Engineering Structures 175 (2018) 371–385

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A 3D discrete macro-element for modelling the out-of-plane behaviour of infilled frame structures

B. Pantò[a,*], I. Caliò[a], P.B. Lourenço[b]

[a] University of Catania, Department of Civil Engineering and Architecture, 95125 Catania, Italy
[b] ISISE, University of Minho, Department of Civil Engineering, Azurém, 4800-058 Guimarães, Portugal

ARTICLE INFO

Keywords:
Seismic assessment
Infilled Frame Structures (IFS)
Out-of-plane behaviour
Simplified model for non-linear analyses
Discrete macro-model
HISTRA software
DIANA software

ABSTRACT

A high percentage of new and existing framed buildings (either in concrete or steel) are built with unreinforced masonry infilled walls leading to the structural typology known as Infilled Frame Structures (IFS). In these structures, the masonry infills are built after the construction of the main structural frame and are considered as non-structural elements. For this reason, the contribution of unreinforced masonry infills is generally neglected, in the structural analysis of IFS, leading to inaccuracies in the prediction of their seismic nonlinear response. In this paper a three-dimensional discrete element method, able to simulate the complex interactions, in-plane and out-of-plane, in IFS is presented. In the proposed approach, the infill wall is modelled by means of an original spatial discrete element previously introduced for the analysis of UnReinforced Masonry (URM) Structures. Since the attention is focused on the behaviour of the masonry infills, the frame elements have been assumed as linear elastic beams interacting with the macro-elements through plane nonlinear interfaces. In the paper, after a theoretical description of the proposed approach, several experimental–numerical comparisons are provided for investigating the out-plane behaviour of infilled frames. The achieved results demonstrate the accuracy and the significant potential of using the proposed approach for the non-linear analysis of IFS under different loading conditions.

1. Introduction

Many new and existing reinforced concrete frame structures are realised with unreinforced masonry infill walls for architectural needs leading to a composite system known as Infilled Frame Structure (IFS). IFS still represent a current solution for building new and low-cost earthquake resistant structures in many seismic densely populated regions worldwide. According to the geographical location and to the age of the construction, two main typologies of buildings can be identified: buildings designed for vertical loads only and buildings designed according to a seismic code. In all these cases, the contribution of masonry infill panels has generally been neglected in the structural design leading to inaccuracies in the prediction of lateral stiffness, strength and ductility resources of the building. However, as highlighted by many authors [1–7], ignoring the role of infill-frame interaction is not always safe, as the infill contribution to the actual structural response can lead to a substantial modification of the seismic demand. The presence of infill walls can significantly modify the stiffness, resistance and ductility spatial distribution along the structure, leading to a distribution of damage that cannot be predicted through modelling approaches not accounting for the infills' contribution. Furthermore, the out-of-plane collapse of masonry infills increases the number of injured persons or casualties, also when the structural skeleton of the building does not suffer any damage but the earthquake induced relative displacements provide heavy damage in the unreinforced masonry infills.

The seismic response of IFS is a challenging problem with relevance for the actions needed for the mitigation of seismic risk. The masonry infills contribution to the lateral stiffness and strength of the system can introduce structural irregularities often leading to soft-storey conditions or torsional behaviour. These structural scheme alterations can cause brittle or low-dissipative collapses [1]. Given the repeated field observations from damaging earthquakes, recently [8] a simplified procedure for the prediction of expected inter-storey drifts for infilled frame structures, based on the corresponding demands of bare configurations has been introduced. The procedure is based on the knowledge of a simple parameter accounting for structural properties and the presence of infills.

Some recent researches [9,10] investigated the local effects on RC frames induced by masonry infills through FEM simulation and in-plane

---

[*] Corresponding author.

E-mail addresses: bpanto@dica.unict.it (B. Pantò), icalio@dica.unict.it (I. Caliò), pbl@civil.uminho.pt (P.B. Lourenço).

https://doi.org/10.1016/j.engstruct.2018.08.022
Received 19 March 2018; Received in revised form 9 August 2018; Accepted 10 August 2018

tests. Additional shear on the frame structural elements generally arises due to the infill. New construction techniques, aimed at improving the seismic performances of RC infilled frames, have been recently proposed and experimentally tested [9]. According to these techniques, each infill is constituted by an assemblage of sub-panels connected by horizontal sliding joints. The higher system flexibility leads to a reduction of the seismic demand as well as an increase of ductility limiting or avoiding the damage on the infill and the local effects in the surrounding frame.

Several numerical and experimental contributions have been presented in the last decades in order to understand the in-plane behaviour of IFS, including the presence of openings [2–6]. However, the out-of-plane failure of the infill masonry panels often anticipates or follows the in-plane collapse, causing their brittle behaviour. The simultaneous presence of in-plane damage and out-of-plane actions sensibly reduces the strength and ductility of the infills in the out-of-plane direction. The cyclic bi-directional horizontal actions of the earthquake loading can initially lead to in-plane damage, with the partial detachment of the infill panel from the surrounding frame, and subsequently the expulsion of large portions of the panel in out-of-plane direction [6–16]. Several experimental tests have been performed, in order to investigate the in-plane [6–14] and the out-of-plane [15,16] behaviour of unreinforced masonry infills surrounded by reinforced concrete frames. These tests have been generally performed by means of applying monotonic and cyclic uniform static loads to the infill panel to simulate the effects of inertia forces, after the vertical loads were applied to the surrounding frame.

