CONTRIBUTION OF NON-STRUCTURAL MASONRY WALLS TO THE ROBUSTNESS OF RC FRAMED STRUCTURES WHEN SUBJECTED TO EXTREME EVENTS

Mariana Barros¹, Eduardo Cavaco²(*) , Luís Neves³, Eduardo Júlio⁴
¹Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Portugal
²CEris, ICIST, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Portugal
³Centre for Risk and Reliability Engineering, University of Nottingham, FCT/UNL, Caparica, Portugal
⁴CEris, ICIST, Instituto Superior Técnico, Universidade de Lisboa, Portugal

(*) Email: e.cavaco@fct.unl.pt

ABSTRACT
The main objective of this work is to evaluate the viability of using non-structural masonry walls as a reserve of robustness of reinforced concrete (RC) framed structures when submitted to unforeseen extreme events. First, the concept of structural robustness is discussed and then its importance in the mitigation of consequences of damages resulting from extreme events is addressed. Following this, the influence of non-structural masonry walls on the behaviour of RC buildings subjected to a localized column failure, as a result of an unforeseen extreme event, is analysed. Finally, damaged buildings are presented as case studies, and main conclusions are presented.

Keywords: Robustness, damaged, RC frames, extreme events, masonry walls.

INTRODUCTION
Robustness is a critical concept in structural engineering that has been extensively investigated in the last years due to concerns about human casualties in extreme accidents. Despite the progress of structural engineering supported by the technological advance, sudden collapses of structures still occur (Pearson and Delatte, 2005; Andersen and Dietsch, 2011). In the last decades, different definitions of robustness have appeared, but the lack of robustness is generally related with disproportionate consequences when compared with the original damages.

In the case of RC buildings, the analyses of structures subjected to extreme events have pointed to a significant contribution of the masonry walls to the global structural robustness, in particular after a column failure. Therefore, the possibility of considering non-structural masonry walls as a robustness reserve in the case of certain types of natural or man-caused accidents may have an important impact on the construction practice, especially in countries like Portugal where most building have this configuration (Tiago and Júlio, 2010).

The influence of the masonry infill panels is neglected in the design of RC buildings, and the structural stability is assumed to be guaranteed by the RC frame alone. On the contrary, in the assessment of existing buildings, it can be accepted that these elements can have a significant influence on the structural behavior.
BACKGROUND ON STRUCTURAL ROBUSTNESS

The concept of structural robustness was first introduced in the aftermath of the partial collapse of the Ronan Point Building (UK) in 1968 (Pearson and Delatte, 2005) due to the damages caused by a localized gas explosion. The consequences were considered disproportionate as compared with the original damages. Other structural collapses, such as the collapse of the Bad Reichenhall arena (Germany, 2006) (Winter and Kreuzinger, 2008), the arena Siemens (Denmark, 2001) (Andersen and Dietsch, 2011), the Alfred P. Murrah Building (USA, 1995) (Frangopol and Tsompanakis, 2014) and the Word Trade Center (USA, 2001) (Bazant and Zhou, 2002), showed the diversity of the extreme events that structures can be subjected, the seriousness of the consequences of these accidents, and the importance of the structural robustness.

Studies conducted by different researchers (Agarwal et al. 2006; Asteris, 2003; Baker et al. 2008; Biondini and Restelli, 2008; Cavaco et al. 2010; Frangopol and Curley, 1987a; Ghosn and Moses, 1998a; Lind, 1995a; Starossek and Haberland, 2008; Wisniewski et al. 2006) have shown that different perspectives have been adopted for the structural robustness and different methods of quantifying it have been proposed.

Currently, two main different perspectives for the concept of structural robustness can be found in the literature: the first considers the structural robustness as a property of the structure itself, only dependent on its ability to maintain its integrity according to the design objectives when a damage is inflicted (Biondini and Restelli, 2008; Cavaco et al. 2013; Frangopol and Curley, 1987; Lind, 1995; Wisniewski et al. 2006b); the second has a broader sense since it considers the structural robustness as a property of both the structure and the surrounding environment. In this case, a structure is robust if both direct and indirect consequences resulting from the structural collapse are not disproportionate to the original cause. It is important to note that robustness, according to the latter definition, is a much wider concept involving complex socio and economic variables, among others, outside the civil engineering domain. Thus, robustness becomes more difficult to assess because it depends on the developments on structural environment.

