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Autor: Stoian, Valeriu / Olariu, Irina

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Steel-Concrete Seismic Resistant Structure for Multi-Storey Buildings

Valeriu STOIAN
Prof., PhD, Civil Eng.
Politechnica University
Timisoara, Romania

Valeriu Stoian, born 1949, received his civil engineering degree at the Politechnica of Timisoara in 1972 and his PhD in 1982. He is Professor of structural engineering at Politechnica University of Timisoara and Technical Manager in a building construction enterprise, being involved in major building projects.

Irina OLARIU
Civil Eng.
CADFEM-10 Ltd.
Timisoara, Romania

Irina Olariu, born in 1945, received her civil engineering degree at the Politechnica of Timisoara in 1968. She is structural engineer in a design office in Timisoara. Her activity is related to structural analysis, structural modelling and CAD.

Summary

The building structure was designed to resist seismic action. Therefore specific details were conceived to satisfy anti-seismic provisions according to Romanian seismic codes.
Composite beams were designed as steel beams interconnected with the reinforced precast concrete slabs with shear connectors. Steel concrete composite column has structural steel made up by steel welded bands and reinforcement realised from steel rolled bars.
Special attention was paid to the structural model to perform the linear modal analysis and to obtain the non-linear behaviour of the structure.

1. The building assembly

The construction belongs to a building assembly composed by three main buildings having different number of stories, being separated by an interior street covered with transparent glass. The functional requirement to have wide spaces at each level, led to a skeletal scheme for the buildings. Being placed at the ground level, the interior street floor slab connect only functionally the buildings, thus each of them has an independent behaviour and it was design accordingly to this assumption. Structurally being conceived similarly, the design process was identical for all three buildings.

2. Structural system

The main construction is a multistory building consisting of 9, partially 12 levels (Fig.1).
The underground level consists into an rigid box made up from reinforced concrete realised from an assembly of structural walls together with the floor and footings. The upper levels are realised as space skeleton bar structure using plane frames placed on two orthogonal directions, being connected through the floor slabs (Fig.2).
The entire structure is realised as a steel-concrete composite construction. 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.

