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CONSTRUCŢII. ARHITECTURĂ

NEGATIVE INFLUENCES (EFFECTS) OF MASONRY INFILLED RC FRAMES TO SEISMIC RESPONSE OF RC FRAME SYSTEMS AND PRACTICAL METHODS (SOLUTIONS) FOR THESE PROBLEMS (STATE OF THE ART)

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Abstract. A series of earthquakes across the globe (1990 Luzon earthquake, 1992 Cairo earthquake, 1999 Izmit earthquake, 2001 Gujarat earthquake, 2008 Sichuan earthquake, 2009 L’Aquila earthquake etc.) have demonstrated real modalities of imposing a fragile seismic response to reinforced concrete frame systems with infilled masonry walls. The global structural effects and negative local effects of masonry infill walls proven to be crucial in the last phases of structure collapse. It is desired through this theoretical study to classify the consequences that cause a series of phenomena in this structural system and some practical methods that can help solve them.

Keywords: short columns; soft story; general torsion; transverse reinforcement of columns; MRR concept; “Pure” frame structure concept; flexible (free) partition concept.

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1. Introduction

The ductile concept of seismic response of reinforced concrete frames structures according to the present norms (P100-1, 2013) can be achieved by a global response of the structural system in the form "weak beams – strong columns" (plastic hinges at the end zones of beams and plastic deformations for critical zones of ground floor columns). The efficiency of the ductile seismic response leads to the local degradation of these structural elements. Thus, the primary issue on the masonry infilled reinforced concrete frames is related to the negative influence brought seismic energy dissipation mode by structural system, imposing a different behavior of the structure to horizontal actions (fragile failure of the reinforced concrete columns from the shear force (Fig. 1 *b*), partial or total structural progressive collapse (Fig. 1 *a*) etc.).

Besides this very important issue, in seismic areas (with severe earthquakes), frame structure (made with these infill masonry walls) becomes a structural system that needs a special rehabilitation for the structural elements and for non-structural elements (infill masonry walls) participating in seismic energy dissipation.

a

b *c*

Fig. 1 – *a* – Gujarat Earthquake (India, 2001); *b*, *c* – L'Aquila Earthquake (Italy, 2009).

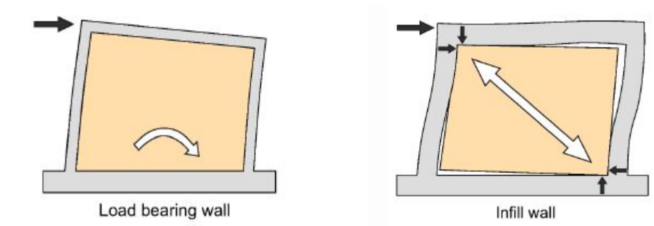
To understand the difference between confined masonry wall and masonry infill wall, can be specified the load transfer mechanism under lateral force action (Fig. 2) (Singhal, 2016):

Confined masonry wall (Fig. 2 a):

- Masonry walls mostly resist the gravity load;
- Under lateral seismic loads, walls behave similar to RC Shear Walls;
- Straightforward transmission of forces;

Masonry infilled RC moment-resisting frames (Fig. 2 b):

- Small fraction of gravity loads are transferred to walls;
- Infill wall panels act as compressive diagonal struts due to lack of good bonding;
- Complicated transmission of forces;



a *b*

Fig. 2 − Load transfer mechanism under lateral force action: *a* – Confined masonry wall; *b* – Masonry infill wall (Singhal, 2016).

2. Seismic Energy Dissipation Modes

From a theoretical point of view is distinguished five failure mechanisms for masonry infilled reinforced concrete frames (Fig. 3) (Meharbi & Shing, 2003). Thus, it can be seen possibilities of seismic energy dissipation through inelastic deformation (plastic hinges) in the columns. Under these conditions, the formation of plastic hinges can occur in any section of the column and the critical area should be considered for the entire height.

From the practical standpoint (experimental observations) and numerical analysis (Koutromanos *et al.*, 2011) are found some of the five hypotheses formation of plastic hinges in columns. The enormous unfavorable influence of the masonry walls on the seismic response of the frame type structure it is mainly observed at the level of the ground floor for the 3-storey structure of (Fig. 4). The shear failure in the half height of the intermediate column is contrary of transverse reinforcement (not being considered the critical zone in the design stage). Thus, energy dissipation occurs through masonry walls and excessive fragile deformations in reinforced concrete columns.

