);
- the relative rotation of the cross section of the beam at 290mm from the outer face of the column with respect to it (LVDTs B);
- the slip between the concrete slab and the steel beam in the vicinity of the column (LVDTs C);
- the horizontal displacements between the top ends of the columns and the horizontal displacements at the level of the composite beams (LVDTs D);
- the rotation of the web column panel and of the beams in the vicinity of the joints (inclinometers E);

Electrical strain gages were used to monitor the local behaviour of the main relevant components of the sub-frames. Those located on the concrete slab in the vicinity of the nodal zones permitted to analyse the slab performance when the concrete is fully effective. The strain gages located at different sections of the steel beams together with those on the most inner and outer couples of the longitudinal rebars (at the same sections) allowed a refined appraisal of the beam curvature. The internal forces of the column were evaluated by monitoring the strain of the column flanges. As to the nodal zones, the transfer force mechanism was appraised via the readings of the strain gages located at the column web panel and, for joints to external column, also in the additional trimming bars. In the case of UCS sub-frame, the strain gages were connected to the computer assisted data logging system before the phase of concreting of the slab. It permitted an appraisal of the internal forces due to the constructing stage and to the shrinkage of the concrete up to the beginning of the test, which plays an important role in the statically indeterminate structures, such as the sub-frames.

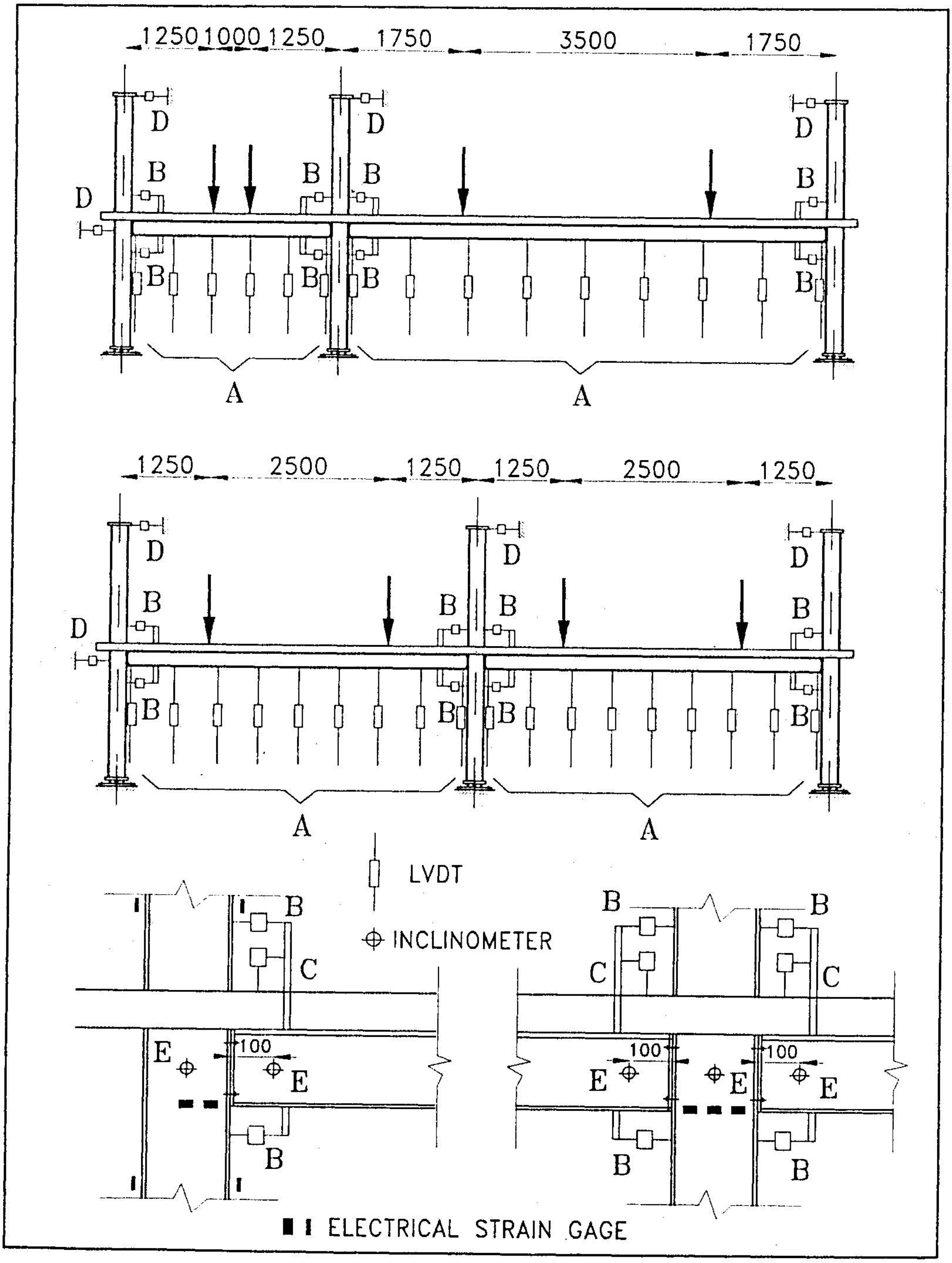

Fig. 4. Instrumentation

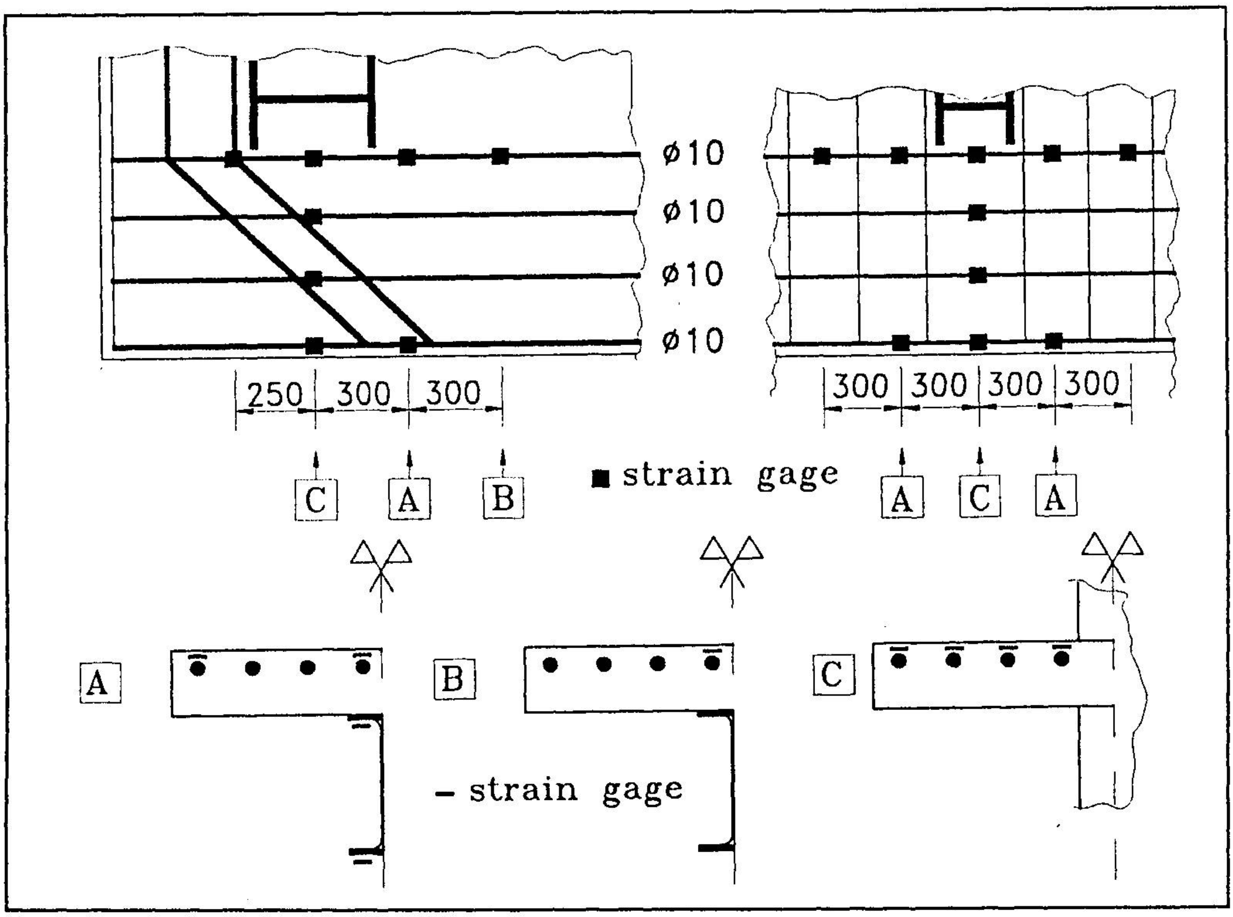

