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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 poor 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 prezintã câteva aspecte referitoare la modul de conformare şi de comportare al nodurilor *grindã latã-stâlp din beton armat, sub aspectul rezistenţei şi în special al deformabilităţii. Este studiatã performanţa seismicã a unei structuri în soluţie de cadre pure din stâlpi şi grinzi late din beton armat prefabricat, respectiv în soluţie de structură duală cu diafragme monolite plus cadre din stâlpi şi grinzi late din beton armat prefabricat. Acesta reprezintã un domeniu puţin cercetat, nefiind tratat în normele de proiectare româneşti ori în cele europene, în condiţiile în care flexibilitatea de compartimentare şi de utilizare al spaţiului acestui sistem este agreată de către beneficiarii de spaţii comerciale însă şi de către arhitecţi, putând realiza trame de 8x8..10x10[m] şi având în acelaşi timp o grosime de planşeu limitată la doar L/20 din deschidere. Analiza şi dimensionarea stâlpilor, îmbinărilor, diafragmelor şi a grinzilor late se face ţinând cont şi de efectele de ordinul II (P-Δ) rezultate în urma unei analize modale, şi verificate folosindu-ne de un calcul neliniar de tip pushover. Este studiată problema determinării lungimii de flambaj a stâlpilor precum şi aportul grinzilor late în preluarea încărcăriilor seismice prin efectul de cadru. Structura analizată este proiectată pentru un amplasament caracterizat de o acceleraţie de proiectare a terenului a_g=0.24g, şi de o perioadă de colţ 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 pãtrate de 8,50x8,50[m] şi cu un regim de înãlţime de P+2E, înălţimea 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, $L_y/4$ 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 L/15 than the beam is an ordinary one, for L/8 is a high depth beam, while a depth smaller than 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 L/15..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 strickle 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.

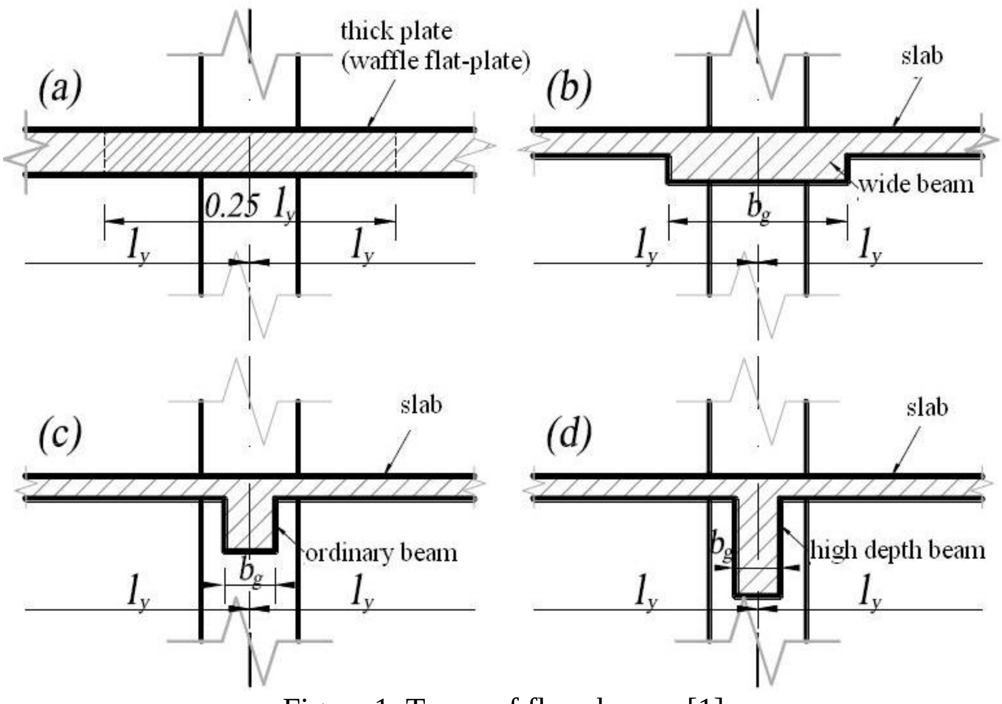


Figure 1. Types of floor beams [1]

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

<u>Location information :</u>
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.

