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THEORETICAL AND EXPERIMENTAL STUDIES REGARDING STEEL–CONCRETE COMPOSITE JOINTS

BY

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Abstract. Theoretical approaches supplemented with an experimental testing program were developed at the „Politehnica” University of Timişoara for a specific steel–concrete composite joint, used into a multi-storey skeletal structure. Starting with the joint type used, two series of joints were tested. Two loading hypotheses of the joint were considered: symmetrical and asymmetrical.

For the structures placed in seismic areas the energy dissipation during earthquake is important. The dissipation of energy consists in appearance of plastic hinges located in to the beams. For this study the pursued aim was to obtain the collapse mechanism in the joint panel rather than outside the joint, in order to compare the bending resistant moment of steel joint with the bending resistant moment of composite joint.

Using the previsions of EC4 [1], in the theoretical phase the joints were analysed together with their connections – the beams and the columns in order to establish the dimensions of the joint components, thus satisfying the desired collapse mechanism. Also a numerical study was performed in the elastic and post elastic range. Finally the experimental work was performed using special testing equipment and the international recommended testing procedures. This paper presents some aspects regarding the behaviour of steel and steel joints tested.

Key words: composite joints; numerical analysis; experimental tests.

1. Introduction

Due to the technological process, a composite structure is initially a steel structure. After placing the reinforcement and the concrete casting the structure becomes a composite one. The type of studied joint was used in a multi-storey building in Timişoara, with 12 storeys. The entire structure was built as a steel–concrete composite construction. The structural type is a space skeleton bar structure using plane frames placed on two orthogonal directions, being connected through the floor slabs. The structural solution is justified by the span width with unexaggerated cross sectional dimensions for the columns, adequate lateral stiffness and cost effective fire protection due to the presence of the concrete. The general view of the composite joint is presented in Fig. 1. Few relevant aspects from the constructive site are represented in Fig. 2.

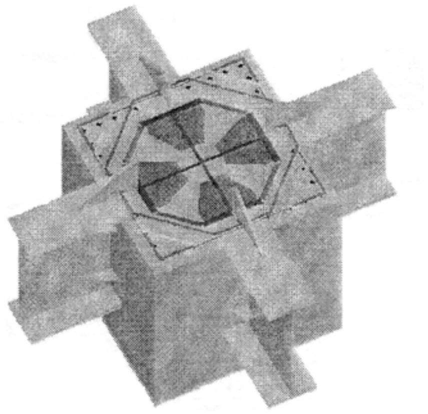


Fig. 1 – Steel–concrete composite joint details.

Fig. 2 – Details of constructive work for composite column and joint.

As it is known the structure becomes a composite one after the longitudinal reinforcement and the transversal reinforcement are placed on site and the concrete are cast into the column mould. The composite steel–concrete joint type which was tested belongs effectively to the composite steel–concrete structure already erected and finished. The reasons which for the joints as composite element were studied were based on the following aspects, revealed into the design process:

a) the contribution of the reinforced concrete floor slab at the cross section of the beams was neglected into the overall stiffness evaluation of the space frame;

b) the cross section of the composite beam is composed by a reinforced concrete precast slab and steel I profile; the connectors were provided only along the steel beam, but not into the joint zone;

c) in the joint zone, the continuity of the reinforced concrete slab was interrupted due to the technological process, thus the reinforced concrete precast slab, as part of the floor system, was not provided as a continuous reinforced concrete element over the joint zone.

Initially, using the real dimensions utilized in practice, for the column and beam, a numerical analysis was performed and we observed the tendency to have a plastic hinge at the exterior of the joint. Because the purpose of the testing was the study of the joint failure mode and the checking of its bearing capacity, in the situation presented above, it was suggested the increase of the beam bearing capacity by increasing its flange width and its web as well, and by maintaining the column section and the height of the beam respectively.

2. Theoretical Study of Steel and Steel–Concrete Composite Joints; Calibration of the Experimental Specimens

In order to evaluate the stress state in the joint and the behaviour study of the dimensioning element, on the geometrical dimensions basis, some numerical analyses has been performed using the finite element method. In the first stage the SAP 2000 numerical analysis program was used, the modelling being obtained by SHELL finite elements type, for the structural steel of the joint. After the calibration of structural steel, the evaluation of the stress state in the composite joint elements has been done after several numerical analyses in the post elastic range using nonlinear analysis software, taking into account all the constitutive elements of the joint: structural steel, reinforcements and concrete.

