Behavior and analysis of masonry-infilled reinforced concrete frames subjected to lateral load

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Abstract

Infilled frame constructions have been in use for more than 200 years. Masonry infills have often been treated as nonstructural elements and their structural presence is often ignored by engineers. The infill panels may interact with bounding frames when the structure is subjected to strong lateral loads induced by seismic load. Such interaction shows some positive and negative effects on the structure and has been the subject of many debates. The experimental results demonstrated that the masonry infill walls benefit the buildings due to the amount of increase in the initial stiffness of the reinforced concrete frames. On the other hand, infill walls have been related to failures, such as the development of soft stories and the brittle shear failure of columns induced by the short-column effect. In spite of the structural effects of bounding frames, masonry infills have not been treated in EC 8. During the last 50 years, a number of different analytical models (micro- and macro-models) have been developed to evaluate infilled structures under in-plane and out-of-plane horizontal dynamic actions. This paper presents a literature review of analytical research conducted on infilled frames, compares design provisions related to masonry infill in seismic design codes of different countries and discusses the shortcomings of the national guidelines.
Keywords: masonry infilled, RC Frame, lateral load, micro and macro modeling.

1 Introduction

Masonry-infilled panels can be found as interior and exterior walls in reinforced concrete (RC) and steel-framed structures in several countries worldwide. The interaction of the masonry infills with the surrounding frames has a major

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influence on the structural response of the full composite structures. The masonry infill is stiff and has sizeable strength. Moreover, it has good sound and heat insulation as well as waterproofing properties.

However, there is a common misconception that masonry infills in RC or structural steel frames can only enhance their lateral load performance and must always be beneficial to the earthquake resistance of the structure. In the last earthquakes of Kashmir (2005), Bam (2003), and Turkey (1999), which observed a high death toll, buildings with masonry infill walls either collapsed or were damaged.

The masonry infill panel increases the lateral stiffness of the structure, thus deferring the natural time period on the earthquake response spectrum in the direction of higher seismic base and story shear, and active lateral forces to the structures are not designed to suffer them. In addition, if the frame acts as a moment resisting frame, neglecting the contribution of infills, the stiffening effect of the infills may increase the column's shear strength and result in the formation of plastic hinges at the column. Furthermore, if the masonry infill is irregularly distributed in the entire building, a soft story may develop due to abrupt change of the stiffness along the height of a building.

The behavior of masonry structures, both analytical and experimental, has been extensively studied in the last five decades. The experimental studies have been carried out to consider the responses of full or scaled structures subjected to monotonic or cyclic loading.

Based on recent research [3, 4, 7, 12, 21, 24, 27] in the last decades, the different failure modes of masonry infill panels can be categorized into three main modes:

1. Shear Failure

(i) Horizontal sliding along the mortar joint: This type of failure has been mainly observed in non-integral infilled frames with low normal forces and with low to medium aspect ratios (height to the length of infill). This failure mode indicates a short-column behavior and plastic hinges can generate at the mid-height of the column.

(ii) Stepped cracking along the mortar joints: When the mortar joints are weak in compression with the masonry units diagonal cracking can occur from one loaded corner to the other. This type of failure has been observed consistently in laboratory test and is the common failure mode of the infilled masonry.

(iii) Cracking due to diagonal tension: This type of failure may occur because the stress state exceeds the tensile strength of the masonry unit. These cracks start in the central zone of the infill at the point with higher tensile stresses, and spread widely towards the corners. The inclination of the running cracks is approximately equal to the diagonal degree of the panel. The mortar joints are strong in comparison with masonry units or if normal stress in masonry infill is medium to high.

2. Compressive Failure

(iv) The diagonal compression mode of failure: In this mechanism diagonal cracks occur from one loaded corner to the other. In this case, the infill develops a diagonal strut with a compressive strength conditioned to masonry thickness, compressive strength of masonry and the length and height of infill. This type of failure occurs as a result of diagonal tension cracking.
(v) Corner crushing: The corner crushing occurs in the loaded corner due to a biaxial compression-compression stress. This failure indicates often a distinct diagonal strut mechanism with two distinct parallel cracks.