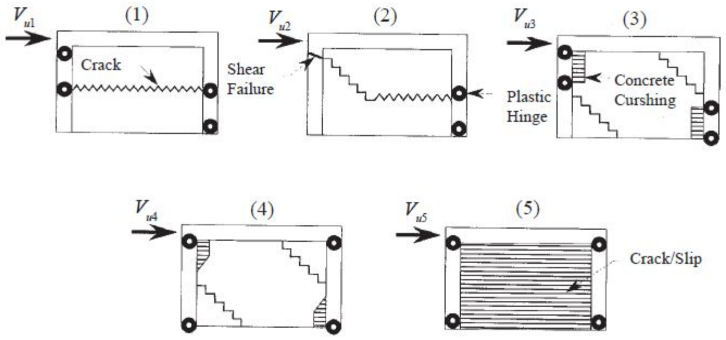


Fig. 3 − Theoretical failure mechanisms (Meharbi & Shing, 2003).

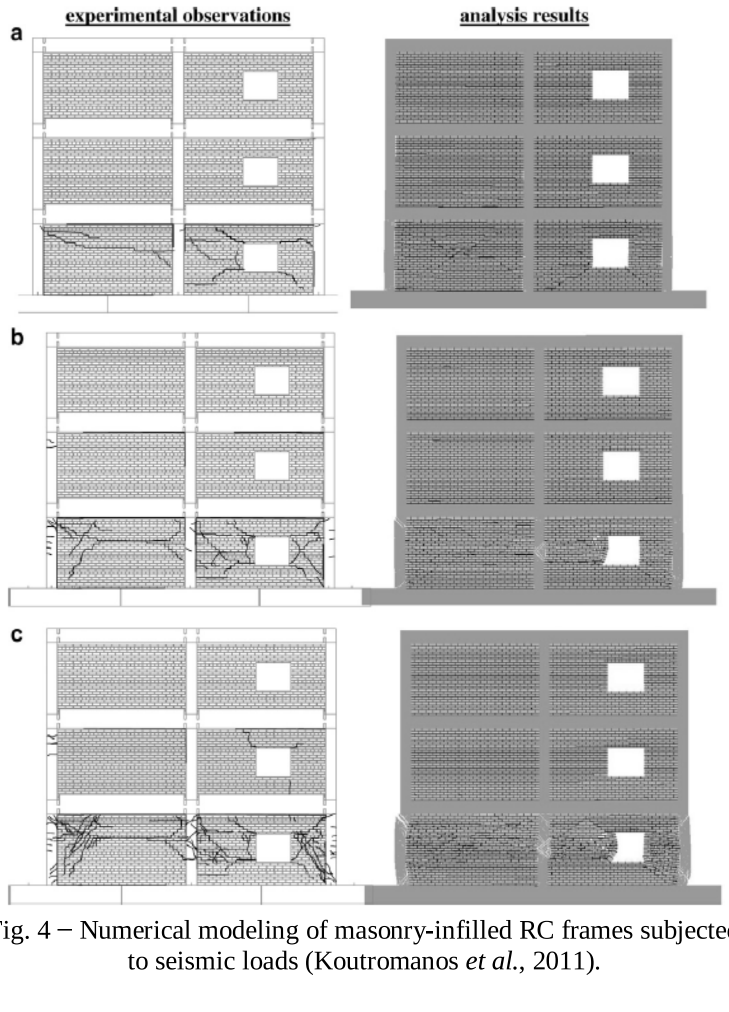


Fig. 4 − Numerical modeling of masonry-infilled RC frames subjected to seismic loads (Koutromanos *et al.*, 2011).

A similar seismic response can be observed in (Technical Report MCEER-99-0001, 1999) and in other special experimental studies (Pujol & Fick, 2010; Jiang *et al.*, 2015; Asteris *et al.*, 2011; Penava *et al.*, 2018; Dautaj *et al.*, 2018; Ning *et al.*, 2019). In none of these studies has not been registered a favorable seismic energy dissipation for masonry infilled RC moment-resisting frame structures.