2.1. Numerical Analysis for Symmetrical and Asymmetrical Load Cases

To have a clearer view of the stress state in the joint, the choise of the analysed model was accordingly to the testing mode. For the symmetrical load case, taking into consideration the possibility of making an experimental test, we drew the conclusion that the instruments that we had at our disposal allow the loading of the column and the mounting of some joint supports at the extremity of the two beams that concur in the structural joint [2]. In fact this loading type simulates the real situation when the loading is actually on the beams. The results of the structural steel numerical analysis of the experimental element, obtained initially as a result of the design, are presented in Fig. 3.

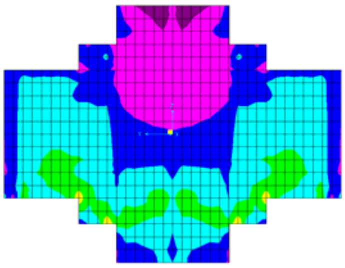


Fig. 3 – Isostresses, σ_{max}, for steel joint (mid-plane view).

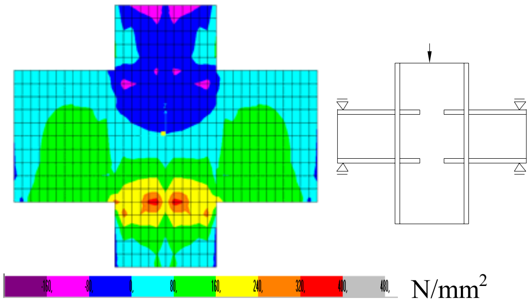


Fig. 4 – Isostresses, σ_{max}, for the steel joint symmetrical load (mid plane view).

Analysing the stress level in the joint we can observe that there is a concentration of stresses in the vertical stiffeners which connect the beam to the column. The value of the maximum stresses in the stiffeners is of 450 N/mm^2, and in the web of the column or in the beam of ~300 N/mm^2. These observations lead to the idea that in the case of an experimental testing on a model, made up as above, there is the possibility of tearing outside the joint, starting from the vertical stiffeners and continuing with the beam.

Because the purpose of the testing was the study of the joint failure mode and the checking of its bearing capacity, in the situation presented above, it was suggested the increase of the beam bearing capacity by increasing its flange width and its web as well, and by maintaining the column section and the height of the beam, respectively. The purpose of the testing being to obtain information on the stress state inside the joint and thus to cause the failure in the joint, the decision was to eliminate the vertical stiffeners, which became useless in this case. The vertical stiffeners are useful in real structures because they increase the bearing capacity in the joint zone, the plastic hinge taking place in the beam and not in the joint. In Fig. 4 are presented the isostresses, obtained for the proposed experimental specimen (symmetrical load).

For asymmetrical load case the column was fixed at the extremities and the loads were applied at the end of the beams [3]. Starting with the dimensions of structural steel established in the symmetrical load case another numerical analysis was performed for asymmetrical load case. The distribution of the stresses show a different behaviour of the joint with the maximum stress occurred near the welding of column flanges with column panel (Fig. 5).

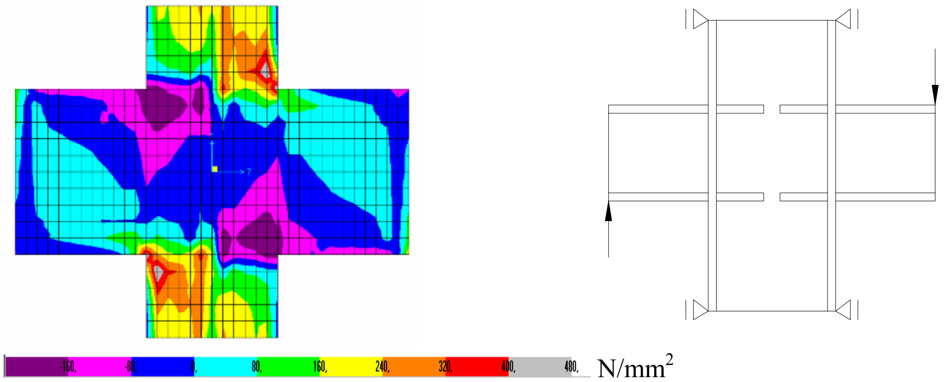


Fig. 5 – Isostresses, $\sigma_{\max}$, for the steel joint asymmetrical load (mid plane view).