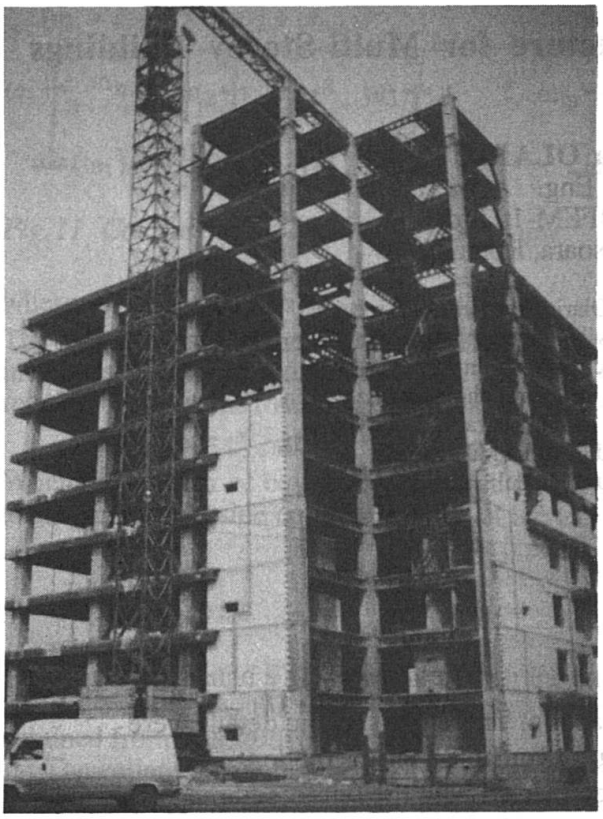

Fig. 1 Front view of the multi-storey building

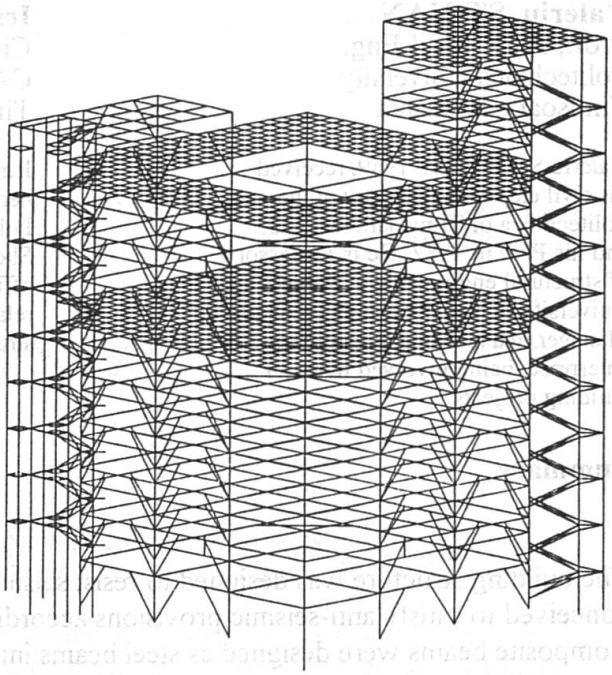

Fig. 2 The space bar model of the structure

2.1 Structural detailing

The building is placed into an seismic zone (with the ratio between the peak ground acceleration to the acceleration of gravity equal to 0.16). In order to perform the analysis, the cross sectional characteristics of the building elements were considered accordingly with the loading type (long term loads, short term loads).
No infill panels were considered in the structural model. Therefore, a joint between the infill masonry and the structural elements was provided.
The columns have squared section because of the beam spans which are identically on both directions. The main stress state in columns is eccentric compression with bending moments approximately equal on both directions. Load bearing capacity to torsion is neglected due to the existence of the floor slab and due to the minor value of the torsion capacity of the secondary steel beams simply supported on the main beams. All the joints are welded. For the steel elements of the structure were utilised the specific dimensions presented in Tab. 1, in which A is the cross sectional area and U is the perimeter of the cross section.

ELEMENT	Frame beams	Secondary grid beams	Braces
A/U (m)	100-165	160-240	115-160

Tab. 1 A/U ratio for the structural elements

The steel-concrete composite frame beams are I sections obtained from welded steel bands connected at the upper flange with the reinforced concrete slab by shear connectors.

The beams were provided with full web at the extremities and with holes in the middle span to access technological ducts. Those without braces were designed at permanent loads, those with braces at seismic loads. The floor slab are realised by precast reinforced concrete slabs monolithically connected at the upper part of the supporting beams. For the inner space between the main beams an rectangular simply supported steel grid was provided. The secondary beams were realised also as composite beams.
The Romanian anti seismic code provisions (P100) imposes for frames rigid connections between beams and columns, the steel beams were designed as follows: two cantilevers welded at the columns adjacent to beam span by the complete penetration technology and a central part which will be welded at yard. An typical detail of the steel joint is represented in Fig. 3. The overall stability in the final phase of the beams was established through the beam connectors which connect the beams with the horizontal diaphragm - the floor slab. The shear connectors are of rigid type and consist of I steel profile welded on the top flange of the beam (Fig. 4).

