The Seismic Performance of Reinforced Concrete Frame Structures using Wide Beams

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Abstract

Present contribution focuses on a few aspects regarding wide beam-column joints made out of reinforced concrete, joints being analyzed under the aspect of strength and especially of deformation capacity. It was studied the seismic performance of a structure taking into account two solutions: in the first is used a reinforced concrete frame system (precast columns + precast wide beams), and in the second one is used an uncoupled wall system (monolithic structural walls + frames with precast columns and precast wide beams). This is a field of study poorly researched, not being discussed in the Romanian standards nor in the European design codes, although the advantages like flexibility in using the interior spaces recommends it to the developers of commercial buildings but also to the architects, the structural solution offers bays of 8by8...10by10 [m] while the thickness of the beam-floor is only L/20 of the beam span. The seismic design and the dimensioning of the structural elements: columns, joints, structural walls and wide beams were made taking into account the second order effect (P-Δ) from a modal analysis, and checked with a non-linear static (pushover) analysis using ETABS 9.6 and SAP2000 14.1.0. The reinforced frame system due to the high flexure needs columns with large sections, while in the second solution we can use more slender vertical elements with a higher seismic performance and even with smaller costs.

Rezumat

Lucrarea prezintă câteva aspecte referitoare la modul de conformare și de comportare al nodurilor grindă lată-stâlp din beton armat, sub aspectul rezistenței și în special al deformabilității. Este studiată performanța seismică a unei structuri în soluție de cadre pur din stâlpi și grinzile latе din beton armat prefabricat, respectiv în soluție de structură duală cu diafragme monolite plus cadre din stâlpi și grinzile latе din beton armat prefabricat. Acesta reprezintă un domeniu puțin cercetat, neînțeles tratat în normele de proiectare românești ori în cele europene, în condițiile în care flexibilitatea de compartimentare și de utilizare al spațiului acestui sistem este agreată de către beneficiarii de spații comerciale însă și de către arhițecți, putând realiza trame de 8x8...10x10[m] și având în același timp o grosime de planșeu limitată la doar L/20 din deschidere. Analiza și dimensionarea stâlpilor, imbinărilor, diafragmelor și a grinzilor late se face ținând cont și de efectele de ordinul II (P-Δ) rezultate în urma unei analize module, și verificate folosindu-ne de un calcul neliniar de tip pushover. Este studiată problema determinării lungimii de flambaj a stâlpilor precum și aportul grinzilor late în preluarea încărcărilor seismice prin efectul de cadru. Structura analizată este proiectată pentru un amplasament caracterizat de o accelerare de proiectare a terenului $a_s=0.24g$, și de o perioadă de colț $T_c=1.6$ sec. Din punct de vedere al caracteristicilor

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geometrice, structura are o dimensiune în plan de 76,50x51,00[m], cu trame pătrate de 8,50x8,50[m] și cu un regim de înălțime de P+2E, înălțimea de nivel fiind de 4m.

**Keywords:** Wide Beam-Column Joint, Column Buckling, Seismic Design, Wide Beam Participation

1. Introduction

Wide beams can be defined as structural elements that have the length much greater than the dimensions of the cross section, the width greater than their height, and they carry vertical loads to the supports through bending and shearing (sometimes torsion) [1].

If the whole depth of the beam is embedded into the thickness of the slab than we have a so called thick plate, plate which stands directly on top of the column [1]. Here the beam is actually a fraction of the wide of the thick plate, column strip, \( \frac{L_y}{4} \) wide [2], Fig. 1 (a). Another solution, which has been proved to be economical from the point of material use, is to use beams (precast, prestressed or monolithic) with a depth greater than the thickness of the slab. If we have a depth of the beam around \( \frac{L}{15} \) than the beam is an ordinary one, for \( \frac{L}{8} \) is a high depth beam, while a depth smaller than \( \frac{L}{20} \) gives us a wide beam, Fig. 1. Using them allows us to avoid the punching problem occurred usually in the thick plate solution.

Using beams with a depth between \( \frac{L}{15}..\frac{L}{8} \) offers us an optimal use of material (concrete and steel). Sometimes, structural engineers need to use other solutions in order to fulfill the architectural requirements, technological needs if an industrial building is involved, the necessary trickle for pipes and ventilation, a minimum story height and a maximum inner height etc. A possible way to fulfill these requirements is using wide beams towards thick plates.

