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In-plane behaviour and damage assessment of masonry infills with hollow clay bricks in RC frames

Maria Teresa De Risi*,[1], Carlo Del Gaudio, Paolo Ricci, Gerardo Mario Verderame

Department of Structures for Engineering and Architecture, University of Naples Federico II, Via Claudio 21, Naples 80125, Italy

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A B S T R A C T

Reinforced Concrete (RC) buildings with clay masonry infills are a very common structural typology worldwide for civil, strategic or productive use. Damage to infills may cause danger for human lives and strongly affects economic losses, as shown during past earthquakes. Despite their role is crucial in terms of global and local response of RC buildings in the event of an earthquake, in current practice, infills are considered as partition elements without any structural function. The behaviour of infills under seismic actions has to be reliably characterized, starting from the analysis of their displacement capacity at different performance levels due to in-plane actions, and a proper complete numerical modelling, able to reproduce their influence on the global behaviour of RC frames under seismic actions.

Some models have been already proposed in literature, but their reliability should be yet proved on the basis of an as wide as possible experimental database. Therefore, in this paper, a homogenous extensive database of experimental tests on RC frames infilled with hollow clay-masonry infills – typical of Italian and Mediterranean RC building stock – is collected and presented. The experimental responses of the infills under lateral loads are obtained and the main related numerical models existing in literature are investigated and compared with the experimental results. A new modelling proposal is carried out to obtain a simple practice-oriented force-displacement envelope to significantly reduce the errors in the prediction of the infill in-plane behaviour under lateral loads. The experimental evolutions of damage under increasing displacement demand are also analysed, and the displacement capacity at given performance levels are identified and correlated to the in-plane behaviour of the infill panels. The analysis of the damage evolution to the infills during the experimental tests finally allows the definition of drift-based fragility functions for these components, representing a key point for a more reliable estimation of losses due to earthquakes.

1. Introduction

Among natural hazards, earthquakes are certainly paramount due to the lack of possibility to predict their occurrence, and due to their impact on civil structures in terms of social consequences, direct monetary losses, loss of functionality, and risk of casualties. As a matter of fact, earthquakes occurred in the last twenty years in Italy had a significant impact at economic and social level. According to the National Engineers Council, resources for emergency and reconstruction allocated after 6th April 2009 earthquake affecting Abruzzi region amount to over 10,000 million euros. The analysis of damage data in Dolce and Goretti [1] and Del Gaudio et al. [2] highlights the key role played by damage to non-structural components, namely, infills and partitions, in Reinforced Concrete (RC) Moment Resisting Frames (MRFs). Nevertheless, infill panels are generally neglected in practice-oriented structural analyses for design or assessment purposes. On the contrary, the seismic performance assessment of infilled RC MRFs – a very widespread constructive solution for RC structures for civil or productive aims – needs to take into account also non-structural components, starting from infills, to estimate expected losses properly. To this end, the seismic behaviour of masonry infills should be reliably characterized aiming at a correct definition of fragility functions for this structural typology. Therefore, a proper nonlinear modelling is necessary to reproduce the influence of infills on the global behaviour of RC frames under seismic actions from the onset of damage to collapse, and the analysis of their displacement capacity at different performance levels (PLs) or Damage States (DSs) is required to improve the damage assessment and costs evaluation due to earthquakes.

Some experimental and analytical investigations were performed on infilled RC structures in last decades, regarding both local effects – due

* Corresponding author.
E-mail addresses: mariateresa.derisi@unina.it (M.T. De Risi), carlo.delgaudio@unina.it (C. Del Gaudio), paolo.ricci@unina.it (P. Ricci), verderam@unina.it (G.M. Verderame).

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to the interaction between infill panels and surrounding RC frame – and global effects – about the influence of infills on the global seismic performance of structures. Several studies have been developed from the second half of 1990s about numerical investigation of the influence of infills on the global seismic behaviour of RC frames (e.g. [3–6], also on the basis of full-scale experimental tests (e.g. [7], or considering the influence of uncertainty on seismic capacity of infilled RC frames through sensitivity or fragility analyses (e.g. [8,4]). Nevertheless, a proper evaluation of the influence of infills on the structural performance depends on the quality of the adopted modelling approach. Generally speaking, infill walls can be modelled either by means of micro- (e.g., FEM) or macro- (e.g., single equivalent strut or multi-struts) models (as reported in Asteris et al. [9,10] in more details). Among macro-models – more suitable to perform a huge amount of numerical analyses – in the early 1960s, Polyakov [11] first suggested the possibility to model infill panels as equivalent diagonal compressive struts. This modelling approach was later adopted starting from studies by Holmes [12] and Mainstone [13] to works by Liauw and Kwan [14] or Panagiotakos and Fardis [15]. In last two decades, more complex macro-models were also proposed (from Chrysostomou et al. [16] to Jeon et al. [17]), different in properties definition and number of diagonal struts, aiming to better reproducing the interaction with the surrounding RC structural elements. In order to characterize such equivalent strut/struts, some numerical models have been already proposed in literature in last years, especially about the prediction of the maximum lateral strength of the infill panel (e.g. [18–20]; FEMA [21] and FEMA [22]). A smaller number of studies characterizes the whole nonlinear in-plane behaviour of infill panels (e.g. [23,15]; Doselk and Fajfar, [24,25], among others). Unfortunately, main existing works about in-plane response of masonry infills from literature were based on heterogeneous datasets [26], or on a quite small number of experimental data (e.g. [27–29]), or on a numerical-basis only [30]. Therefore, the reliability of in-plane models for infills from literature should be yet proved and compared each other - and eventually modified - on the basis of an as wide as possible homogeneous experimental database.