3. Flexural Failure

(vi) Flexural cracking: In this case, flexure effects are predominating (multistory infilled frames), the columns are very weak and a low reinforcement ratio induces the yielding of flexural steel in the windward column.

2 Guidelines in national codes due to effect of masonry infill panels

2.1 Eurocode 8

Eurocode 8 (EC 8) considers basically the masonry infills as non-structural elements and tends to inhibit any frame structural connection with the masonry infills through shear connectors or other ties. If structural connection is not avoidable, then considers the structure as one consisting of confined masonry and not as a RC frame with masonry infills.

EC 8 requires avoiding strongly irregular, unsymmetrical or non-uniform arrangement of infills in plane and elevation. Moreover, if infill panels are irregular in plane and in elevation this irregularity shall be taken into account. EC 8 requires doubling the eccentricity in the analysis of structural systems with an asymmetric distribution of the infills in plane. More attention should be paid to the structures on the sides with fewer infills in plane. They will be subjected to lager deformation than the side with more infill panels. In this case 3D structural models should be used for the analysis of the structures and infills should be considered in model.

Irregularities in elevation may develop a soft story due to reduced stiffness of the story to other stories. Such failure may induce collapse of building and unfortunately seems to be the most common case of damage caused for structure with infill panels. A reduction of the infills in a story relative to the adjacent ones increases the inelastic deformation demand on the columns of the story with the reduced infills. The interstory drift ratio in the story with infill panels (relative horizontal displacement of two floors, divided by story height) is less than story without or with reduced infills. Unequal interstory drift ration may develop plastic hinges in the top and bottom of the columns of soft story. EC 8 requires that these columns should be designed to remain elastic, until the infills in adjunct story obtain the ultimate force resistance. Additionally, EC 8 restricted the interstory drift ratio or masonry infilled frames to about 1%.

In this code large openings are required to be framed with reinforcement elements by the full length of walls. Shear reinforcement in the form of at least 5 mm in diameter is recommended with a minimum spacing of 150 mm.

EC 8 recommends also multiply the internal forces such as bending moments, axial forces and shear forces in the column by the factor η, defined as follows:

$$\eta = \left(1 + \frac{\Delta V_{Rw}}{\sum V_{Ed}}\right) \leq q \qquad (1)$$

V_{Rw} is the total reduction of the lateral force resistance of masonry infills in the story concerned, compared to the story above and ΣV_{Ed} is the sum of seismic shear forces acting on all vertical primary seismic structures of the story concerned. If factor η defined in the above expression lead to the value lower than 1.1, this action effect can be neglected.

Infill masonry may suffer more damage at the ground floor due to the largest shear forces in this story. CEN, 2004 demand to consider the entire length of the column of the ground story as the critical length. This region needs special detailing and confinement requirements. If the infill has an opening or perforations and the height of the infill is smaller than clear length of adjacent columns, the consequence of the increase of the design shear force should be considered in the following expression:

$$V_{cd} = \gamma_{RD} \frac{M_{Rd,c_1} + M_{Rd,c_2}}{\ell_{c_1}} \qquad (2)$$

With the clear length of the column, l_{cl} equal to the length of the column that is not in contact with the infills, γ_{Rd}=1,3 for the columns of the building of the ductility class H and γ_{Rd}=1,1 for those of ductility class M. Moreover, it is required to place the transverse reinforcement along the length of the column in and not in contact with the infills.

If the clear length of the column, l_{cl}, is short, then the design shear force obtained from the equation above may be very large. The changing of the cross-sectional dimensions of the column or configuration of infills would be complex and not common. In this case, it will be suitable to consider and design this column as secondary seismic element. Additionally, this code is required to determine shear capacity of columns for shear forces generated by horizontal component of the strut force of the infill (diagonal strut) or the shear force computed from Eq. (2). In the second case, the contact length is equal to the full vertical width of the diagonal strut of the infill, w/cosθ. The strut width is not definite in EC 8 and can be assumed as a fraction of the panel diagonal length.

Part 3 of EC 8 (the seismic assessment and retrofitting of existing building) do not consider the masonry infills and there are no rules to consider the infill masonry panels. However, several problems are considered by the retrofitting of exiting building and not by designing new building. Hence, there is a need to extend the scope of the Part 3 of EC 8 and to consider the infill panels in the analysis of structures, providing the strength and stiffness of infill panels and to profit from the beneficial effect in the existing building.