![Figure 1. Types of floor beams [1]](image)

If we use precast concrete structures we can obtain a better time programming of the building execution, a higher productivity, a cost reduction of the manufacture and not least, a better control of the work quality. Another benefit of precast solution is the possibility of using prestressed beams
at a reasonable price. The assembly of the structure goes easy, with a satisfactory speed, and most of the time is independent of the climate changes (except the moments when cast-in-place concrete must be poured in site) Fig. 3.

2. Comparative design and structural compliance

Buildings and composite structural systems involving wide beam-column joints have become very popular as the load-resisting frames in non seismicity regions. For a while the potential advantages and applications of the wide beam system in the lateral load-resisting structure were ignored due to the lack of understanding of its seismic performance, as a proof, Design Code BS 8110 [3] strictly restricted the use of wide beam-column joints to resist earthquake loads. In the meantime, tests were carried into to the laboratories and also on sites to establish the moment resisting capacity of a wide beam-column joint, the capacity of energy dissipation in case of a cyclic horizontal loading of a joint between a flexural beam and a strong column. As a result to this scientifical research, structural engineers use reinforced concrete moment resisting frames (RCMRFs) with wide beams in regions with low seismicity, where to obtain satisfactory performance only a very few detailing changes are required in the design of joints and wide beams (such as all bottom beam bars are anchored to develop their full yield capacity at the beam supports, and column shear reinforcement to be provided to prevent shear failure in the case of a soft-storey mechanism forming) [4].

In regions such as the Mediterranean area (Spain, Italy and Portugal) with a moderate seismicity, RCMRFs with wide beam-column connections with one way joists have been very popular. The RCMRFs with wide beam-column connections that were constructed in Spain before the mid-1990s have an ultimate energy dissipation capacity (UEDC) that is approximately one half of the demand level established by the 2002 national seismic code NCSE-02, and due to this fact these buildings need to be retrofitted [5]. In the last decade structural engineers around the world learned from their mistakes and started to design buildings with wide beam-column connections, in medium and high seismically regions, according the most recent seismic standards, with enough UEDC and with a satisfactory seismic performance. Now they are using RCMRFs with two way joists, instead of one way joists, and sometimes in high seismically areas go for a dual system (frame or wall equivalent) or even for a ductile wall system (coupled or uncoupled).

In designing such a building for a region of medium or high seismicity, the use of wide beams is appropriate if the relevant design checks have been made relating to torsional cracking at the exterior connection, while for interior connections where bar debonding appears: P-Delta stability, concrete crushing, and serviceability deflections should be examined [4].

2.1 Structure geometry and site information

Location information:
City: Bucharest (Romania)
Ground type: C (Deposits of medium-dense stiff clay with a thickness of more than 10m)
Ground acceleration: \( a_g = 0.24g \)
Control period: \( T_c = 1.6 \) seconds

The supporting ground is stiff enough not to induce any amplifying seismic response of the superstructure. The superstructure is set on an infrastructure consisted of pocket foundations, continuous foundations and mat foundations, all linked with peripheral and interior ties. In these conditions in the design process of the superstructure no favorable or detrimental interaction with the ground was taken into account. The ties ensure that the whole building is subjected to a uniform seismic excitation.
The seismic performance of the structure is evaluated taking into account two solutions: in the first is used a RCMRF system (precast columns + precast wide beams), and in the second one is used a uncoupled wall system (monolithic structural walls + frames with precast columns which represent less than 35% of the shear resistance). The seismic design and the dimensioning of the structural elements: columns, joints, structural walls and wide beams are made taking into account the second order effect (P-Δ) from a modal analysis, and checked using a non-linear static (pushover) analysis. Regarding the geometry of the studied structure it must be said there is used a square bay 8.50m by 8.50m (Fig. 3), the building has a total of 76.50x51.00[m] in plane (Fig. 2a and 2b), with 3 stories high and with 4.00m the height of the story.
2.2 Used materials and structural elements particularities