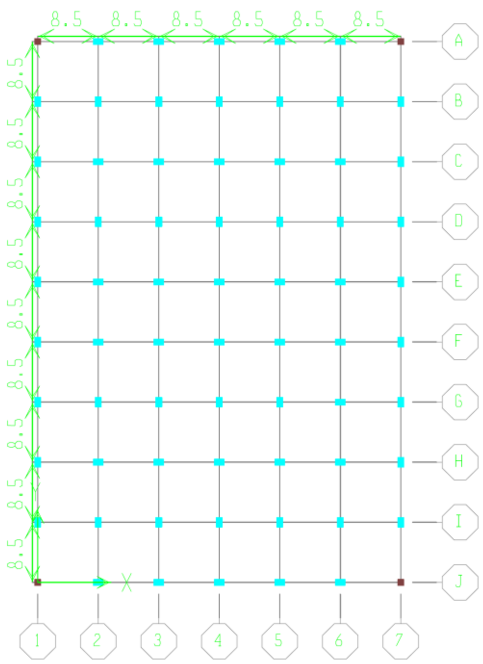


Figure 2a. Positioning plan for columns
RCMRF solution

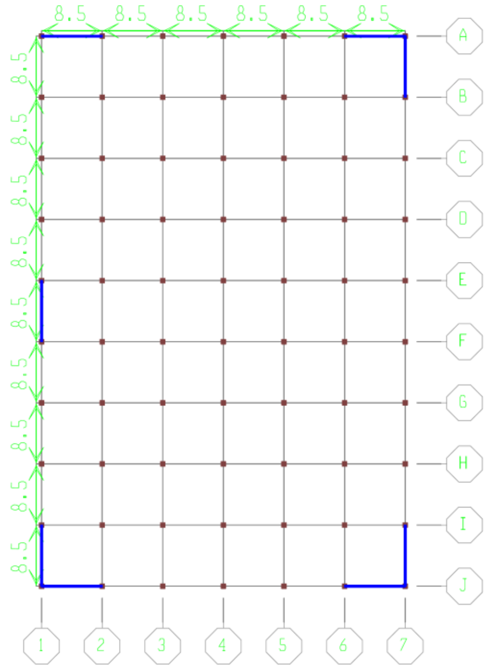


Figure 2b. Positioning plan for columns and walls
Uncoupled Wall system

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.

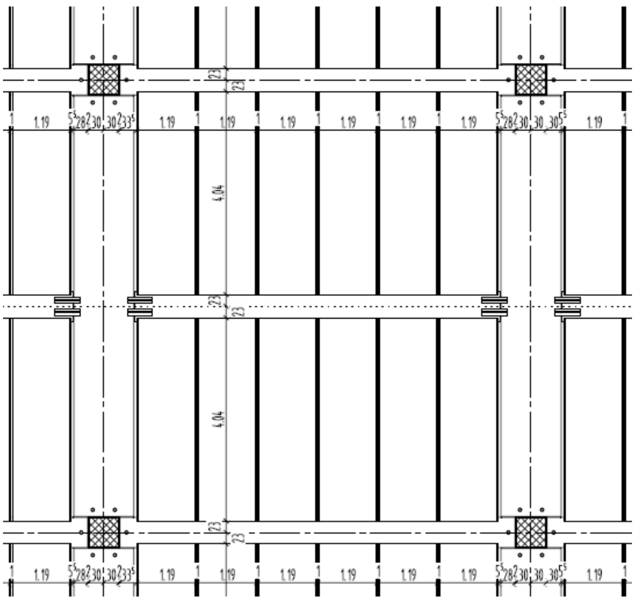


Figure 3. Positioning plan for wide beams

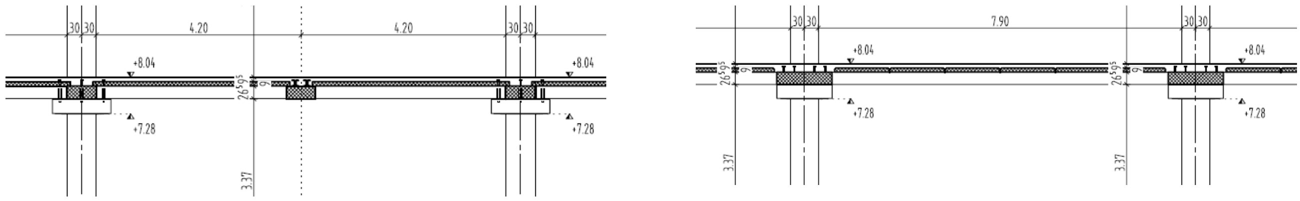


Figure 4. Sections over slab

2.2 Used materials and structural elements particularities

Table 1**:** Materials and structural elements dimensions

Type of element		RCMRFs	Uncoupled wall system
Columns	materials (concrete, steel)	C30, S490 C	C30, S490 C
	corner	80x80[cm]	60x60[cm]
	inner and outer	80x1.30[cm]	
Walls	materials (concrete, steel)	confined masonry with no structural interaction	C30, S490 C
	thickness		25[cm]
Beams	materials (concrete, steel)	C30, S490 C,S1660	C30, S490 C,S1660
	in the X direction	120x41[cm] 25(precast)+16(topping)	120x41[cm] 25(precast)+16(topping)
	in the y direction	60x41[cm] 25(precast)+16(topping)	60x41[cm] 25(precast)+16(topping)
Slabs	Partialy precast solution: preslab (10cm thick)+topping(8cm)		