Fig. 5. Strain-gages on slab reinforcement bars.

3. The sub-frames tests

The tests were carried out by assuming the applied loads as control parameter tests and following a step-by-step procedure up to the achievement of the collapse. The loads were applied by subsequent increments at each step and were kept constant until the full development of the deformation was achieved. The loading history comprised several loading cycles with unloading to zero load condition in order to get a more thorough understanding of the structural behaviour.

3.1 Test on sub-frame SCS

The sub-frame specimen SCS was subjected to a symmetrical loading condition. For each composite beams two loads, nominally equal, were applied in accordance with the scheme of fig. 1.
The monitoring of the different joint components showed that internal joints first entered in the plastic range, due to the almost simultaneous yielding both of the inner couple of rebars and of the column panel zone under compression. As a consequence, a rather rapid decrease of joint stiffness was observed and a significant moment redistribution occurred, which lead to the

formation of a plastic hinge at the inner load location of the right beam. Collapse was then attained due to the local buckling at the plastic hinge location. Despite of the important plastic deformations, joints were not involved in the failure mode and did not show any evidence of particular distress. Their rotation capacity proved more than sufficient to ensure the achievement of the beam plastic failure condition. The moment-rotation curves for the internal and for the external joints (fig. 6) showed a remarkable similarity. The internal joints exhibited a noticeable plateau at a lower level of load due mainly to the yielding of the column web panel in compression.