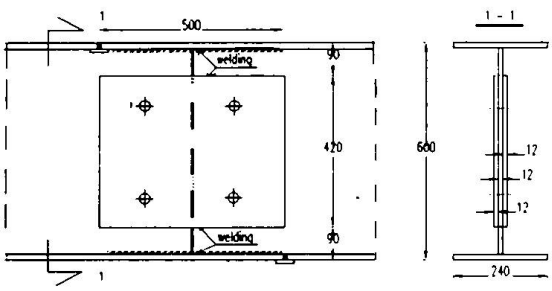

Fig. 3 The typical beam connection

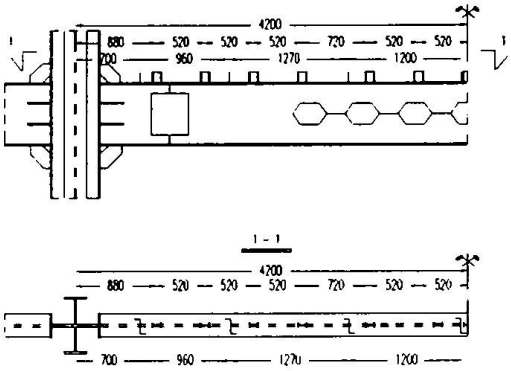

Fig.4 Beam connectors

Due to alternate stresses in the seismic load, in the seismic beam design, at the ends the contribution of the reinforced concrete slab was neglected. The stability of the inferior part of the cross section near the beam column joint was assured with two pairs of horizontal stiffeners, Fig. 5. In the same time, the condition which impose an higher capable moment in the joint section with 20% than of the beam section (Mj/Mb > 1.2) was respected at every joint. The specific detail was conceived taking into consideration the concept, generally recognised now, which located the energy dissipation zones out of the joints. Thus, the special conditions provided in P100-92 for the potential plastic zones at beams were respected. The columns were designed and realised as steel-concrete composite section, using EC4 code (Commission of the European Community, 1992). An typical detail is represented in Fig. 6. The structural analysis revealed that the structure is not sensitive to second order effects.

2.3 Structural stiffening

In order to avoid large lateral displacements of the structure, a set of steel braces are provided, as can be seen schematically in Fig. 2, in which can be seen also the braces positioning. Based on recent conclusions resulting from a large number of theoretical and experimental works it was adopted an eccentrically braced solution. The braces efficiency was evaluated by the relative level stiffness of an unbraced or braced structure and by seismic forces acting on unbraced and braced frames. Two variants of braces positioning were studied:

