APPLICABLE SOLUTIONS REGARDING DUCTILE SEISMIC RESPONSE DEVELOPMENT IN THE PURE MOMENT RESISTING (MR) REINFORCED CONCRETE (RC) FRAME SYSTEM 

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Received: March 14, 2022
Accepted for publication: April 20, 2023

Abstract. Moment Resisting (MR) Reinforced Concrete (RC) frame system presented in the current seismic design standards and required to on-site seismic action develops the soft storey mechanisms. In practice, the idealized and theorized ductile seismic response specified in the seismic design standards for this structural system type does not occur. In these conditions, the current research study presents a logical scheme regarding the development method of the MR RC frame system. The main element of the logic scheme is the seismic response of the RC frame systems designed only for gravity loads. In correspondence with the structural deficiency sources, several aspects regarding the seismic design method were established, followed by the improvement of the ductile design concept. Also, a couple of solutions regarding plastic hinges control and plastic hinges concentration in the marginal zones of the RC beams are presented. These solutions are directed to existing MR RC frame structures and new MR RC frame systems designed in accordance with the current seismic standards.

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**Keywords:** Seismic response, MR RC frame system, RC frame structures designed only for gravity loads, ductile seismic response improvement, plastic hinges.

1. Introduction

The real seismic response of the Moment Resisting (MR) Reinforced Concrete (RC) frame structures required to on-site seismic action differs from the idealized and theorized seismic response specified in the current seismic design standards (P100-1, 2013), (EC8, 2004), (Sococol et al., 2021a).

This structural system type records soft storey mechanisms with vertical superstructure segmentation in linearly elastic rigid boxes and fragile segments with rapid rupture in marginal areas of the RC columns (Sococol et al., 2021a).

In these conditions, the requirement to find the discrepancies between the real seismic response and the theorized seismic response of the MR RC frame structures was updated.

Fig. 1 – Logic scheme regarding idealized development (creation) of the MR RC frame system.
Fig. 1 displays the logic diagram regarding the practical approach of establishing the seismic design conditions for the MR RC frame structures. This logic scheme starts with the seismic response study of the RC frame structures designed only for gravity loads (without knowing a specific seismic design concept), recognizing the initial structural deficiencies. The conclusions and the recorded observations lead to the global and local (on the structural element) seismic design criteria specification of the RC frame structures. Finally, the MR RC frame system is outlined, providing the possibility of developing the current ductile seismic design concept.

In the same logic diagram (represented in Fig. 1) several solutions regarding the plastic hinges control and the plastic hinges concentrating in the marginal zones of the RC beams for the existing MR RC frame structures and the new MR RC frame structures designed in accordance with the current seismic standards criteria are also specified.

2. Seismic response (resistance) of RC frame systems designed only for gravity loads

The seismic response of structures designed only for gravity loads represent the basic source of establishing and developing a seismic design concept.

This idea comes from the initiative to recognize the seismic response of the structure designed for minimal (non-seismic) design conditions.

Based on the obtained seismic response, the seismic deficiencies of the structure are established in order to develop practical solutions for their removal.

The sum of all anti-seismic solutions for removing structural deficiencies conducts to the development of the MR RC frame system and the specific seismic design concept.

In these conditions, experimental studies regarding seismic response of the RC frame structures designed only for gravity loads were performed as part of an extensive research program at New York University (Buffalo). These experimental researches (Technical Report NCEER-91-0018, 1991), (Technical Report NCEER-92-0027, 1992), (Technical Report NCEER-92-0028, 1992), (Technical Report NCEER-92-0029, 1992) had other objectives than establishing the seismic design deficiencies of the current ductile concept. Some of these objectives are:

- investigate the performance and main deficiencies of typical LRC (Lightly Reinforced Concrete) frame buildings during earthquakes through shaking table testing of a 1/3; 1/8 scale model under minor, moderate and severe earthquakes;
- identify the potential collapse mechanisms for typical LRC frame buildings;
• determine the behavior and material properties of individual members and subassemblies of the structure.
• determine the contribution of the components in the overall response of the structure near collapse etc.

Fig. 2 – Graphical representation (Technical Report NCEER-91-0018, 1991): (a) GF+2F RC frame model designed only for gravity loads and reduced to 1/8 scale; (b) Fragile rupture mechanism (soft storey mechanism) recorded by the GF+2F RC frame model.

Thus, the seismic response of the GF+2F RC frame models reduced to 1/8 scale (see Fig. 2 (a)) and to 1/3 scale (see Fig. 3 (a), (b)) was studied.
After shaking the table tests, soft storey mechanisms (see Fig. 2 (b)) with plastic hinges formation in marginal zones of the RC columns were registered (see Fig. 3 (c)). The formation of the RC „beams-slabs-frame nodes” rigid common block that had a decisive role in the RC models collapse was also observed. These experimental results were also confirmed by analytical studies (see Fig. 3 (d)).

3. Theoretical seismic improvements for RC frame system

The RC frame models designed only for gravity loads and tested on seismic platforms emphasize the requirement for the seismic design of the RC columns. These lateral elements (RC columns) dissipate seismic energy through plastic deformations in the marginal zones. Practically, increasing the lateral strength and the lateral stiffness of the RC columns, considering the possible nonlinear inelastic deformations, becomes a necessity.