Table 2**:** Modal analysis output

Structure solution	Vibration				Base shear force		Seismic coefficient	
		mode 1	mode 2	mode 3	X direction	Y direction	X direction	Y direction
RCMRFs	fundamental period of vibration	0.85sec	0.83sec	0.78sec	19445 [kN]	19445 [kN]	18%	18%
	type of vibration	X translation	Y translation	torsion				
	model participation mass ratio	74%	74%	74%				
Uncoupled wall system	fundamental period of vibration	0.34sec	0.32sec	0.19sec	Walls: 27870 [kN] Frames: 2310 [kN]	Walls: 28190 [kN] Frames: 2170 [kN]	31%	30%
	type of vibration	X translation	Y translation	torsion				
	model participation mass ratio	86%	86%	15%				

Table 3**:** Eurocode 8-1:2004 parameters

Structure solution	Importance class	Importance factor γI	Behaviour factor q	Ductility class
RCMRFs	III	1.2	4.68	High
Uncoupled wall system			3.24	

2.3 Wide beam-column joint

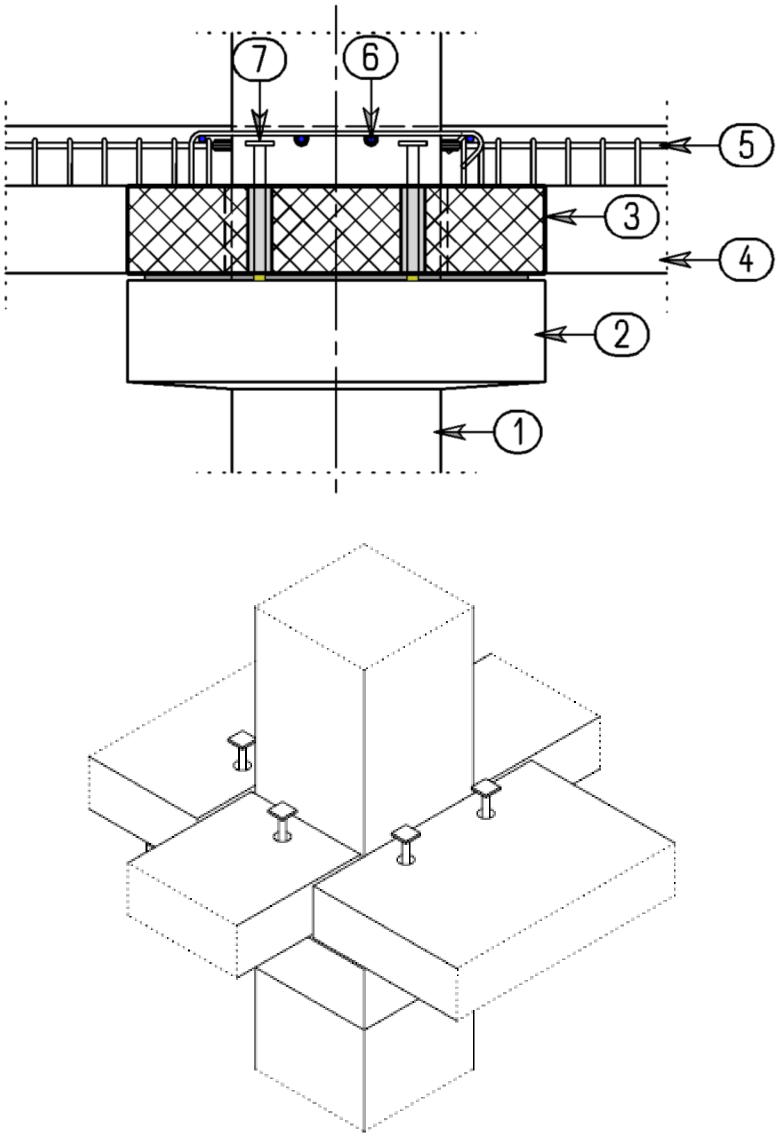


Figure 5. Wide beam-column joint

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 obtain by the other researches 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 descriped 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 reffered 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 analyse was performe. The displacements of the structure, in a linear analyse, were obtain using reduced values of flexural stiffness in order to consider the non-linear behaviour of the materials. The values are $(EI)_{red}$=0.5EI for beams, columns and $(EI)_{red}$=0.8EI for walls. In the absence of data to establish the stiffness reduction for semirigid 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.