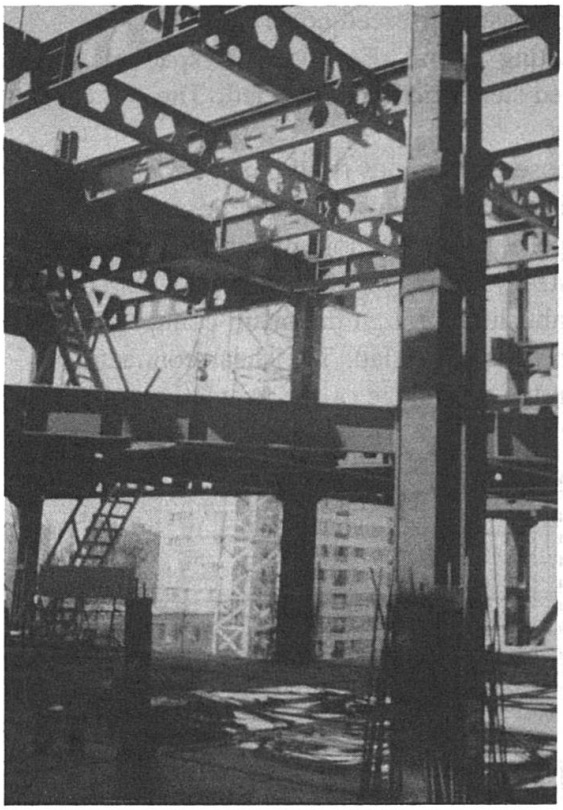

Fig. 5 Structural steel detail

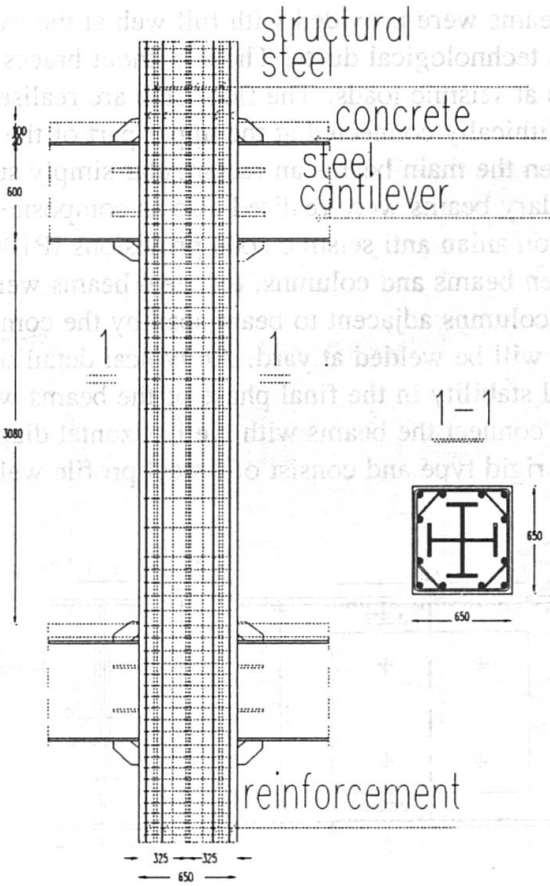

Fig. 6 Composite steel concrete column detail

- A variant - at which the braces are placed on the exterior part of the building in two consecutive spans on each side.
- B variant - at which the braces are placed in the four corners of the exterior part of the building

The square form of the horizontal building plane admits as symmetry axes both the sides and the diagonal. These axes will be found in modal analysis as principal axes, thus:
- side, if it will be accentuated the stiffness upon the side (variant A);
- diagonal, if it will be placed corner braces (variant B) and eccentrically mass positioning.

In this situation the dynamic structural response is coupled. Therefore, providing the braces in the central spans (variant A) has advantage in the distribution of the axial forces due to horizontal loads. Variant B give a coupled dynamic response of the structure and determine a higher general torsion moment. Absolute and relative displacements reflect the monotone character of the structure, with different values at the top levels for the two studied cases. The modal response of the structure, lateral displacements and the relative level stiffness are affected by the number of braces rather than their position.

	T1 (s)	T2 (s)	T3 (s)	T4 (s)	T5 (s)	T6 (s)	d_{max}/H_{level} (mm/m)	d_{min}/H_{level} (mm/m)
VARIANT A	1.48	1.43	1.12	0.55	0.54	0.40	10.356	3.3
VARIANT B	1.53	1.47	1.37	0.55	0.53	0.48	22.372	3.48

Table 2. Structural modal response

As it can be seen in Table 2, the maximum drift (including postelastic displacements) overpasses the maximum allowable drift (7 mm/m) for this type of building in spite of the presence of the steel braces.

2.4 Effect of initial stresses

Erection technology generates initial stresses in the structural steel of the columns. Thus, initial compression stresses in the cross section of the structural steel is about 30 MPa, respectively an initial strain $\varepsilon_i = 0.15$ mm/m. This strain can be represented as a translation in the strain diagram (Fig.7).

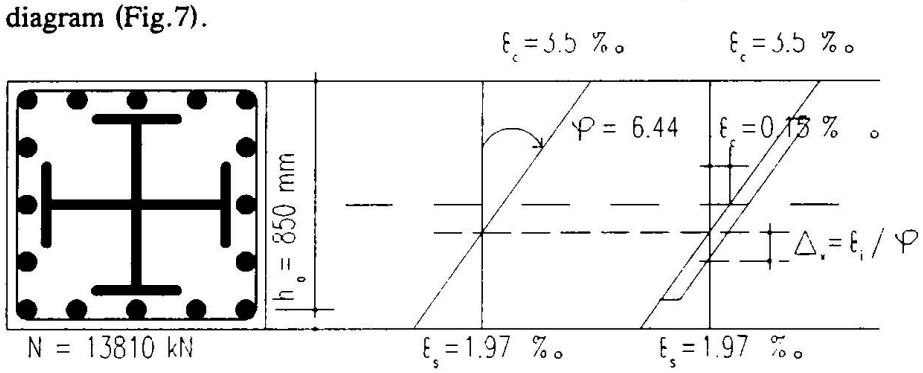

Fig. 7 Influence of the initial stresses

This translation can be quantified with two parameters: rotation φ and axial strain ε_i. Neutral axis will move down with Δ_x, increasing the height of the compression zone. The effect will be the increasing of the sectional ductility together with an reduction of the load bearing capacity of the column.