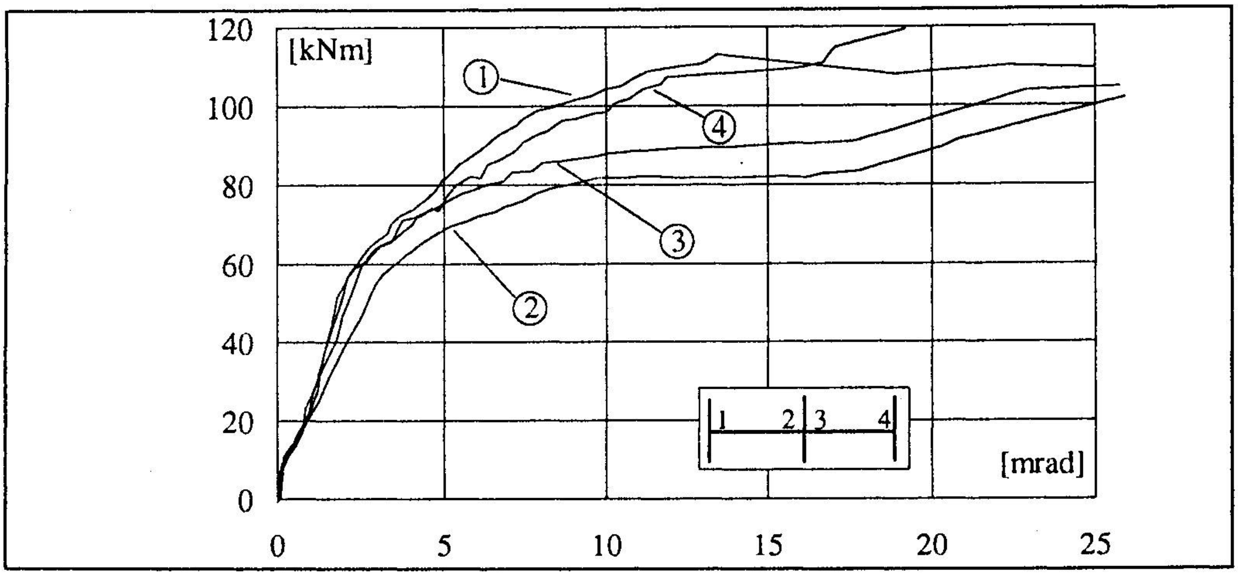

Fig. 6. M-φ curves for SCS joints

3.2 Test on sub-frame UCS

As previously mentioned, the response of the unsymmetrical composite sub-frame (UCS) was monitored also in the constructing stage [9]. During the concreting of the slab the beams were unpropped and the steel decking was supported for a short period (about 5 days). It appears clearly from fig. 7, in which the strain readings of the internal column (subject to the more severe state of deformations) and the room temperature are reported as a function of the concrete age. The discontinuity at a time of approximately 120 hours corresponds to the removal of the slab propping system. The trend of the strain-time relationships is significantly affected by the shrinkage of the concrete. It is important to note that to the increase in time corresponds a gradual decrease of the slope of the strain readings (in terms of mean values), due to the action of the shrinkage which is more relevant in the first period/immediately after the concreting of the slab. This is also confirmed by the measurements on concrete specimens in the same conditions of the slabs. After 550 hours from concreting the shrinkage deformation value was approximately 2.1×10^{-4}, and it increased up to 2.7×10^{-4} before testing of the sub-frame (about 2 months after the concreting of the slab).