Different methods of quantifying robustness can also be found in the literature either related with the structural perspective of robustness or with a wider perspective that includes the environmental consequences. Fig. 1 shows a classification of the proposed methods based on its nature, if probabilistic or deterministic based.

![Methods for quantifying Structural Robustness](image)

**Fig. 1 - Methods for quantifying Structural Robustness (adapted from (Cavaco et al. 2013))**
In this paper special focus is given to the deterministic based measures related to a structural perspective adopted for robustness. In the following paragraphs the most significant proposals for measuring robustness are presented.

Frangopol and Curley (1987) proposed a redundancy index \( R \) as a measure of robustness by using the following deterministic expression:

\[
R = \frac{L_{\text{intact}}}{L_{\text{intact}} - L_{\text{damage}}}
\]

where \( L_{\text{intact}} \) and \( L_{\text{damage}} \) are the collapse load of the undamaged and damaged structure, respectively, considering that one or more members are damaged. The obtained values for the redundancy index can range from \([1, +\infty]\), where \( R = 1 \) identifies a structure with no strength reserve and \( R = +\infty \) if damage has negligible impact on the structure strength. Thus, a lack of sensitivity can be identified in this index due to the wide range of possible values.

Biondini and Restelli (2008) proposed a robustness measure \( \text{Rob}(D) \) driven towards the damaged induced by deterioration given by the following equation:

\[
\text{Rob}(D) = \frac{F(D)}{F(D=0)}
\]

where \( F(D=0) \) is the performance of the intact structure and \( F(D) \) is the performance of the damage structure, considering a damage level equal to \( D \). The measure proposed by Biondini and Restelli 2008 might result ambiguous since robustness depends on the damage level.

Cavaco et al. 2013 improved this approach by considering the average performance of the structure when subjected to the overall damage spectrum:

\[
R = \int_{d=0}^{d=1} f(x) \, dx
\]

where \( f(x) \) is the normalized performance of the structure, given by the ratio \( F(D)/F(D=0) \), and \( d \) is the normalized damaged, given by \( D/D_{\text{max}} \), where \( D_{\text{max}} \) is the maximum possible damage inflicted to the structure. The robustness index \( R \) ranges from 0 to 1, for a null and full robust structure, respectively. If damage is a discontinuous variable, the integral on equation (3) should be replaced by a summation.

LITERATURE REVIEW

On the Influence of masonry infill walls on the behaviour of RC framed structures

In Portugal, the most common structural typology consists in RC framed structures with façade and partition walls on clay masonry. In the last years, it became widely accepted that the structural behavior of framed structures when subjected to seismic actions is significantly affected by the presence of masonry walls. Their contribution is not always positive in particular in cases of non-uniform distribution, causing torsion effects due to the asymmetries in terms of mass and stiffness (Appleton, 2013a; Asteris, 2003; Ozkaynak et al. 2013; Pires, 1990; Polyakov, 1960; Pujol et al. 2008; Sattar and Liel, 2010). However, several studies suggest the opposite (Asteris, 2003; Murty and Jain, 2000a; Pujol et al. 2008; Sattar and Liel, 2010; Uva et al. 2012; Xavier et al. 2013). Pujol et al. (2008) performed an experimental work comprised by a full-scale three story flat-plate structure strengthened with masonry brick walls and tested under horizontal displacement reversals. The results demonstrated that continuous infill masonry walls can contribute to reduce the vulnerability of reinforced
concrete buildings with few stories. These walls were effective in increasing the strength (by 100%) and stiffness (by 500%) of the original reinforced concrete structure, therefore significantly increasing robustness.

The first study on the interaction between an RC frame and a masonry wall infill was conducted by Polyakov in the 50’s (Polyalov, 1960). It was concluded that RC frames subjected to a horizontal force applied at the frame plan exhibit a monolithic behavior, up to the appearance of the first cracks in the connection between the frame and the masonry wall, due to distortion. The latter increases the masonry confinement and the stresses are distributed between the two diagonally opposite corners of the wall. A diagonal strut is formed against the joints of the frame (see Fig. 2).

Smith (1966) suggested that the failure modes of the concrete infilled frames subjected to horizontal forces are dependent on the relative strength and stiffness between the concrete frame and the masonry walls. Five different failure modes were identified by El-Dakhakhni et al. (2003): one related with the formation of plastic hinges in the beam-column connection neighborhood, usually occurring for high strength masonry walls; and the four remaining related with the masonry failure and consisting on its crushing at the corners, in the center of the panel wall, cracking along the diagonal strut and shear failure along the mortar joints.