3. Nonlinear analysis

In order to provide a satisfactory behaviour of the eccentrically braced frame system during the earthquake motions and to determine the collapse scenario of the structure, an non-linear analysis was performed with dedicated software (ANELISE). Was check the collapse mechanism type based on the strength hierarchy. For the nonlinear analysis an condensed model was used. The structural condensed model was subjected to three different accelerograms: Vrancea 1977 (81%), Bucuresti 1986 (100%), El-Centro 1940 (52%). In the Table 3 a short synthesis of the linear and nonlinear structural analysis is presented. In this table, A_{gr} is the ground acceleration, V_{gr} is the ground velocity, E_{ind} is the induced energy and E_{dis} is the dissipated energy, H is the total height of the structure.

CASE	FORCE (kN)	F.POS (H/H_{max})	DISPL (mm)	ROT (rad)	A/A_{gr}	V/V_g	E_{ind} (kNm)	E_{dis} (kNm)
CODE	5149.62	.56	255.6	0.0097				
ACC1	16363.7	.39	302.2	0.0237	3.4	2.07	5083.5	1286.3
ACC2	6185.42	.48	66.2	0.0028	2.4	2.27	520.3	0.0
ACC3	6005.55	.45	77.9	0.0027	2.36	1.77	447.3	0.0

Table 3. Structural response to seismic loads

The collapse mechanism of a braced steel frame with eccentrically placed braces was suggested by the relative ratio between the capable bending moments versus the effective bending moments on the frame beam. The design idea was to avoid the braces stability loose before the beam plasticity. The top level displacements and the required ductility in columns are represented in Fig. 8.

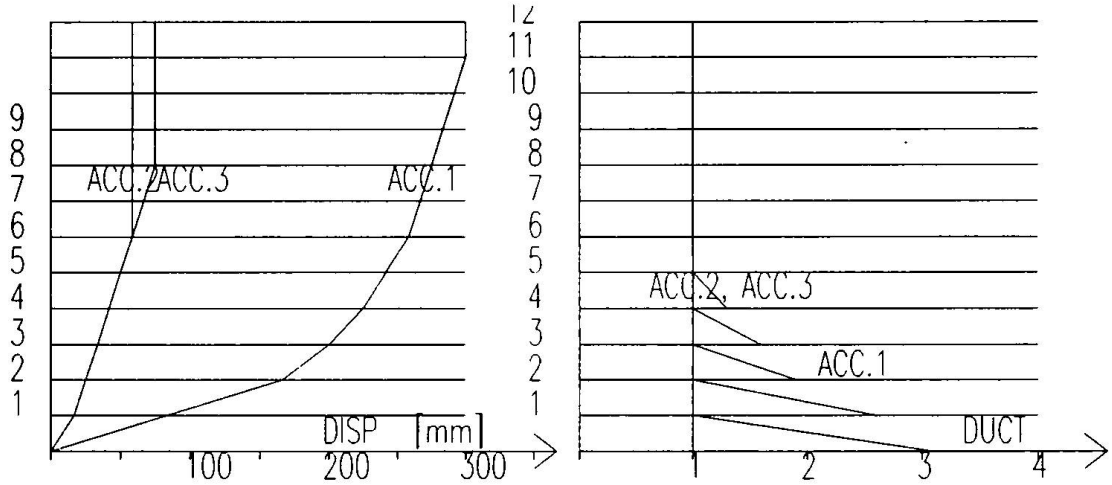

Fig. 8 Lateral displacements and column required ductility

The analysis shows that the structure has an typical frame structural behavior, even in the presence of the braces. The structure is sensitive to Vrancea type accelerograms which has an low incidence in the region where the building is placed. Seismic loads and lateral displacements demonstrate that the reduction coefficient for seismic loads was well choose for the accelerograms 2 and 3. For these accelerograms no plastic hinges were detected and any ductility requirements, the structure remaining in serviceability limit state. For severe earthquakes this structure is mainly governed by a moment braced frame behaviour and the structure goes into the damageability limit state.
The anchorage section for the structural steel of the column was provided at the midheight of the underground level for several reasons such as: incompatible dimensions of the anchorage zone with the column section, avoid to create a shear sensitive section at the base of the structure, inconsistent provisions for the composite steel-concrete column base sections, difficulties for the detailing design in these sections and insufficient knowledge of the behaviour of these anchorage zones.

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