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Modelling of masonry infilled RC frames subjected to cyclic loads: State of the art review and modelling with OpenSees

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ABSTRACT

Reinforced concrete frames with unreinforced masonry infill walls represent a widely adopted building system. During seismic events, infill walls, usually considered as non-structural elements, may significantly affect the characteristics of the system in terms of in-plane stiffness, strength, and energy dissipation capacity. The assessment of framed structures infilled with unreinforced masonry walls has been investigated since the 1950s. Developing reliable numerical models of infill walls has become an important issue since then. The analytical simplified model based on equivalent diagonal struts is often used to assess the infilled frames response. The nonlinear behavior of the equivalent diagonal strut is usually described by constitutive laws that account for the stiffness, the strength and the hardening or softening behavior of the infill. The present work focuses on the evaluation of various parameters needed to define the monotonic and hysteretic response of infill walls modelled by equivalent struts. In order to select a simple and reliable analytical model that suitable for representing the infill wall response, different strut formulations and hysteretic models have been analysed in detail and used to reproduce several experimental tests available in the literature. The numerical analyses are performed by means of the *OpenSees* computer program. Three uniaxial material models available in *OpenSees* are used to assess their capability in reproducing the experimental hysteretic response. Finally, from the comparison among different models and between numerical and experimental results, suggestions are made to properly model the in-plane non-linear response of infills.

1. Introduction

Reinforced concrete (RC) frame buildings with unreinforced masonry (URM) infill walls, henceforth denoted as masonry infilled RC frame structures, are widely used in building constructions. Damage observation from past earthquakes (e.g. [1–3]) show that the seismic response of these buildings is strongly affected by the presence of masonry infill walls. The URM infills may increase lateral stiffness, strength, and energy dissipation capacity of the bare RC frame [4–6]. The presence of the infill walls on the bare frame might induce unexpected forces distribution and lead to local collapse when it is subjected to cyclic loading [7]. These effects depend on the infills geometrical distribution in plan and elevation, infill mechanical properties, infill aspect ratio, configuration of openings, and construction methods [6,8].

The seismic behavior of masonry infilled RC frame buildings has been investigated since the 1950s. Many experimental studies were conducted (e.g. [9–18]) to investigate the response of infill walls and their interaction with the surrounding RC frame. Concurrently, analytical studies have been carried out by researchers (e.g. [4–6,19–25]) to model and evaluate the performance of these buildings under both monotonic and cyclic loads. Although there are numerous studies in the literature, the issue related to the assessment and the modelling of masonry infilled RC frames remain unresolved. Lack of a standardized guideline on how to configure an infill in a global seismic analysis of infilled frames is a main issue. Besides, the infill influence on the seismic behavior of framed structures is widely recognized but how it is incorporated in the design process differs noticeably from one country to another [26]. Nevertheless, masonry infill walls are often neglected in the design process and analytical modelling, and are considered as non-structural elements.

Reliable analytical methods are needed for the assessment of infilled framed structures [6]. This task is rather challenging due to the complex interaction between the frame and the infill, particularly in the nonlinear range. Moreover, the selection of the most appropriate model is related to the analysis overall objectives:

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the evaluation of local interaction effects requires the adoption of detailed models whereas for the assessment of global response, simpler models, capable of combining simplicity and accuracy are more appropriate. In this regard, macro models, which involve replacing the masonry infill with one or multiple equivalent struts, offer a good compromise between efficiency and precision [6,21], provided that proper rules are adopted for the definition of the struts mechanical characteristics. As the masonry wall is a non-homogenous anisotropic material, a valid constitutive law is difficult to find. Previous studies highlighted that the application of different equations to estimate the equivalent strut parameters lead to noticeable differences in the infilled frames response [7]. Consequently, selecting adequate models for the analyses of masonry infilled RC frames is imperative.

The aim of this study is to develop general guidelines for evaluating the parameters to define the monotonic and hysteretic response of the masonry infill walls, specifically for the in-plane lateral cyclic response. Outline of the paper is as follows. First, various modelling approaches available in the literature are reviewed. Specific attention is devoted to the single-strut modelling method, in which the many different formulations are discussed and compared. Afterwards, numerical analyses of several one-story, one-bay infilled RC frames tested experimentally are performed through the Open System for Earthquake Engineering Simulation (*OpenSees*) software package [27]. These analyses are dual-purpose: (i) identify the most appropriate formulae for the definition of the strut constitutive law and (ii) verify the suitability of numerous material models available in the *OpenSees* [27]. From the comparison among different models and between numerical and experimental results, suggestions are made to properly model the in-plane non-linear response of masonry infilled frames.