The beneficial effect of masonry infill walls has also been stated in RC framed structures severely damage due do failure of a column or a set of columns. Cachado et al. (2011) carried out a parametric study to evaluate the behavior of structures with one or more damaged columns and the corresponding role of masonry walls. The obtained results revealed that the masonry infill walls increase the safety of damaged buildings, with 2 to 4-stories and with several damaged columns. For buildings with 6-stories or more, the influence of masonry walls was not sufficient to guarantee the safety of all the structural elements.

Helmy et al. (2015) simulated a ten-story RC structure and executed a parametric study constituted by the nonlinear dynamic analysis (AEM) of five different cases: the sudden removal of (i) a corner column, (ii) an edge column, (iii) an edge shear wall, (iv) internal columns, and (v) internal shear walls, from the ground floor. It was concluded that, in cases (i), (ii), (iii) and (v), and neglecting the contribution of the masonry infill walls infill, a partial collapse of the structure would occur. Progressive collapse is likely to be avoided, provided that masonry walls exist in perpendicular bays in consecutive floors above, in the neighborhood of the lost column.
Shan et al. (2015) performed a set of experimental tests comparing the performance of bare and infilled RC frames with 4-bays and 2-stories considering the instantaneous loss of the internal columns, followed by a push down load at the top of the latter. It was observed that the masonry walls can provide an alternative path to the loads originally supported by the beams.

As observed, strong evidences exist that masonry walls can provide a significant strength reserve, crucial to avoid progressive collapse. However, additional research is still needed since very few studies have been published in this field up to the present date. The Eurocodes (CEN, 2002) do not consider the contribution of clay masonry walls against progressive collapse and the UFC regulation (US Department of Defence, 2013) was found to be the only standard to address this issue. However, due to the lack of research, and in order to account for the contribution of the masonry walls to stop progressive collapse triggered by the failure of a column, the UFC suggests to adapt the results from the seismic research.

On the simulation of the masonry infill walls effect

Several numerical models have been used in the last decades to simulate the behavior of RC frames infilled with masonry walls and subjected to horizontal loads in the plane of the frame (Al-Chaar, 2002; Asteris, 2003; Cachado et al. 2011; Crisafulli et al. 2000; El-Dakhakhni et al. 2003; Farazman et al. 2013; Krstevska and Ristic, 2004; Mainstone, 1971; Murty and Jain, 2000b; Paulay and Priestley, 1992; Polyalov, 1960; Riddington and Smith, 1977; Sattar and Liel, 2010; Smith and Carter, 1969; Smith, 1966; Uva et al. 2012; F. Xavier et al. 2013). Most of these studies focus on macro simulation and simple models of equivalent diagonal struts (Al-Chaar, 2002; Farazman et al. 2013; Mainstone, 1971; Paulay and Priestley, 1992; Pires, 1990; Polyalov, 1960; Smith and Carter, 1969) which allow their application in the design stage (Riddington and Smith 1977).

As referred to, the pioneer experimental work of Polyalov 1960, suggested the first equivalent diagonal strut. This is a simple model that considers the masonry contribution in the frame global behavior. However, it does not consider the subsequent local effects resulting from the interaction between the masonry panel and the frame. For this reason, the local formation of plastic hinges may not correspond to the reality (Crisafulli et al. 2000).

Mainstone (1971) and Smith (1966) deepened the study related with the equivalent diagonal strut and defined the relation between the masonry and frame properties and the equivalent strut. Smith and Carter (1969) concluded that the masonry stiffness and diagonal strength depend on the masonry dimensions and the contact lengths between the masonry and the frame in the deformed shape. The authors defined the relative infill to frame stiffness ($\lambda H$) that should be evaluated using the following formula:

$$\lambda H = H \times \sqrt{\frac{E_m \times t \times \text{sen}(2\theta)}{4 \times E_c \times I_c \times h}}$$

where $H$ is the frame high, $E_m$ and $E_c$ are the Young’s modulus of masonry and concrete respectively, $t$ is the masonry thickness, $h$ is the high of masonry panel, $I_c$ is the column moment of inertia and $\theta$ is the diagonal slope. The authors defined the equivalent strut width ($a$) of the panel, dependent on the relative infill to frame flexibility of the panel as shown in Equation 5.

$$a = 0.175 \times D \times (\lambda H)^{-0.4}$$

were $D$ is the diagonal strut dimension.
Several model variations were presented later with more than one strut (Fig. 3). Schmidt (1989) proposed a model with non-parallel compressive struts with offsets at both ends (Fig. 3a). Chrysostomou (1991) suggested the use of a strength and stiffness degrading three-strut model to simulate the response of infilled frames under earthquake loading (Fig. 3b). El-Dakhakhni et al. (2003), proposed a three strut model to predict the stiffness and the ultimate load carrying capacity of concrete masonry infilled steel frames that fail in corner crushing mode. Crisafulli et al. (2000), investigated the limitations of the single strut model and compared the results obtained from models with single, double, and triple struts, from those corresponding to an equivalent finite element model. The analyses were conducted under static lateral loading with linear elastic behavior.