3. Negative Effects Due to the Interaction of the Reinforced Concrete Frame System with Non-Structural Wall Systems (Masonry Infill Walls) in Seismic Areas

In the current design for seismic areas, use masonry infill walls leads to additional design work. Thus, the design engineer is required to use a model with diagonal compression area for checking structure in order to avoid the risk of general torsion. However, it should be pointed out that the discussion of compressed diagonal must be limited to the appearance of important cracks in some masonry infilled RC frames. After their failure, we have a structure with affected structural elements (nodes and columns). Besides this, the vertical rigidity presents discontinuities with increased local degradation at node level and the end zones of columns for regions of collapsed masonry panels. In these conditions, the general torsion effects are intensified and there are possibilities of forming the weak story and progressive collapse of structure. All of these possible effects must be seen as consequences that can occur in the cycle, depending on each other.

Thus, the following negative effects can be listed:

a) increasing the lateral stiffness of the structural system, which in the case of flexible structures produces a decrease of the fundamental vibration period in the conditions when the structure was designed for smaller seismic forces (corresponding to the pure structure) (P100-1, 2013);

b) the appearance of the weak first story or weak story (with short columns) (Fig. 5 *a*) due to the vertical irregularity (the succession of rigid and flexible levels (Fig. 5 *b*) or due to the possibility of detachment a masonry infill wall at a certain level;

c) as a consequence of the cracking of a masonry wall at a certain level, the situation “Weak-column/Strong-beam” (Fig. 5 *c*) appears quickly, and the case of irregular mass (when the mass of a story substantially exceeds the mass of the adjacent levels) (Fig. 6 *a*);

d) production of general torsion effect (change of the rigidity center position (Fig. 6 *b*) due to the horizontal irregularity (the cause of the total or partial collapse of a masonry infill wall);

e) the irregular positioning of the openings in the infill masonry wall produces local shear cracking effects and/ or serious degradation of the beams (Fig. 7) (Penava *et al*., 2018);

f) the collapse of the masonry infilled RC moment-resisting frame panel serves for progressive collapse of reinforced concrete framed building (Fig. 8) (Eren *et al*., 2019);

g) local degradation effect of the frame node;

h) local deformation effect of the columns (creation of the short columns) by the presence of the parapets or partial rigid walls (masonry infill walls etc.) (Fig. 5 *a*), (Fig. 7).

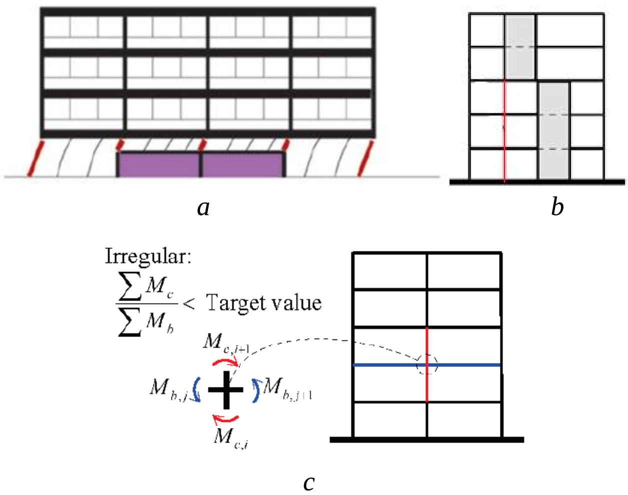


Fig. 5 – *a* – Creation of inadvertent short columns (FEMA 454, 2006); *b* – In-Plane Discontinuity (FEMA P-2012, 2018); *c* – Weak-column/Strong-beam (FEMA P-2012, 2018).

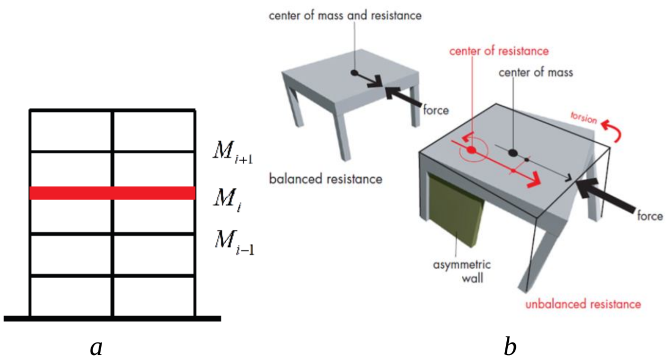


Fig. 6 – *a* – Irregular mass (FEMA P-2012, 2018); *b* – Torsional forces (FEMA 454, 2006).

Fig. 7 – Damage to structural column ("captive column") due to restraint caused by partial height masonry wall in the 2001 Peru Earthquake.