The evaluation of the stress state in the composite joint elements has been performed after several numerical analyses in the post elastic range using nonlinear analysis software. A vertical section was considered in the mid-plane of the joint, practically in the middle of the joint panel axis (Fig. 6). In this case it was assumed that the joint is in a plane stress state. In the model all the component materials and elements were considered. Practically the model was created similar to a specific reinforced concrete joint but taking into account the structural steel.

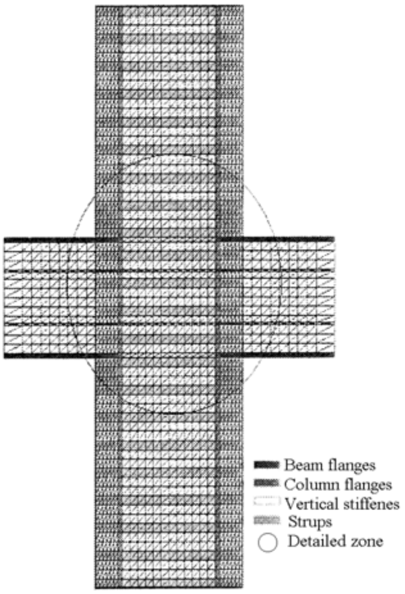


Fig. 6 – Mesh of analysed composite joint (vertical section).

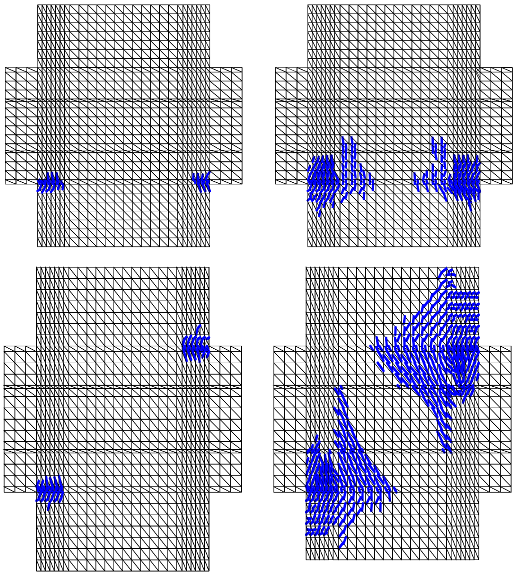


Fig. 7 – Evolution and distribution of cracks symmetrical and asymmetrical loads.

Related to the behaviour of the composite joints the cracks distribution during different charges was analysed [4]. From this point of view the results shows a similar behaviour of composite joint with a reinforced concrete joint. For the symmetrical load case when the joint is in bending, the cracks initiated at the level of flanges in tension. For asymmetrical load case the joint panel is in shear (Fig. 7), with distribution of cracks on diagonal.

3. Experimental Studies

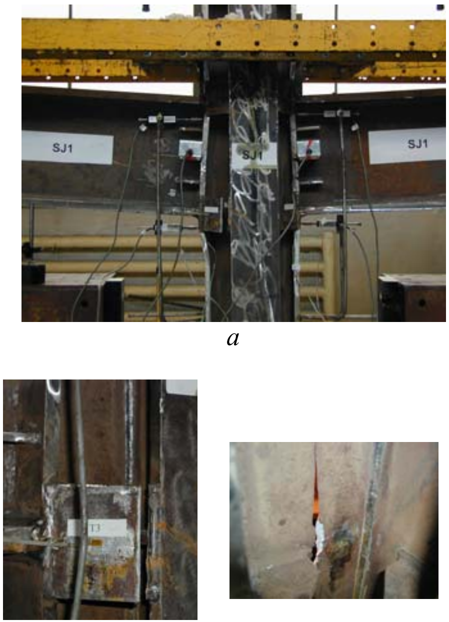
All the experimental tests were performed using the proceeding indicated by ECCS. For the symmetrical load case the load was applied at the top of column for each tested element.

For the asymmetrical load case the load was applied at the top and at the bottom of beams flanges of tested element. The tests were controlled using displacements devices of the hydraulic jacks. The instrumentation consisted in displacement transducers, inclinometers and strain gauges. For each loading case considered two steel and two composite joints were tested.