Furthermore, in last years, several valuable studies (e.g. [31–35] have been focused on the definition of displacement thresholds corresponding to given physical damage levels on infill partitions and on the uncertainty related to their assessment. Some authors define different DSs through the observation about the extent and severity of cracking patterns observed on the panels or about the failure of brick units; some others, additionally, relate such damage levels to the attainment of the peak strength of the infilled frame or the achievement of given strength reduction factors. Typically, three or four DSs have been defined in literature, corresponding, respectively, to *(i)* the onset of cracking and first detachment between infill panel and surrounding RC frame, *(ii)* the widening of previous damage pattern, *(iii)* the crushing and spalling of a considerable portion of brick units and *(iv)* the partial/total collapse of the panel. In some cases [23,36,9], drift-based fragility functions were also proposed for each DS, thus providing a probabilistic estimation of the level of damage experienced in masonry infill walls generally considering together experimental data related to different frame typologies (RC or steel), brick typologies (solid clay; hollow clay; concrete units), and configurations (solid panels or panels with openings).

1.1. Research significance

In this paper, a homogenous extensive database of experimental tests on RC frames infilled with *hollow clay-masonry bricks* – typical of Italian and Mediterranean RC building stock – is collected and presented to investigate about a double goal necessary for a reliable losses estimation: (i) the in-plane response of such kind of infills, on one hand, and (ii) their displacement capacity at given DSs aiming at the definition of drift-based fragility functions, on the other hand.

This database collects 75 tests effectively used, thus representing a huge collection of data referred to the specific brick typology herein investigated. Such a database should be considered as an extension of those already presented in literature, such as the extensive database collected in Chiozzi and Miranda [35] - characterized by 46 tests on RC frames with infill panels constituted by hollow clay bricks - or the database collected in Cardone and Perrone [32] - characterized by 24 tests related to the analysed typology.

Starting from the collected data, the experimental responses of masonry infills under lateral loads are obtained by means of the experimental responses of the infilled frames and the corresponding bare frames. The main and widely used numerical models existing in literature for infills are investigated and compared with the experimental results in order to select the model that minimizes the prediction error. In particular, such an analysis is performed in the context of single-strut models, able to well reproduce the influence of the infill panel on the global response of the infilled frame [5]. Predicted-to-experimental ratios related to the main parameters that describe the envelope of the infill response are obtained and analysed for models proposed by Bertoldi et al. [23] and Panagiotakos and Fardis [15]. Finally, a modification of the latter model is proposed to obtain a simple practice-oriented force-displacement envelope to significantly reduce the mean percentage errors in the prediction of the infill in-plane behaviour under lateral loads.

Thanks to the analysis of the evolutions of damage under increasing displacement demand for the collected tests, the displacement capacity at given performance levels is also identified. An explicit correlation between displacement capacity thresholds at each DS and the in-plane response of the infill panels is evaluated. Empirical cumulative distribution functions are then calculated for four different DSs based on the collected homogenous dataset of experimental tests related to the investigated typology. Lognormal fragility functions are used to fit such data by means of the Method of Maximum Likelihood. Finally, a preliminary evaluation of the influence of openings on the damage assessment of hollow clay brick panels is performed.

2. Collected database

The first step of the present research is the collection of a comprehensive database of tests on infilled RC frames. More than 200 experimental tests performed and presented in literature during last four decades have been analysed and divided in homogeneous subsets depending on the infill and frame typology. In particular, only tests characterized by unreinforced masonry (URM) with hollow clay (HC) bricks are considered herein, being one of the most widespread partition typology used in RC MRF of Mediterranean building stock.

Starting from the whole database (see Fig. 1), 105 one-bay-one-storey tests with RC frames and, in particular, first of all the tests without opening (89) have been selected. Sixty of these tests were completely described by the Authors of the experimental campaigns, including the description of the infill panel damage evolution, but only in 38(/60) cases the experimental response related to the corresponding bare frame was also explicitly presented by the Authors. Therefore, starting from the 89 tests about infill panels without openings, only 60 are useful for the purposes of this study. In particular:

- 39(/60) tests are characterized by a description of the infill damage depending on the imposed lateral displacement, which can be associated with the DSs defined and adopted herein;
- for 38(/60) tests, it was possible to evaluate the experimental response of the infill panel, since it was provided by the Authors or explicitly calculated as the difference between the response of the infilled RC frame and the corresponding bare frame (as explained later in Section 3); 17 of these 38 tests are characterized by the complete description of the damage evolution to the infill panel.

Main geometrical properties related to such 60 tests are reported in Tables 1 and 2, where H and L represent height and length of the RC