Table 1: Materials and structural elements dimensions

<table>
<thead>
<tr>
<th>Type of element</th>
<th>RCMRFs</th>
<th>Uncoupled wall system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>materials (concrete, steel)</td>
<td>C30, S490 C</td>
<td>C30, S490 C</td>
</tr>
<tr>
<td>corner</td>
<td>80x80[cm]</td>
<td>60x60[cm]</td>
</tr>
<tr>
<td>inner and outer</td>
<td>80x1.30[cm]</td>
<td></td>
</tr>
<tr>
<td>Walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>materials (concrete, steel)</td>
<td>confined masonry with no structural interaction</td>
<td>C30, S490 C</td>
</tr>
<tr>
<td>thickness</td>
<td></td>
<td>25[cm]</td>
</tr>
<tr>
<td>Beams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>materials (concrete, steel)</td>
<td>C30, S490 C,S1660</td>
<td>C30, S490 C,S1660</td>
</tr>
<tr>
<td>in the X direction</td>
<td>120x41[cm]</td>
<td>120x41[cm]</td>
</tr>
<tr>
<td>in the y direction</td>
<td>60x41[cm]</td>
<td>60x41[cm]</td>
</tr>
<tr>
<td>Slabs</td>
<td>Partially precast solution: preslab (10cm thick)+topping(8cm)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Modal analysis output

<table>
<thead>
<tr>
<th>Structure solution</th>
<th>Vibration</th>
<th>Base shear force</th>
<th>Seismic coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mode 1</td>
<td>mode 2</td>
<td>mode 3</td>
</tr>
<tr>
<td>RCMRFs</td>
<td>0.85sec</td>
<td>0.83sec</td>
<td>0.78sec</td>
</tr>
<tr>
<td></td>
<td>X translation</td>
<td>Y translation</td>
<td>torsion</td>
</tr>
<tr>
<td></td>
<td>74%</td>
<td>74%</td>
<td>74%</td>
</tr>
<tr>
<td>Uncoupled wall system</td>
<td>0.34sec</td>
<td>0.32sec</td>
<td>0.19sec</td>
</tr>
</tbody>
</table>
Table 3: Eurocode 8-1:2004 parameters

<table>
<thead>
<tr>
<th>Structure solution</th>
<th>Importance class</th>
<th>Importance factor γI</th>
<th>Behaviour factor q</th>
<th>Ductility class</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCMRFs</td>
<td>III</td>
<td>1.2</td>
<td>4.68</td>
<td>High</td>
</tr>
<tr>
<td>Uncoupled wall system</td>
<td></td>
<td></td>
<td>3.24</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Wide beam-column joint

![Wide beam-column joint diagram]

Figure 5. Wide beam-column joint

1. precast reinforced concrete column
2. reinforced concrete corbel (30cm high)
3. precast prestressed wide beam (120x25 cm)
4. precast prestressed wide beam (60x25 cm)
5. topping reinforcing on the Y direction
6. topping reinforcing on the X direction
7. bolt (Φ=25mm)
Between the pinned and the rigid connections, there are intermediate behaviours, resulting in semi-rigid connections. The use of moment-resisting connection usually results in rigid connections. When using a precast RCMRF structures, the main objective is to obtain a final structure that behaves as similarly as possible to the cast-in-place concrete structures, whose structural analysis processes are well known.

To evaluate the influence of the strength and stiffness of the connection on the behaviour of the structure, the results of analytical calculus, of a typical multi-storey building with wide beam-column joints, were calibrated with the results obtained by the other researchers on precast concrete element joints consisting of dowels and top reinforcement which were part of the slab topping. The bending rotation curve for the two types of joints have been developed upon the mathematical relation described by Prof. M.K. El Debs, PhD student A. M. Miotto and Associate Professor A. L. H. C. El Debs in the paper „Analysis of a semi-rigid connection for precast concrete” [6], and based on the laboratory tests referred in the paper cited before. The main results concerning semi-rigid connections are the bending moment-rotation curves.

After determining the bending moment-rotation curve for the joint, using ETABS 9.6 [7] and SAP2000 14.1.0 [8], a static analysis was performed. The displacements of the structure, in a linear analysis, were obtained using reduced values of flexural stiffness in order to consider the non-linear behaviour of the materials. The values are $(EI)_{\text{red}}=0.5EI$ for beams, columns and $(EI)_{\text{red}}=0.8EI$ for walls. In the absence of data to establish the stiffness reduction for semi-rigid connections, the mean value of 0.60 was considered [6]. In order to analyse the stiffness effect of the connection, the following alternatives were considered: pinned connection, semi-rigid connection (Fig. 6a and 6b) and rigid connection. In the case of the dowel well fixed into the precast element (Fig. 6a), using cast-in-place grout, the joint influence over the structure behaviour was similar to a rigid connection.