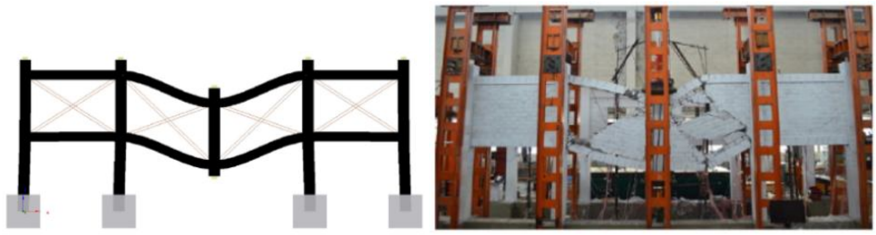


Fig. 8 – Progressive collapse of reinforced concrete framed buildings (Eren *et al.*, 2019).

4. Practical Methods for Improving the Seismic Response for Masonry Infilled RC Moment-Resisting Frame Structures

The multitude of problems presented in the previous chapters can be partially (practically) solved by the following these concepts (methods):

- MRR (**M**ore **R**esistance and **R**igidity) concept;
- "Pure" frame structure concept;
- Flexible (free) partition concept;
- Concept of the masonry infill structural fuse (Aliaari & Memari, 2012).

MRR (More Resistance and Rigidity) concept

This concept is based on increasing the strength and stiffness of the structure by correspondingly increasing the strength and stiffness of each level (especially for soft levels) without implications in the inelastic behavior. This approach (the calculation of each story) is equivalent to the design method of structures at horizontal action, applied in the Japanese norms. Thus, the RC frame structures with masonry infill walls can use some of the solutions proposed by (FEMA 454, 2006) of (Fig. 9).

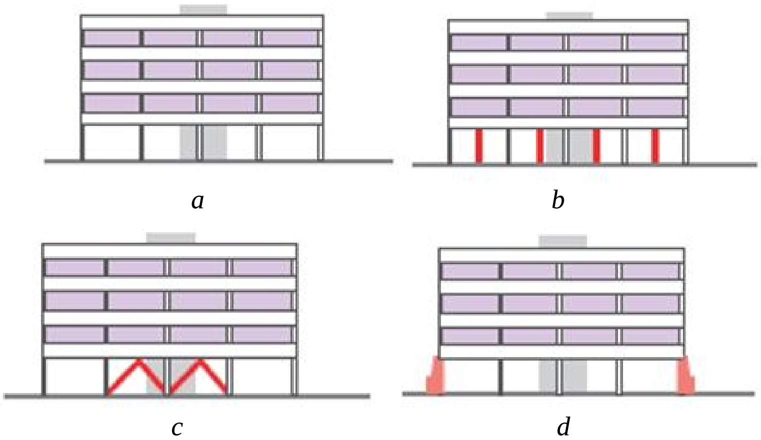


Fig. 9 – Some conceptual solutions to the soft first story (FEMA 454, 2006): (a) Soft story; (b) Add columns; (c) Add bracing; (d) Add external buttresses.

"Pure frame structure" concept

This concept is based on the masonry infill walls isolation, regardless of their nature (parapet, full wall or wall with openings), regardless of the lateral structural elements. Thus, it can be used reinforced concrete frames surrounding masonry (Figs. 10 and 11) or steel frames (Fig. 12) for adequate isolation of the masonry walls. The space between the seismic resistance frame and the nonstructural elements isolation frame must be larger than the relative displacement (d_r^{SLU}) for SLU.

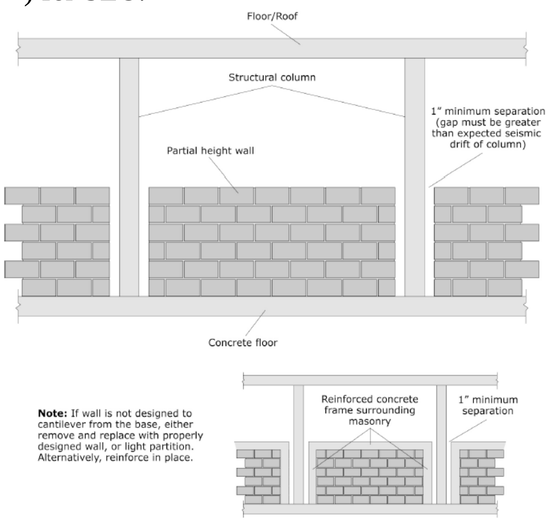


Fig. 10 – Partial height heavy partition (FEMA E-74, 2012).