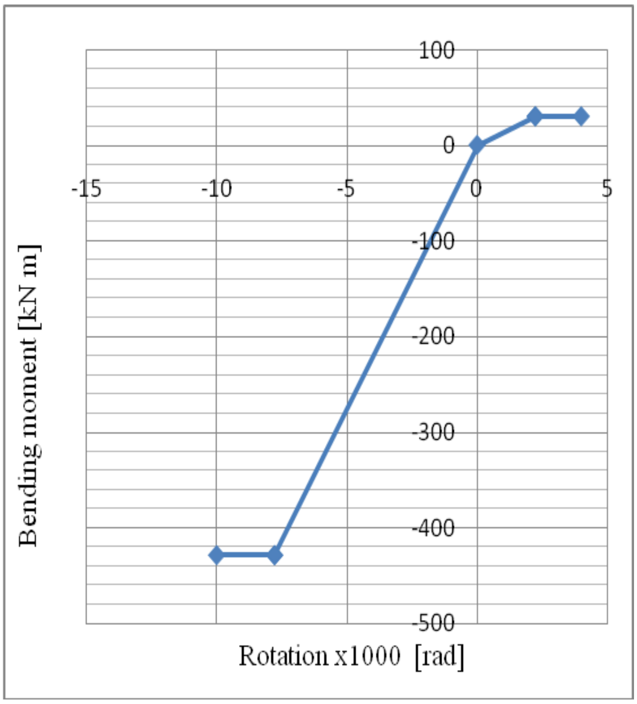


Figure 6a. Theoretical bending-rotation curve

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 appeared due to the large rotation of the connection without bending resistance. Even so, considering that the global effect in the seismic analyse 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 resistence. 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.

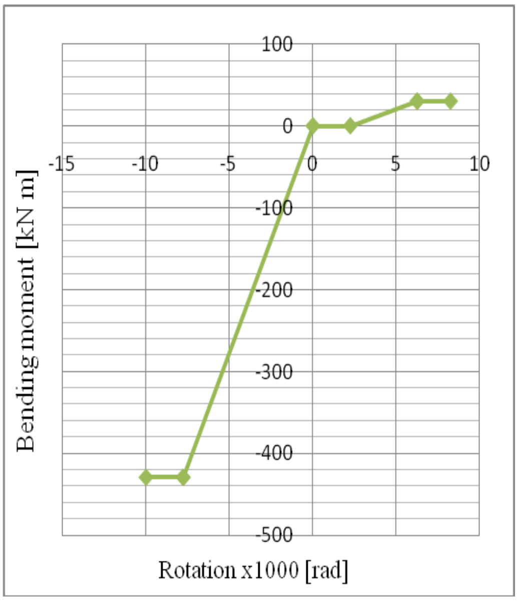


Figure 6b. Theoretical bending-rotation curbe for connection with monolithic grout for connection without monolithic grout

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.

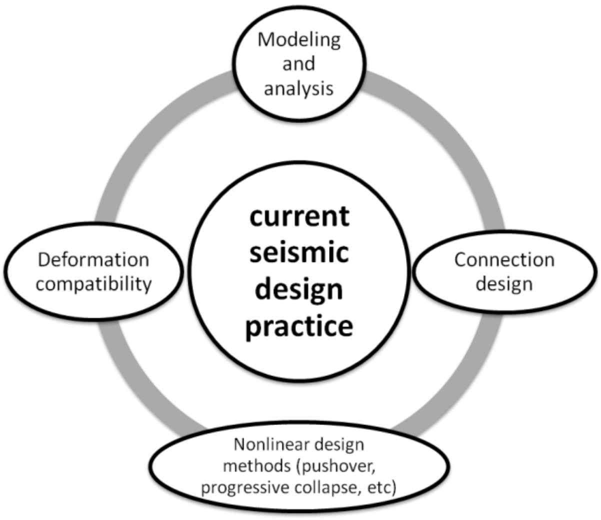
2.4 Structural elements design

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

	RCMRFs				Uncoupled wall system			
Type of element	Cross section [cm]	Longitudinal reinforcing (%)	Total amount of materials concrete and steel		Cross section [cm]	Longitudinal reinforcing (%)	Total amount of materials concrete and steel	
Corner columns	80x80	1	874mc	245to	60x60	1	302mc	70to
Inner and outer columns	80x130	1.4						
Walls	15	0.15	115mc	15to	25	0.3	195mc	49to
		Total:	989mc	260to		Total:	497mc	119to

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-Δ effects on the column buckling. The neccesary 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 o 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 flate-plate system than a frame system.

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