![Figure 6a. Theoretical bending-rotation curve](image)

While in the case of dowel left as a dry connection (Fig. 6b), the negative moments and associated rotation developed on the end of the beam were similar with the rigid connection, the positive moments didn’t appear due to the large rotation of the connection without bending resistance. Even so, considering that the global effect in the seismic analysis of the structure, using connection presented in Fig. 6b, was similar with the one using rigid connections, plus the reduced possibilities...
of a brittle behaviour at a positive bending moment, and the reduced labour makes this joint more appropriate to use in areas with medium to high seismicity level in the case of uncoupled wall system. In the case of RCMRFs, using connection with bending moment-rotation relation from Fig. 6a is out of the question because of the lack of the bending resistance. But, if we use concrete columns with large cross sections, the using connection type exposed in Fig. 6b can be practical but only with further investigations.

![Figure 6b. Theoretical bending-rotation curve for connection with monolithic grout for connection without monolithic grout](image)

The bold can be fixed monolithic with high resistance grout (Fig. 6a) or the connection can be left dry (Fig. 6b)– which will develop significant rotation before a positive bending moment appears on the end the beam due to the lack of instantaneous contact between the steel part (bolt) and the precast concrete element.

### 2.4 Structural elements design

**Table 4: Material amounts for the vertical elements**

<table>
<thead>
<tr>
<th>Type of element</th>
<th>RCMRFs</th>
<th>Uncoupled wall system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cross section [cm]</td>
<td>Longitudinal reinforcing (%)</td>
</tr>
<tr>
<td>Corner columns</td>
<td>80x80</td>
<td>1</td>
</tr>
<tr>
<td>Inner and outer columns</td>
<td>80x130</td>
<td>1.4</td>
</tr>
<tr>
<td>Walls</td>
<td>15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The two type of structures were designed considering the wide beam-column connection presented in Fig. 6b, due to the enough UEDC that provides. Seismic design of the structure was done considering the $P-\Delta$ effects on the column buckling. The necessary cross section for the columns in
the solution on RCMFR together with the big amount of necessary reinforce steel turn the solution into a expensive one and therefore the columns become uncompetitive comparing to the ones from the second solution, Table 4. The structural elements were designed according to the methods presented in EC2 [2] and EC8 [9], and checked for their rotation capacity after a pushover analysis was performed.

In the design of the structural systems were followed the next steps, in an iterative manner, in order to obtain a reasonable seismic performance of the building:

1. Modeling and analysis;
2. Connection design;
3. Nonlinear design methods (pushover);
4. Deformation compatibility.

Figure 7. Flowchart of the design process.

3. Conclusions

Using a wall coupled system with precast wide beams, in regions with high seismicity, after running the analyses and the seismic design, has been proved that the before mentioned system is appropriate and can assure a good seismic performance of the building. Reinforced concrete walls positioned favorable (not to induce torsion sensibility) have the following advantages: reduces the P-Δ effect on columns (a shorter buckling length), reduces the story drifts, and gives us the opportunity to obtain a more slender and economical building from the consumed quantity of concrete and steel point of view, also maintaining a satisfactory seismic performance. After this study we can say that using wide beams-column joints with enough UEDC (as the connection characterized by moment-rotation curve presented in Fig. 6b) gives a better seismic performance than the same building with a wall coupled system and pinned wide beam-column joints and protects the structure against brittle fracture of the connection between precast elements.

The storey drifts obtained in the analyses on RCMRFs with wide beam-column connection, with competitive columns cross sections, would produce severe damage to both structural and non-structural elements (performance level: Operational and Immediate Occupancy), while in high levels of performance (Life Safety and Collapse) the drifts obtained can lead to global instability of the structure owing to P-δ effects. If we use more slender columns the column buckling problem intervenes together with large story drifts, and the risk of structural instability becomes inevitable. The most adequate calculation method for this type of structure should be based on deformation and less on strength.

Using a non-grouted dowel connection reduces the possibilities of a brittle failure at a positive
bending moment – issue often seen at precast structures, also the necessary force labour is reduced. The concrete frame structures using wide beams behave rather as a waffle flat-plate system than a frame system.

4. References