Using recorded data from the monotonous displacement increase tests made on the steel joint and the composite joint there were evaluated the limit of the elastic range *F*, [kN], and the corresponding displacement, e_y , [mm]. The elastic limit was used to generate the cyclic tests according with recommended testing procedure [5].

3.2. Comparative Study Concerning the Behaviour of the Structural Steel and Steel–Concrete Composite Joint under Symmetrical and Asymmetrical Loads

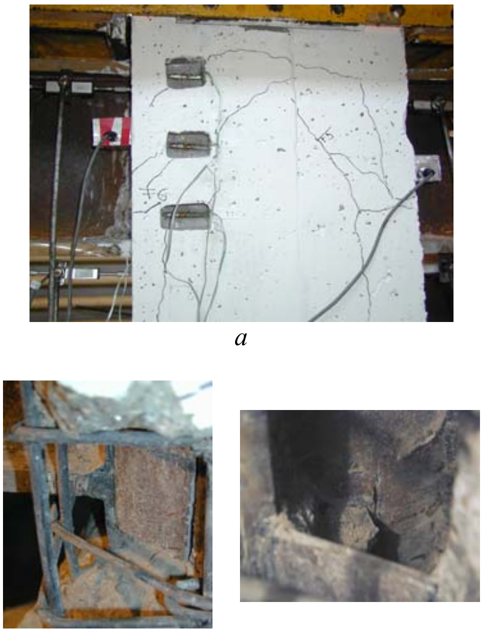
In Figs. 8 and 9 it can be observed a comparative study between the failure mechanism of steel joints and steel–concrete composite joints.



a

b *c*

Fig. 8 – Failure mechanism of steel joint symmetrical load: *a* – front view of steel joinr; *b* – tearing of vertical stiffener; *c* – large crack in the joint panel.



a

b *c*

Fig. 9 – Failure mechanism of steel–concrete composite joint, symmetrical load: *a* – distribution of cracks at the composite steel concrete joint; *b* – tearing of vertical stiffener; *c* – small crack in the joint panel.

The behaviour of joints under symmetrical loads were similar, the failure mode being practically the same. The failure mechanism consists in tearing of vertical stiffener from beam to column flanges and cracking of joint panel at the end of horizontal stiffeners. As we expected, in the case of composite joint the crack length and opening in the joint panel was smaller than in the steel joint due to the presence of concrete and stirrups into the joint.

The comparative study between the experimental elements is based on moment *vs.* rotation characteristic diagram recorded at the lateral face of joints.

The moment *vs.* rotation diagram for monotonous tests show different initial stiffness and maximum bending resisting moment of composite joint in comparison with steel joint (Fig. 10). In Fig. 11 is represented the rotation moment diagram for the steel and steel–concrete composite joint under symmetrical load, cyclic tests.

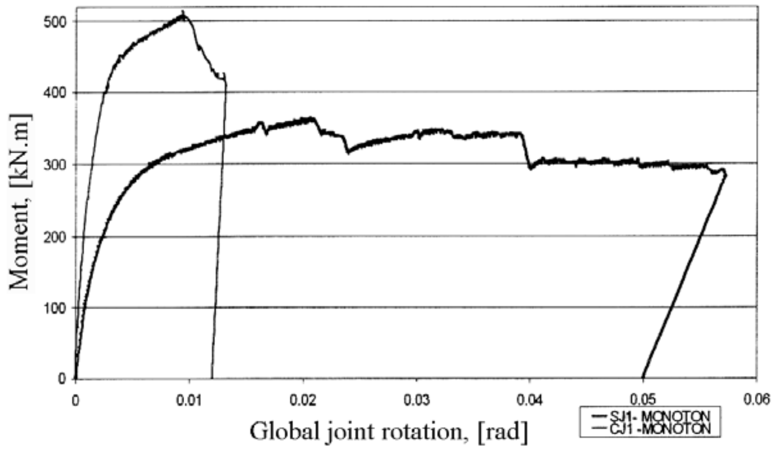


Fig. 10 – Moment *vs.* rotation diagram for steel and composite joints under symmetrical loads – monotonous tests.