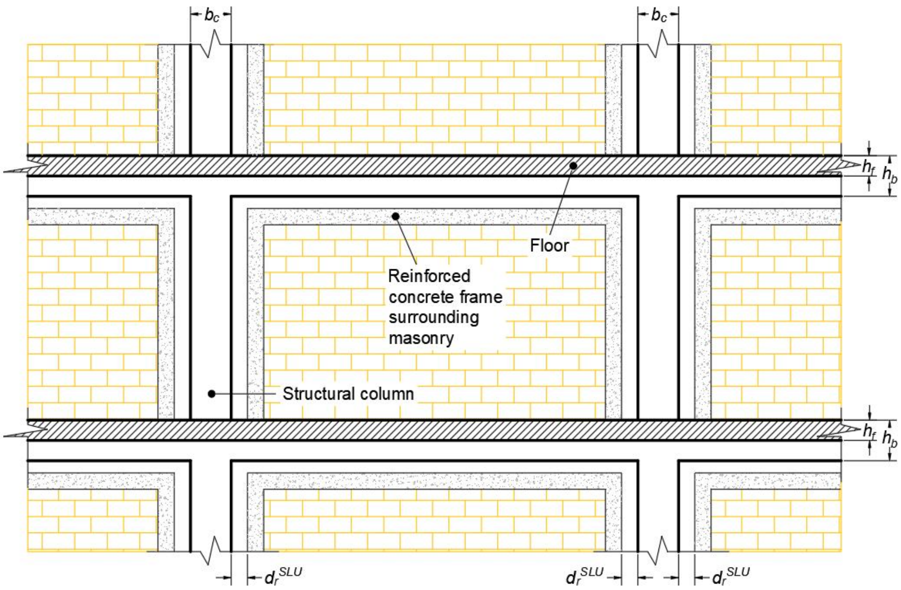


Fig. 11 – Isolation of masonry infill walls through reinforced concrete frames.

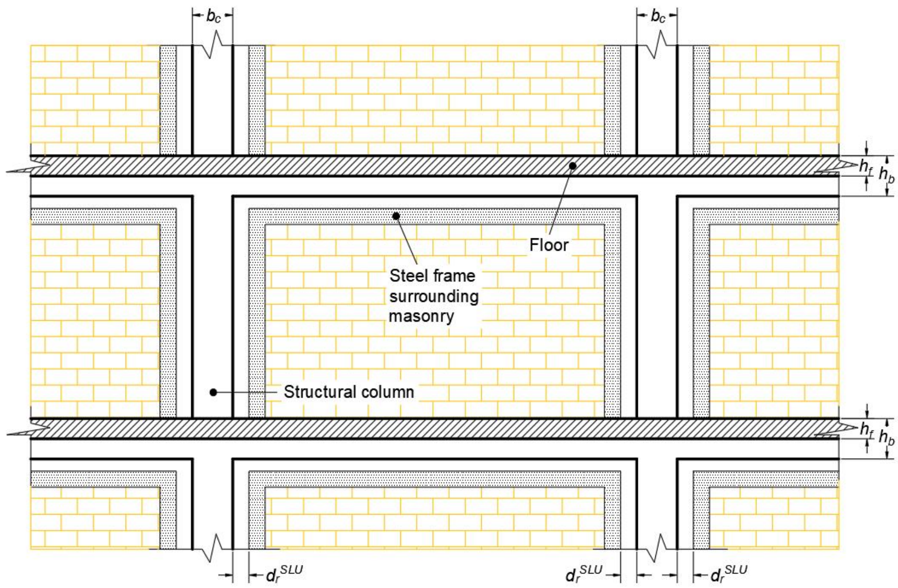
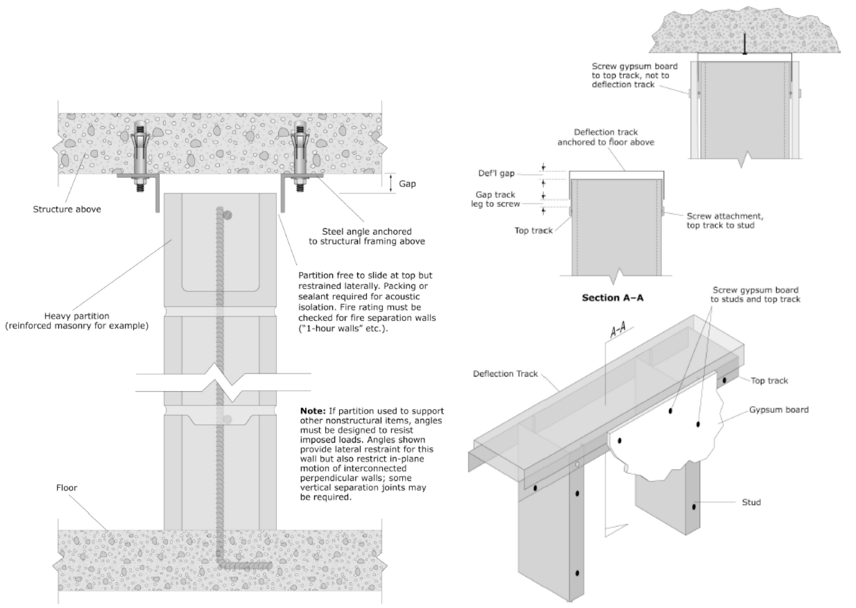