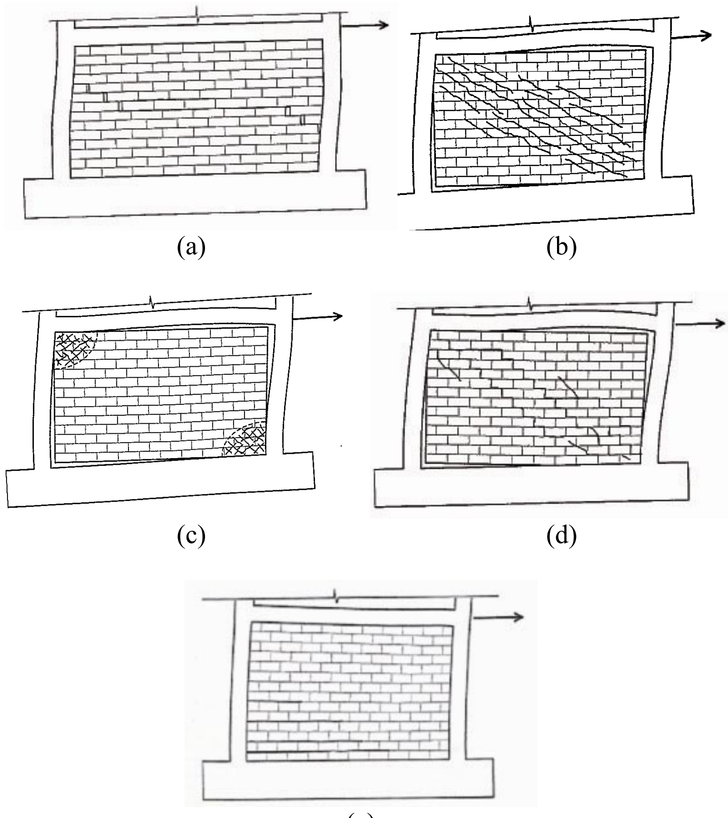

Figure 1: (a) Sliding shear, (b) diagonal tension cracks, (c) corner crushing, (d) shear cracking along the mortar joints, stepped cracks (e) flexural failure [4].

The failure of the surrounding RC frame is already investigated and is detailed as follows:

1. Flexural collapse: When plastic hinges are developed at the ends of the columns with maximum bending moment the flexural collapse may occur in infilled frame. The plastic hinges in the columns do not always cause the collapse of the structure because the system behaves as a braced system until the masonry panel failed. The sliding shear in masonry infill can

develop plastic hinges in the middle height of columns. This effect is named in literature review as knee braced frame.

2. Failure due to axial load: Gravity loads and the truss mechanism produce axial compressive forces in the columns. Buckling of the longitudinal reinforcement may occur due to severe cyclic loading and resulting in a compressive failure. However, this failure mode is not very common because of high compressive strength of the columns.
3. Shear failure of the column: The shear forces in the columns may exceed the maximum along the contact length, near the loaded corner. One or more diagonal cracks appear in columns. Horizontal Sliding along mortar joints expedite the shear failure of the column due to develop a short column effect.
4. Beam-column joint failure: large shear forces and bending moment in the loaded corner and along the contact length in the zones near loaded corner can develop wide diagonal cracks running across the from the interior to exterior corner.

In the summary, the type of failure that will occur in an infilled frame is generally not simple to predict, depending on distinct factors, such as the strength of infill panel and frame component, relative stiffness of the frame and the infill panel and the dimensions of the structure. It is obvious that the strength of the mortar joints has also major effects on the behavior of the infilled frame.

In the sprite of the significant effects of masonry infills panels, there are a lot of national codes, neglecting to consider the role of masonry-infill walls while designing RC frames.

The various national codes have been developed to consider the role of masonry infill panel as a primary structure while designing the reinforced frames. A very few codes suggest isolating the infill panel from the RC frames. The isolation can prevent the problem and be effective. However, it is difficult to ensure the panel against out-of-plane seismic forces.