2. Modelling approaches for masonry infilled RC frame

Comprehensive reviews on the experimental, analytical, and numerical research works by Crisafulli et al. [28], Shing and Mehrabi [29], Asteris et al. [6,7], and Tarque et al. [23], categorized five main failure mechanisms of the infilled-frames: (1) the corner crushing (CC) mode; (2) the sliding shear (SS) mode; (3) the diagonal cracking (DK) mode; (4) the diagonal compression (DC) mode, and (5) the frame failure (FF) mode. The first failure mode, CC, occurs when a weak masonry infill panel is surrounded by strong frame members and the connection between the infill and the frame is weak. The second failure mechanism, SS, which is given by the horizontal sliding through multiple bed joints at approximately mid-height of the panel, occurs when the strength of mortar joints is low and the infill is surrounded by a strong frame. This failure mode also introduces the short column behavior, in which plastic hinges develop at mid-height of the columns. This can also lead to the shear failure of the columns. The third failure mechanism, DK, that takes place when the frame is more flexible than the masonry infill, consists of a crack along the compressed diagonal of the masonry infill panel, which might be joined with a horizontal crack at the mid height of the panel. The fourth mechanism, DC, displays crushing at the centre of the masonry infill panel due to high compression forces. Masonry crushing may also develop when a slender flexible infill experiences large out-of-plane deformations. The last mechanism, FF, consists of a purely flexural mode, in which there is no separation between the infill and the frame under a low load level. Under a moderate load level, if the infill panel and bounding frame are not properly tied together, the infill panel will separate partially from the frames and flexural hinging at the top and bottom of the column will develop. This failure mode is particularly important when investigating the existing structures, which in many cases display the frame weaknesses. The general conclusion from these studies is that different failure modes may develop depending on the infill and frame relative stiffness.

The possible failure mechanisms described above are only for solid infill walls (without openings). Previous studies also involved experimental work on masonry infill walls with openings [12,14,29–33]. Experimental results highlighted that masonry infills wall with openings can still enhance the performance of RC frames, in terms of resistance, stiffness, ductility, and energy dissipation capacity, but to a lesser extent than a solid infill wall. An experimental study by Kakaletsis and Karayannis [12,14] reported that masonry infills with an opening crack and detach from the bounding frame at an early stage before the column yielding. The location of the openings also influences the global performance [30,33]. Moreover, when the frames are only partially infilled, short column effect consisting in a brittle shear failure may develop. However, there are inconsistent evidence were accumulated whether the openings lead to a more brittle or more ductile behavior than the solid infill wall [34].

Theoretically, the knowledge of both the geometric properties of the infill and of the cyclic behavior of the masonry material should allow a straightforward modelling. The intricate infill-frame interaction lead to diverse possible modelling assumptions characterized by different computational efforts and accuracy [35]. Different approaches have been developed and validated with experimental test results for the modelling of masonry infills in order to capture the different possible failure mechanisms that take place in infilled RC frames. They are divided into two main groups based on the modelling approach: micro-modelling technique e.g. [4,36] and macro-modelling technique [20,41]. A third approach, which have similar precision with micro-modelling technique, is known as the meso-modelling technique [7,23]. These approaches differ mainly in the degree of their infill panel modelling detail, as described in the following sections.

2.1. Micro-modelling and meso-modelling

The micro- and meso-modelling approaches using nonlinear finite element (FE) methods are able to provide an accurate description of the interaction between the frame and infill at the local level [4]. The micro-modelling approach includes two different modelling strategies: the detailed and the simplified micro-modelling [36]. The former is based on the use of continuum elements for masonry units and mortar joints, whereas the unit-mortar interface is represented by discontinuous elements (three-phase material) for the simulation of fracture behavior in brick units and mortar joints [11,7,34]. The latter resorts to expanded units represented by continuum elements and the discontinuous elements (two-phase material) for the mortar joints and the unit-mortar interface [7,8]. The response of each element is described through proper constitutive relations. Chiou et al. [37] developed several plasticity-based continuous interface models to capture the shear sliding in the joint.

In the meso-modelling approach (one-phase material), units, mortar, and their interface are smeared out and the masonry is treated as a continuum through a homogenization process [7]. Contact, gap or spring elements can be considered for modelling the interface infill-frame, allowing the separation of the infill from the bare frame [38]. Smeared crack elements can be used to model both reinforced concrete frames and brick infills. For instance, in the analyses reported in [19,39], infill panels are modelled as a homogeneous material before fracture, and the effect of mortar joints is smeared out [29,40].

Overall, the above-mentioned methods are quite complex due to a large amount of information required for the constitutive models and high computational effort involved which lead to delayed