Al-Chaar (2002) developed the equivalent masonry strut connected to the frame members as shown in Fig. 3d. The masonry wall equivalent strut should be pin-connected to the column at a distance $l_{\text{column}}$ from the face of the beam. The author considers that the strut model leads to lower stiffness compared with the reality. In order to correct this, it is considered that the surrounding concrete frame must have rigid element in the corners to simulate the formation of plastic hinges. Al-Chaar (2002) used in his strut model the formulations suggested by Smith and Carter (1969) and Mainstone (1971) to define the strut properties.

The models mentioned above are all based in frames subjected to horizontal actions. However, it is believed that these models can also be applied in cases of gravity loads resulting from the failure of vertical supports, with the necessary adaptations, as suggested by the UFC regulation (US Department of Defence, 2013). The UFC regulation uses the story drift as the nonlinear deformation measure for horizontal load-bearing wall structures. The horizontal deformation of the wall panels is defined as the ratio of the lateral deflection at the top of a wall to the overall height of the wall panel. The regulation considers that this information can be used directly to the progressive collapse analysis and adapted for vertical deformations due to removed wall sections.

This effect was verified in the following case study, presented by Tiago and Julio (2010). In the year of 2000, a substantial landslide occurred in Coimbra, Portugal, and led to the impact of a large mass of soil on a residential RC framed building with 16 floors, erected in the early
1980’s. This event resulted in the failure of three edge columns in two consecutive floors, creating a cantilever with 7.0 m span, 9.5x7.0 m² area, and 12 floors high (Fig. 4).

Fig. 4 - Damaged Building : (a) General view of the damaged building, (b) Damaged building after land removal.

According to Tiago and Júlio (2010), the resulting cantilever could not sustain alone the gravity loads and thus progressive collapse was only prevented due to the contribution of masonry walls. A strut-and-tie system was developed, having the masonry wall working as struts and the floors as ties (see Fig. 5), this way creating an alternative path to the gravity loads. To validate this statement, Tiago and Júlio (2010) performed a finite element linear analysis of the damaged RC structure, assuming two different scenarios: considering and neglecting the effect of masonry walls. The latter led to structural collapse whereas the former exhibited acceptable stress values at both masonry walls and RC members and a maximum deflection between 3 and 8mm, matching on-site observations. Therefore, the contribution of the masonry walls was proved to be determinant in preventing the collapse of the damaged building.

Fig. 5 - Strut-tie system of damaged building (adapted from Tiago and Júlio 2010).
CONCLUSIONS

Research on the effect of masonry wall infills in the behavior of RC frames subjected to horizontal actions suggests a significant increase in terms of the frame strength and stiffness. Although the majority of research has been carried out focusing the seismic behavior of structures, some few studies have suggested that masonry walls can also be of utmost importance to stop progressive collapse and increase robustness of RC framed structures subjected to severe damages as the failure of a column or a set of columns.

It was verified in previous studies that the masonry walls can influence positively both stiffness and strength of the damaged structure. Considering the robustness as a structural property, it can be assessed comparing the strength of the damaged structure with that of the intact structure. If the contribution of masonry walls increases the strength of the damaged structure, this leads consequently to an increase of the structural robustness. This evidence is supported by the case study presented by Tiago and Julio (2010). However, additional research is still needed to fill the evident lack of published studies in this area.

It is well known in the literature that the existence of openings on the masonry walls can contribute negatively to the panel strength (Al-Chaar, 2002), but there are still key questions to be answered regarding the structural behaviour, such as, if the type of clay unit, the dimension, and the brick-to-brick connection used on the masonry walls can influence that behaviour. There are also doubts about the influence of the type of plaster used on the masonry walls, the properties of the mortar, and if the existence of reinforcement can change significantly the structural strength of a damaged structure. All these issues need to be investigated in future studies.

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