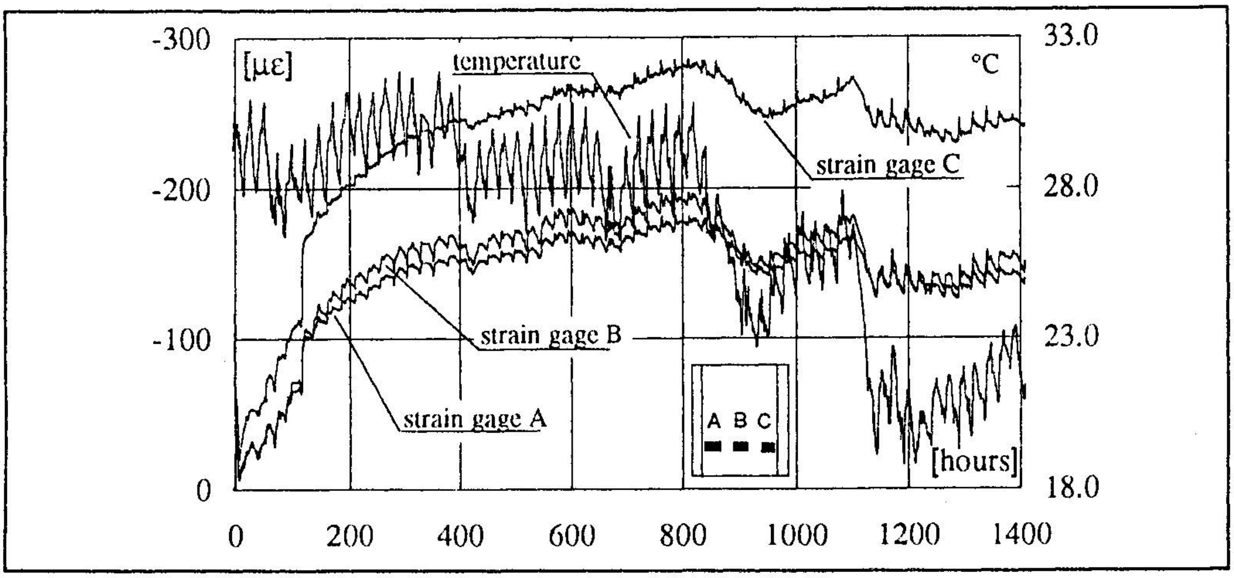

Fig. 7. Strain in the web panel of UCS specimen before the test

An appraisal of the bending moment due to the self-weight of the composite beams and to the shrinkage effects was assessed on the basis of the deformations of the web panel of the columns. As results from fig. 8, the values of the bending moments before the test are non negligible, ranging from 11 to 16 kNm for the internal joints and from 4 to 10 kNm for the external ones, and taking into account that the theoretical values for the cracking and yielding hogging moments of the composite joints are 32 kNm and 92 kNm, respectively.