Fig. 12 – Isolation of masonry infill walls through steel frames.

Flexible (free) partition concept

This concept enable flexible gripping of non-structural elements to the seismic resistant RC frame or allows the utilization of walls with a lower stiffness than the rigidity of the structural frame system. In the first case, flexible gripping can be performed according to the principle of (Fig. 13), and for the second case, wood walls (not shear walls) can be used. A particular advantage for this type of wall (wood infill wall) is that it can be execute for the entire surface of the "pure" RC open frame, without the necessity for a special space between wood wall and the seismic resistant RC frame (Fig. 14).



(a) (b)

Fig. 13 – (a) Full height heavy partition (FEMA E-74, 2012); (b) Top connection for metal studs with deflection channel with double track (FEMA E-74, 2012).

Alternative if not used flexible (free) partition concept

If the rule "all non-structural elements are flexibly linked to the lateral elements of the structure" is not used, then will be considered all the five possibilities of theoretical failure mechanisms for masonry infill walls (Fig. 3).

Under these conditions, the entire height of the columns will be considered a critical zone and the transverse reinforcement will be performed accordingly (Fig. 15). This situation should be avoided for any type of frame structure located in a seismic zone, indifferent of the height regime, number of openings, etc.

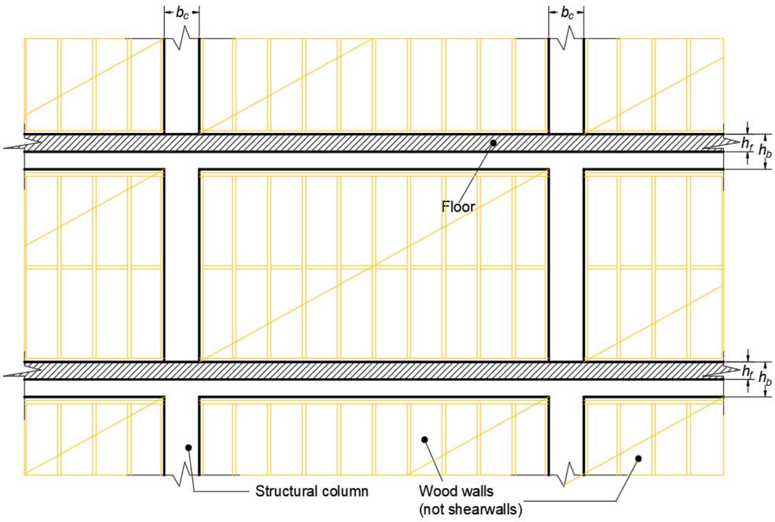


Fig. 14 – Wood infilled RC moment-resisting frames.

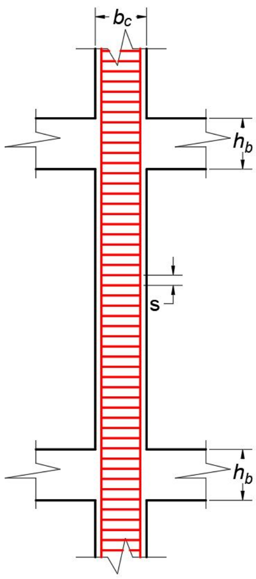


Fig. 15 – Transversal reinforcement of RC column.