The present paper discusses the guidelines of Eurococde 8, Fema 306 and the theoretical models reported in the literature for predicting the seismic behavior of masonry infilled frames.

3 Fema 275, Fema 306

In Fema 273, the masonry infills are considered as primary elements of a lateral-force-resisting system. The solid infill can be modeled as equivalent strut to assess the stiffness and strength of the structure. This code recommends the following equation to compute the effective width of diagonal compression strut, w, which was developed by Mainstone [11]: The angle is computed from the equation below:

$$\theta = \arctan\left(\frac{L_m}{H_m}\right) \tag{3}$$

$$w = 0.175\left(\lambda_1 H\right)^{-0.4} D \tag{4}$$

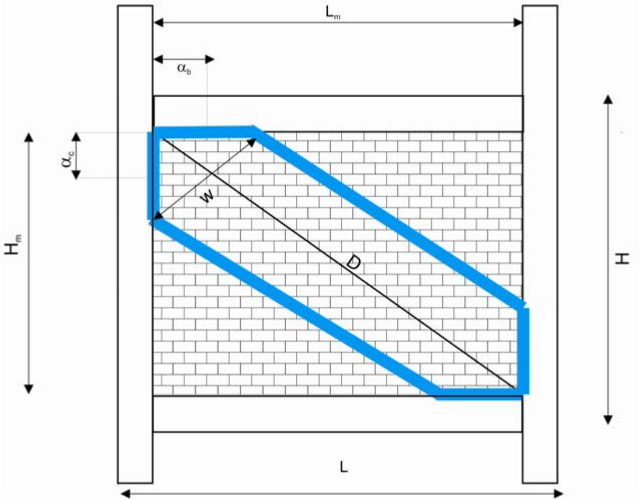

Figure 2: Diagonal strut modeling.

λ_1 is given by

$$\lambda_1 = \left(\frac{E_m t_{inf} \sin 2\theta}{4E_{fe} I_{col} H_m} \right)^{0.25} \tag{5}$$

where E_{me} and E_{fe} are modules of elasticity of masonry (secant modulus of elasticity between 5% and 33% of masonry prism strength) and frame material, D and t_{inf} are the diagonal length and actual thickness of masonry infill, H and H_m are the column and masonry infill height and θ is the inclination of diagonal strut. E_m can be calculated from the experiment test or in absence of tests the recommended Fema 306 value of E_m is specified as 550 times the prism compression strength of masonry (f_m). Fema 306 proposed four possible failure modes for masonry infill: sliding-shear failure, compression failure, diagonal failure and diagonal tension failure of panel. There are equations in this code, which calculate the strength capacity or shear force demand of an infill panel. Furthermore, Fema 306 considers three distinct failure modes for RC frame namely: flexural failure of beam and/or columns due to yielding of reinforcement shear failure of beam and/or columns, and shear failure and bond failure of beam- column joints.

Moreover, Fema 306 requires interstory drift limit for different solid panels: for brick masonry, 1.5%, for grouted concrete block masonry, 2%; and for ungrouted concrete block masonry 2.5%. It is expected that these values are too large and these codes recommends experimental studies to verify these limit states.

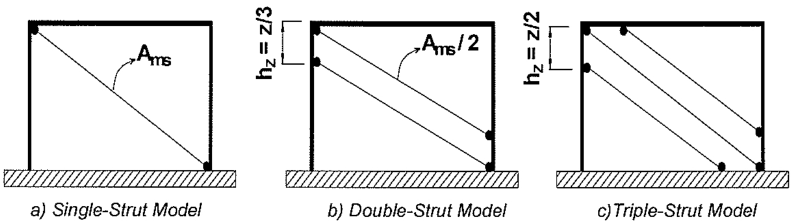

Figure 3: Strut models [1, 3, 23].

4 Theoretical models

The various theoretical models reported in the literature for prediction of the seismic behavior of masonry infilled frames depending on the level of accuracy and the simplicity desired, can be broadly classified into two distinct categories (i) macro modeling and (ii) micro modeling.