It was also observed that the RC beams „borrow” the bending stiffness from the RC slabs. In these conditions, the RC beams do not require a special seismic design. The reinforced concrete (RC) beam-column joints form a common body with the RC beams and the RC slabs and intensely crack.

All these aspects regarding the seismic response of the RC frame models designed only for gravity loads contradict the ductile seismic design concept of the RC frame structures and coincide with the seismic response of the MR RC frame structures required on-site to severe seismic action.

In these conditions, several development elements of the MR RC frame system that are not specified in the current seismic design standards are suggested:
Ion Sococol and Petru Mihai

- seismic design of MR RC frame structures for higher horizontal actions (through the behavior factor $q$), avoiding the DCH ductility class and limiting to the DCM ductility class (Sococol et al., 2021 b);
- seismic design of RC beams and RC columns with different $q$ factors (Sococol et al., 2021 b);
- limiting the seismic design of this structural system type only in certain seismic areas through $a_g$ values (of the seismic zoning map) under conditions of current seismic design standards;
- considering the RC columns as lateral elements with a high risk of plasticization in the design stage;
- increasing the stirrups density for RC columns and considering the entire height of the RC columns as a potentially plastic area (Sococol et al., 2019);
- use of ductile RC beams (with a cross-sectional height of at least $1/16L$ and a width of at least 200 mm) (Prevederi de completare și modificare a reglementării tehnice P100-1/ 2013, 2019), (Sococol et al., 2020).

4. Specific solutions regarding ductile seismic response improvement of the MR RC frame structures developed in current seismic design conditions

In the current seismic design situation of the MR RC frame structures according to the ductile concept, it is necessary to practice innovative methods of directing and locating (concentrating) plastic hinges in the marginal areas of RC beams.

These innovative methods come as practical solutions to ensure the real production of the ductile seismic energy dissipation mechanism.

In these conditions, Fig. 4 displays several patented inventions (Fig. 4 (a)-(f)) and inventions to be patented (Fig. 4 (g)-(j)). Details regarding the description of the inventions may be studied in each patent.
Fig. 4 – Practical methods of directing and controlling plastic hinges in the marginal zones of the RC beams: (a), (b) Reinforced concrete frame connecting structure (Patent CN 108729547 A of 2018.11.02); (c), (d) Reinforced concrete frame and construction method thereof (Patent CN 108867854 A of 2018.11.23); (e) Reinforced concrete frame beam (Patent JP 2003105921 A of 2003.04.09); (f) Reinforced concrete frame structure (Patent CN 207646865 U of 2018.07.24); (g) RC beams and RC slabs with reduced cross-section through vertical drilling method in potential plastic areas to improve the seismic energy dissipation mechanism (Patent application A/00045 of 12.02.2021 – Romania); (h) Numerical analyses results obtained through the ATENA 3D software (ATENA software, 2012); (i), (j) Reinforced concrete beams with fragile marginal subassembly for seismic energy dissipation (Patent application A/00092 of 05.03.2021 - Romania). (Note: Details regarding technical aspects, innovative elements and assemblies numbering in the figures can be studied in each patent corresponding to each figure).

5. Conclusions

The seismic response of the RC frame systems designed only for gravity loads demonstrates the seismic design requirement of the RC columns. Moreover, it has been proven that the RC beams „borrow” the bending stiffness from the RC slabs and form a common body with the RC slab and the RC beam-column joints. Thus, there is no significant requirement for the special seismic design of the RC beams.

Under these conditions, it was observed the inadequate direction of the seismic design (in accordance with the ductile design concept) for current MR RC frame structures which places special emphasis on the RC beams design (being considered the main ductile elements).

Several innovative and practical methods of directing and concentrating plastic hinges in the marginal areas of RC beams for MR RC frame structures designed in accordance with current seismic standards have been specified.
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SOLUȚII PRACTICE PRIVIND DEZVOLTAREA RĂSPUNSULUI SEISMIC DUCTIL ÎN SISTEMUL SEISMO-REZISTENT PUR TIP CADRU DE BETON ARMAT

(Rezumat)

Sistemul structural seismo-rezistent tip cadru de beton armat prezentat în normativele actuale de proiectare seismică dezvoltă la o acțiune seismică în amplasament mecanisme de etaj/ parter slab. Practic, răspunsul seismic ductil idealizat și teoretizat în standardele seismice de proiectare al acestui tip de sistem structural nu are loc (nu se produce). În aceste condiții, se prezintă în prezentul studiu de cercetare o schemă logică privind modalitatea de dezvoltare a sistemului seismo-rezistent tip cadru de beton armat. Cheia principală a schemei logice o reprezintă răspunsul seismic al structurilor tip cadru de beton armat proiectate doar la încărcări gravitaționale. Găsind sursele deficiențelor structurale, se poate stabili corect modalitatea de proiectare, urmată de o îmbunătățire a conceptului ductil de proiectare seismică. De asemenea, se prezintă câteva soluții privind dirijarea și concentrarea articulațiilor plastice în zonele marginale ale grinzilor de beton armat pentru structurile seismo-rezistente tip cadru existente și a structurilor tip cadru care se proiectează în condițiile standardelor seismice actuale.