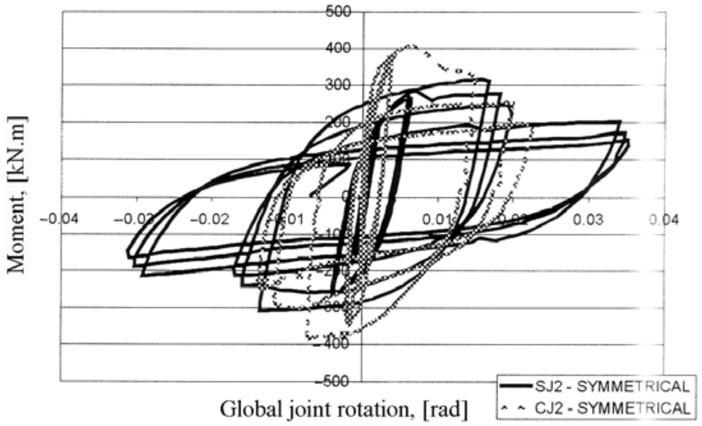


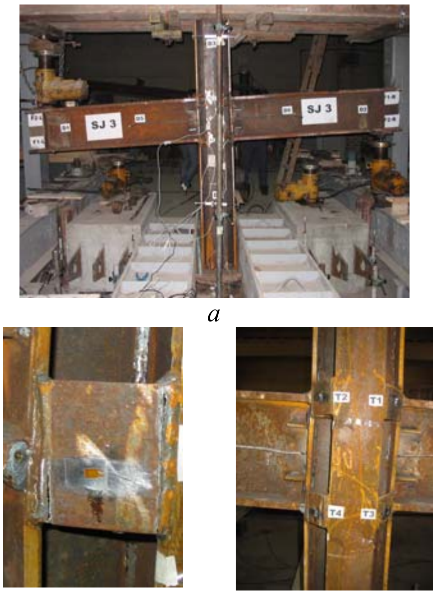
Fig. 11 – Moment *vs.* rotation diagram for steel and composite joints under symmetrical loads – cyclic tests.

The characteristic values obtained during the cyclic tests for joints under symmetrical loads are presented in Table 1. As can be observed the elastic limit for both joints had similar values, the bending resisting moment for composite joint is greater with 26% than the steel one.

Table 1
Basic Parameters for Cyclic Test Symmetrical Load

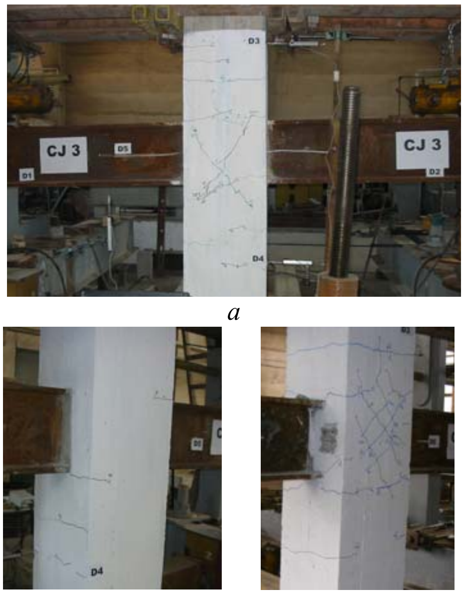
	Steel joint (SJ2)/ cyclic test		Composite joint (CJ2)/ cyclic test	
Maximum bending moment, [kN.m]	+315.5	–310.39	+405.6	–382.8
Ultimate rotation, [m.rad]	+35.2	–29.3	+22.3	–13.8
Elastic limit, e_y, [mm]	6.18		6.38	
Experimental bending moment (elastic limit), [kN.m]	+201.4	–215.8	+273.4	–284.9

In Figs. 12 and 13 can be observed the obtained results of a comparative study between the failure mechanism of steel joints and steel–concrete composite joints under asymmetrical loads.



a
b *c*

Fig. 12 – Failure mechanism of the steel joint asymmetrical load: *a* – general view of steel joint – asymmetrical load; *b* – tearing of vertical stiffener; *c* – general view of joint at failure.



a
b *c*

Fig. 13 – Failure mechanism of the steel concrete composite joint asymmetrical load: *a* – distribution of cracks at the composite steel concrete joint asymmetrical load test; *b* – distribution of first cracks in joint and column; *c* – cracks distribution at failure.

The basic parameters of tested joints under asymmetrical loads are presented in Table 2.