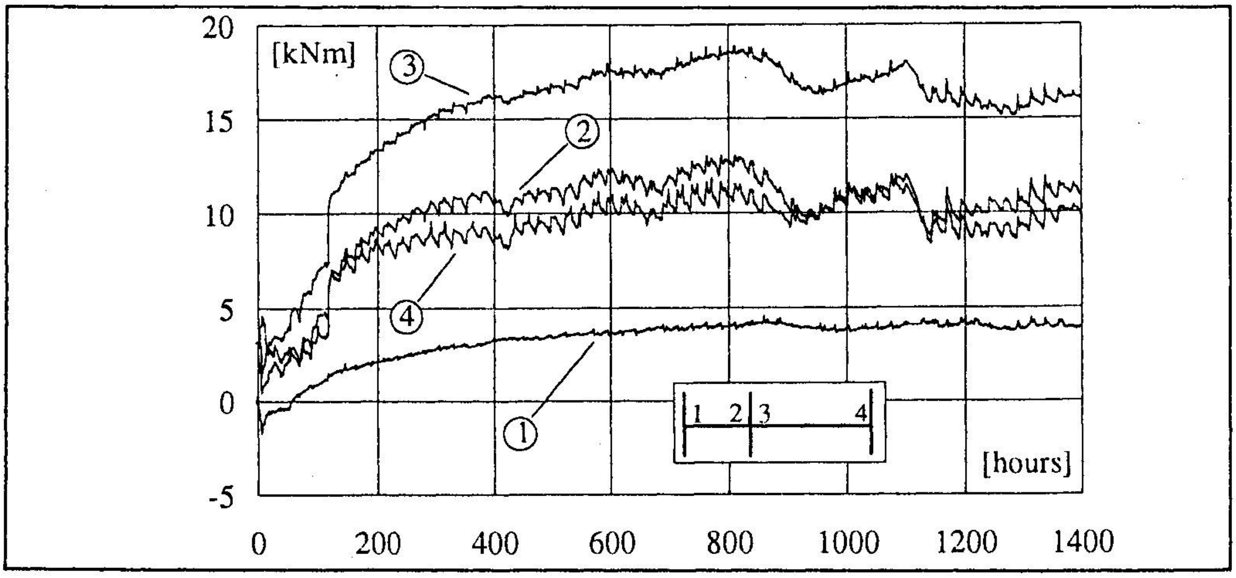

Fig. 8. Bending moments at the joints of UCS specimen before the test

During the test on the unsymmetrical sub-frame, in accordance with the scheme of fig. 1, equal loads were applied on each span until the collapse was achieved on the longer beam. Then the loads on this beam were kept constant by increasing the two loads on the shorter beam.
As to the beam with the longer span, the internal joint entered first in the plastic range, exhibiting a noticeable plateau due to the almost simultaneous yielding both of the inner couple of rebars and of the column panel zone under compression. The decrease of joint stiffness and the consequent moment redistribution led to the formation of a plastic hinge at the load location closer to the column. Collapse was caused by local buckling at the plastic hinge location. It should be remarked that before the collapse occurred, relevant slips between the concrete slab and the top flange of the steel beam developed in the zone between the load application points and the internal column.
In the second part of the test, which led to the collapse of the shorter beam the failure mode was similar to that of the longer one. The beam plastic hinge formed at the load location closer to the external column.