The highly non-linear masonry infill response, and the ever-changing contact along the frame-infill interfaces, make the numerical simulations of an infilled frame building a challenging problem. A detailed simulation of the complex nonlinear behaviour of infilled frames requires the rigorous use of expensive computationally nonlinear finite element models, capable of reproducing the degrading behaviour of the masonry and the complex interaction between the frame and infill. Refined numerical models, such as the smeared cracked or discrete crack finite element models [17–23], despite being able to simulate the cracking behaviour and the compressive failure of concrete in frame members and infills, often require huge computational resources and specific expertise making these strategies unsuitable for daily practical applications. More recently, the extended finite-element method (XFEM) has been adopted to model the cracking behaviour and the compressive failure of concrete in frame members as well as masonry units in infill panels, and the discrete interface element has been employed to simulate the behaviour of the masonry mortar joints and the joints at the frame-to-infill interface [24].

Consequently, it is important to develop operative tools for the nonlinear structural analysis of IFS, capable of simulating the collapse mechanisms and to assess the effectiveness of retrofitting techniques. These tools should be appropriate for practical engineering purposes but sufficiently accurate to provide a reliable structural response. With this aim, many authors have developed simplified methodologies for predicting the nonlinear seismic behaviour of IFS. According to the classification proposed in [25,26], the numerical approaches can be classified in two main categories, macro and micro models. The macro models try to grasp the global behaviour of the IFS without obtaining a detailed nonlinear response and describing all modes of local failure. On the contrary, the micro-models are conceived for a detailed behaviour simulation trying to encompass all the possible damage and collapse mechanisms.

The most commonly used macro-model practical approach is the so called ‘diagonal strut model’, where the infilled masonry is represented by a diagonal bar under compression. Since its first formulation [27], many alternative proposals for the equivalent strut have been made [28,29] taking into account the presence of openings. Some of these models try to simulate the frame-infill separation, as done in FEMA-356 [30], even if the out-of-plane failure representation is generally ignored, with exception of recent contributions [31,32]. The equivalent strut model approaches neglect the continuous interaction between the frame and the infill and generally fail in coupling in-plane and out-of-plane effects. Recently, an alternative approach for the simulation of the seismic behaviour of IFS suitable for research and engineering applications, was proposed [33–34], in which the infills are modelled by 2D equivalent mechanical macro-models while the reinforced concrete frame is modelled by beam–column elements with concentrated plasticity. This novel low cost computational tool has been applied to mixed reinforced concrete masonry structures [35–38], being suitable to assess the nonlinear seismic behaviour arising from the interaction between masonry and reinforced concrete. Although the original plane macro-element proposed in [33] allows an efficient implementation of the model in presence of openings and is able to simulate the complex contact conditions between the infill and the frame, it does not take into account the infills out-of-plane behaviour.

In previous works the authors proposed and validated first a plane macro-element [33,39] and subsequently a spatial element [40,41] to be adopted for simulating, respectively, the in-plane and the out-of-plane behaviour of unreinforced masonry buildings. According to the already proposed strategies each macro-element interacts with the adjacent macro-elements through discrete nonlinear interfaces that incorporates the mechanical characteristics of the masonry assumed as a homogenised orthotropic material. In this paper the spatial discrete macro-element, already validated for the modelling the in plane and out of plane behaviour of unreinforced masonry structures [40,41], is adopted for the simulating the behaviour of masonry infills. In this case, it is needed to numerically predict the interaction between the masonry infills and the surrounding frames, described according to a FEM approach. To this aim, a new ‘non-zero’ thickness interface, accounting for the actual dimensions of beam and columns, is here formulated. The new frame/infill interface allows efficient modelling of the complex interaction between the infill and the surrounding frame. The validation of the proposed model is achieved through the simulation of a masonry infilled frame for which experimental and numerical results are available in the literature. Aiming at investigating the influence of openings on the out-of-plane structural response a parametric numerical study is performed. The achieved results are of help for the characterization of IFS, and are preparatory for the introduction of guidelines for the design and assessment of infilled frame buildings and for the definition of code prescriptions regarding demand and capacity of masonry infills, which are currently lacking in EC6 [42] and EC8 [43].

2. In plane macro-model for infilled frame structures

An innovative hybrid FEM macro-element approach has been recently introduced and validated by the authors [33,37,38]. In this approach, the masonry infills have been modelled by means of a 2D macro-element, originally conceived for the simulation of the nonlinear in-plane behaviour of unreinforced masonry walls [34], while the frame structure has been represented by means of inelastic frame elements with concentrated plasticity. The plane macro-element adopted for the infills can be represented as an articulated quadrilateral, connected by four hinges and two diagonal nonlinear springs, whose rigid edges can interact with other elements or surrounding frames by means of distributed interfaces discretized through nonlinear one-dimensional links. Each interface is constituted by n nonlinear orthogonal springs, perpendicular to the panel side, that simulate the flexural and tensile/compression behaviour, and an additional longitudinal spring parallel to the panel edge that simulates the sliding mechanism. The diagonal shear behaviour of the panels is simulated by the two diagonal nonlinear springs.

Fig. 1 shows discretizations of infilled frames with and without a central door opening. Fig. 1a, d provide the geometrical layouts of the infilled frames, Fig. 1b and e report the corresponding discretization according to the basic needed mesh while the representations of Fig. 1c,