Table 2.
Basic Parameters for Cyclic Test Asymmetrical Load

	Steel joint (SJ4)/ cyclic test		Composite joint (CJ4)/cyclic test	
Maximum bending moment, [kN.m]	+252.4	–248.31	+345.15	–343.95
Ultimate rotation, [m.rad]	+61.4	–54.08	+31.3	–23.92
Elastic limit, e_y, [mm]	5.62		5.80	
Experimental bending moment (elastic limit), [kNm]	+186.5	–190.2	+259.70	–239.50

In Fig. 14 are represented the comparative diagrams for tested joints under asymmetrical loads. The similar behaviour for steel and steel concrete composite joint can be observed also for asymmetrical loads.

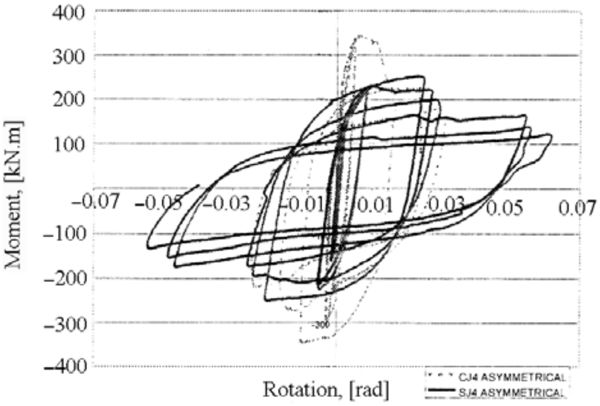


Fig. 14 – Moment *vs.* rotation diagram for steel and composite joints under asymmetrical loads.

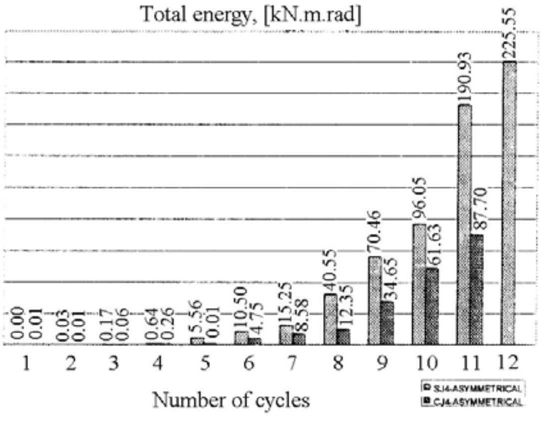


Fig. 15 – Total dissipated energy for steel an steel composite joint under asymmetrical loads.

For asymmetrical load case the total dissipated energy for steel joint is greater than the total dissipated energy for composite joint (Fig. 15). At the end of test, cycle *11*, the total energy dissipated by steel joint is double in comparison with the steel–concrete composite joint.

4. Conclusions

Taking into account the results of experimental tests and theoretical study made on steel and steel–concrete composite joints under symmetrical and asymmetrical loads the following conclusions may be formulated:

1. In the composite joint a redistribution of the stresses occurs between the concrete, reinforcement and structural steel.
2. The connection between the structural steel flanges and the web is in a zone where the stress distribution must take into account the presence of the reinforcement and the concrete and therefore the stress state is far from a pure steel stress state.
3. The buckling of joint panel and vertical stiffeners in compression zone at the composite joint is avoided due to presence of concrete and transversal reinforcement (stirrups) in the joint; the presence of the concrete in the joint has the effect of increasing the load bearing capacity of the joint.
4. It is considered that the vertical stiffeners play a significant rôle in the increase of the joint bearing capacity, the weak point being the welding at the column flange. The connection by welding of the vertical stiffeners cannot be made by complete penetration due to technical considerations.
5. For the symmetrical load case the initial stiffness of steel–concrete composite joint is with 18% greater than initial stiffness of steel joint.
6. For asymmetrical load case the initial stiffness of steel–concrete composite joint is with 23% greater than initial stiffness of steel joint.

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STUDII TEORETICE ŞI EXPERIMENTALE PRIVIND NODURILE COMPUSE OȚEL–BETON

(Rezumat)

Proiectarea elementelor compuse oțel–beton pentru structuri în cadre amplasate în zone seismice se face ținând seama de mecanismele de disipare a energiei din structură. Pentru nodurile de cadre compuse oțel–beton datorită tehnologiei de execuție sunt necesare detalii specifice de alcătuire. Se prezintă rezultatele unor studii teoretice şi încercări experimentale pe un tip de nod compus oțel–beton solicitat simetric şi antisimetric, utilizat la o structură multietajată. Se prezintă comparativ modurile de cedare şi comportarea nodurilor.