Concept of the masonry infill structural fuse

According to this concept, infill wall can participate in lateral load resistance and provide additional stiffness for wind loading and low-to-moderate seismic events, but to be isolated under major events (Aliaari & Memari, 2012). This concept has been developed for metal frame structures (Fig. 16), but it can easily become an alternative for reinforced concrete frame structures with infill masonry walls. More details regarding this concept works is found in (Aliaari & Memari, 2012).

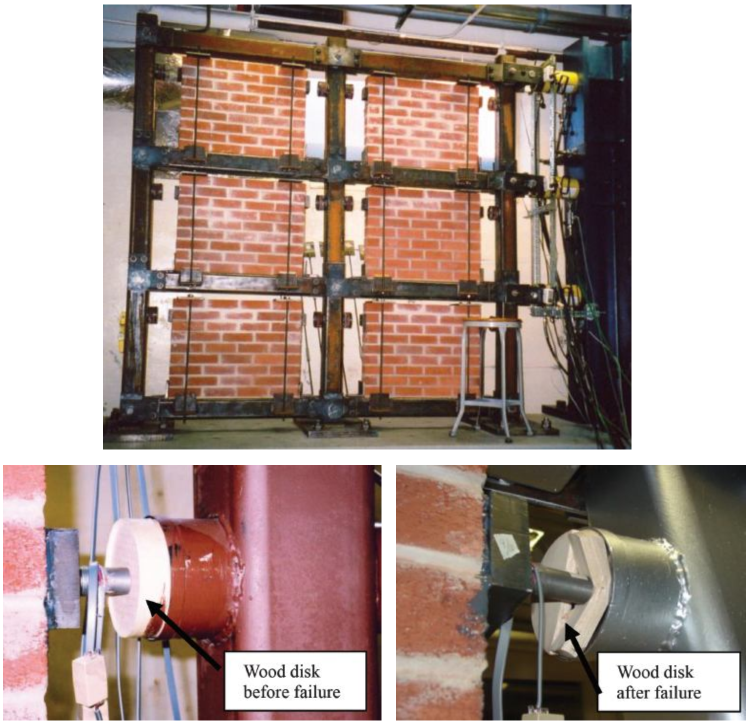


Fig. 16 – Pictures of experimental test with implication of the masonry infill structural fuse concept (Aliaari & Memari, 2012).

5. Conclusions

The masonry infill walls with ceramic blocks still retains a wide domain of practical application for reinforced concrete frame systems, but involves the problem of the interaction between the RC seismic resistant frame structure and the masonry walls, which in design practice is largely ignored.

The vast majority of experimental studies and numerical studies have demonstrated the unfavorable seismic response of "hybrid" structures with reinforced concrete frames. The practical solution would be to isolate the nonstructural walls from the lateral structural elements, or to rigidize the structure so that it will resist to severe seismic actions, without the implication of an inelastic response. The cover value of 2.5% (story relative displacement) adopted in Annex E of the code (P100-1, 2013) for reinforced concrete columns can not be considered satisfactory also for the collapse of the infill walls.

Isolation of masonry walls permit adequate rehabilitation of structural reinforced concrete elements following a severe earthquake, without significant masonry wall degradation In these conditions, for the reinforced concrete frame structures, the mechanism of seismic energy dissipation can be realized according to the design principles.

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EFECTELE NEGATIVE ALE PEREȚILOR DE ZIDĂRIE ÎNRĂMAȚI ÎN CADRE DE BETON ARMAT ASUPRA RĂSPUNSULUI SEISMIC AL ACESTUI TIP DE SISTEM STRUCTURAL ŞI METODE PRACTICE DE SOLUȚIONARE A ACESTOR EFECTE (STATE OF THE ART)

(Rezumat)

O serie de cutremure din întreaga lume (Luzon, 1990; Cairo, 1992; Izmit, 1999; Gujarat, 2001; Sichuan, 2008; L'Aquila, 2009 etc.) au demonstrat modalități reale de impunere a răspunsului seismic fragil sistemelor structurale tip cadru de beton armat dotate cu pereți de zidărie înrămați. Efectele structurale globale cât şi efectele negative locale ale pereților de zidărie înrămați în cadre au dovedit a fi cruciale în ultimele etape ale colapsului structurii. Prin intermediul acestui studiu teoretic se doreşte să se clasifice consecințele care provoacă o serie de fenomene în acest sistem structural şi nu în ultimul rând, unele metode practice care pot ajuta la rezolvarea lor.