The moment-rotation curves for the internal and for the external joints are reported in fig. 9. The curves are obtained by shifting the experimental curves in order to represent, in accordance with fig. 8 for the UCS sub-frame, the joints response due to the sole loads applied during the test (i.e. neglecting the contribution of the concrete shrinkage).

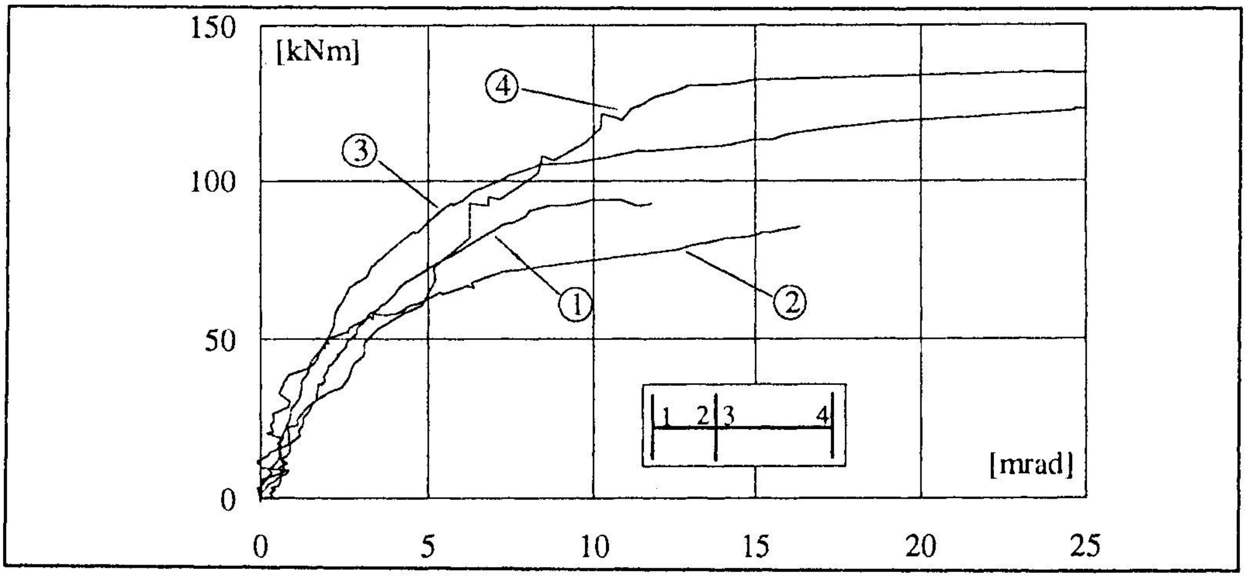

Fig. 9. M-φ curves for UCS joints

4. Preliminary conclusions

The experimental programme of a joint research project between the Universities of Trento and Trieste is briefly presented together with the main features of the tests carried out on two steel-concrete composite sub-frames. An extensive analysis of the data obtained from the complex measuring system adopted to monitor the behaviour of the tested sub-frames is presently in progress.
The very first results seem to indicate that the joint behaviour is more than satisfactory. Despite the important plastic deformations, joints were not involved in the failure mode, and did not show any evidence of particular distress. Their rotation capacity proved more than

sufficient to ensure the achievement of the beam plastic failure condition. The anchorage detailing of the trimming bars for joints to the external column confirmed a highly satisfactory behaviour.
Finally, with reference to the UCS sub-frame, it is necessary to underline the importance of the shrinkage of the concrete slab to the joints performance.

Acknowledgements

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