4.1 Macro modeling

The equivalent strut concept is the most popular macro method to predict the lateral stiffness and strength of multi-story infilled frames, which is developed from Stafford–Smith (1967) [24]. The effective width, w, of an equivalent strut depends on the contact length between the frame and the infill. There are many empirical approaches to determine the effective width of an equivalent strut. Holmes [16] proposed a width equal to one third of the length of panel. Paulay and Priestly [21] recommended a conservative value about one fourth of the length of the panel. Mainstone [19] proposed an approach to obtain the width of strut that is adopted from Fema 273 and Fema 305.

The single diagonal strut model has been modified by distinct researches. The literature review presents other models to obtain the behavior of masonry infill such as multi strut (two or three) model (Figure 3).

The result of previous numerical models and experimental results demonstrated that the single-strut model, despite its simplicity, offers adequate estimation of the stiffness of the infilled frame. However, the use of a concentric strut model alone does not accurately model the shear demand on frame members for ductile behavior. Figure 3 (b) and (c) show multi strut models proposed by Chrysostomou [3] and Syrmakesis and Vratsanou [23], respectively. These models represent the action in the frame more precise. Eccentric strut models result in conservative shear demand for frame; however it appears that multi-strut models may be more suitable solution for infill frame evolution, there may need to be further research into the use of these models when panel damage occurs and provide limited shear demand in column.

4.2 Micro modeling

The nonlinear behavior of a RC frame with masonry infill was investigated by several researchers [2, 4, 14, 20, 22] The finite element models considered the fracture behavior of RC frames, masonry units, mortar joints, and the frame-panel interface. The tension and compression behavior of the frame were modeled with smeared crack element and the fracture of the mortar joints, the interface of the frame-panel and the shear cracks in columns were modeled using interface elements. The results are compared with experimental tests of half-scale, single-story, RC frames with masonry infilled by finite element modeling.

There are other studies [2, 4, 14, 20] which presented new finite element models for infilled frames subjected to monotonic and cyclic loading, in which the interface between the frame and the infilled were simulated by using a non associated interface model, infilled frame was modeled using panel elements and the frame elements. Other studies [14] assumed the infill as homogenous material and only the interface between the frame and the infilled is considered.

The results by the finite element modeling showed that numerical micro models were superiorly capable of obtaining detailed data on the behavior of infilled frame.

5 Shortcomings in existing national codes and previous research

The various national codes and previous researches exhibit several shortcomings and there are major open problems as follows:

- There is a need for estimating the empirical natural period of masonry infilled frames with irregularities in elevation and plane. Existing approaches do not estimate the natural period of such structures and may lead to inaccuracy determination of the maximum shear forces in the structures.
- Stiffness and strength of masonry infill are not very specific in existing national codes and should be explicitly included in the seismic analysis model of such structures.
- The feasible effect of weak or soft stores should be considered in the seismic analysis of the building. The various researches did not treat this issue very specific. Hence there is a need for more investigation of this problem.
- Expand the scope of national codes and develop of guidelines, so that in the case of seismic retrofitting, structure can profit from masonry's benefits.
- The material properties (masonry units, the mortar and infill) should be better investigated.
- Force-deformation curve of masonry infill under cyclic loading should be developed and the effect of large opening in the panel with reduced stiffness and strength of the infill should be considered.

6 Conclusions

The present paper has illustrated some negative and positive effect of masonry infill. The previous studies induced that the masonry infills alter the stiffness and strength of structures and they should be considered in seismic design of such structures. Moreover, in symmetric buildings with vertically continuous infilled frames, the increased stiffness and strength may reduce the major damage due to excessive lateral drift.

Although Eurocode 8 and some other national codes neglected the effect of masonry panels, or required the masonry infill to be isolated from the RC frames. EC 8 recommended also simplified static analysis method for regular buildings, and detailed three-dimensional dynamic analysis methods for irregular building. This code addresses the problems associated with plane and vertical irregularities in masonry infilled reinforcement concrete frames and restrict the amount of eccentricity between center of mass and center of rigidity.

Fema 306 considered masonry infill and recommended modeling infill panels using equivalent diagonal strut. This code proposed approaches to determinate the width of an equivalent diagonal strut controlled by stiffness of masonry infill and surrounding frame.

In both of the codes and previous researches obviously have shortcomings. There is an urgent need for more investigations and extensive design codes for masonry infill panels.

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