Engineering Structures 143 (2017) 603–616

Contents lists available at ScienceDirect

Engineering Structures

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

Development of a detailed 3D FE model for analysis of the in-plane behaviour of masonry infilled concrete frames

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ARTICLE INFO

Article history:
Received 17 October 2016
Revised 4 April 2017
Accepted 6 April 2017
Available online xxxx

Keywords:
Concrete masonry infills
RC frame
In-plane behaviour
Finite element
Failure surface
Mortar dilation
Fracture energy

ABSTRACT

This paper detailed the development of a numerical model for simulating the nonlinear behaviour of the concrete masonry infilled RC frames subjected to in-plane lateral loading. The ABAQUS finite element software was used in the modeling. Nonlinear behaviour as well as cracking and crushing of concrete and masonry blocks were simulated using the Concrete Damaged Plasticity (CDP) model. The cohesive element method combined with hyperbolic Drucker-Prager and shear and tensile failure criteria were used to capture the possible failure mechanisms in mortar joints. Concurrent with the finite element modeling, an experimental study was also conducted and results of masonry infilled RC frame specimens incorporating infill openings and interfacial gaps were used to validate the model. The validation showed that the model can accurately simulate the behaviour and predict the strength of masonry infilled RC frames. A sensitivity study was subsequently conducted where the influence of mortar joint failure surface parameters, mortar dilatancy, and fracture energy on the lateral behaviour of infilled RC frames was investigated. Results showed that the in-plane behaviour of infilled RC frames was significantly affected by the input parameters of mortar failure surface and dilatancy and less affected by those of mortar fracture energy.

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1. Introduction

Masonry walls are often used to infill reinforced concrete (RC) or steel frames in modern construction to act as either interior partitions or exterior cladding. It is understood that if an infill is built in tight contact with its surrounding frame, its inherent large in-plane stiffness will attract large forces to the frame region and in turn alter the dynamic characteristics of the entire structure. Thus, an accurate assessment of the infill-frame interaction is crucial for a safe design. However, the frame, commonly made of steel or reinforced concrete materials, deforms in a ductile and flexural mode while the masonry infill, made of brittle materials, tends to deform in a shear mode. This difference in behaviour, coupled with development of inelasticity of both materials at high load levels, makes it difficult to quantify the exact extent of the infill-frame interaction for the entire loading history. For the past six decades, both experimental and numerical studies [1–9] have been conducted in an effort to provide rational methods for considering the infill contribution to the system stiffness and strength. The diagonal strut method has then emerged as the most adopted method for evaluating the capacity and stiffness of infilled frames. In this case, the infilled frame may be considered as a braced frame where the infill is replaced by a diagonal strut connecting loaded corners. Once the strut width is known, a simple frame analysis can be performed to determine the stiffness of the system. The strength of the infill can also be related to the strut width. Based on the diagonal strut concept, much research work was contributed to the development of this method to incorporate effects of material nonlinearities, various failure mechanisms, geometric properties of the infill and frame, and boundary conditions [8,10]. The effect of infill openings, infill-to-frame interfacial gaps, and vertical loading on the infill behaviour was investigated in more recent research [1,3,7,11–14].

With the development of computing technology in the last two decades, numerical modeling encoded in computer programs has been increasingly used to simulate the behaviour of masonry infilled frames. Both finite element methods (FEM) [4,6,15–17] and discrete element methods (DEM) [18,19] have been employed in modeling with the former being the more popular one. While the DEM is robust in simulating mortar joint effect between blocks, it is quite limited in providing different geometry and material models for continuums such as the block itself or frame members.

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http://dx.doi.org/10.1016/j.engstruct.2017.04.049
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In the case of reinforced concrete frames, interaction between reinforcing bars and continuum medium of concrete cannot be adequately defined using DEM. In this study, the FEM was used and thus the following literature review is focused on studies of FEM in masonry infilled frames. Mehrabi et al. [4] developed interface models for shear cracking of concrete and mortar joints as well as bond-slip behaviour of steel bars in concrete. Lotfi and Shing [20] developed a smeared crack formulation to account for nonlinear behaviour of masonry blocks and concrete in infilled RC frames. Al-Chaar et al. [21] adopted smeared crack quadrilateral elements for masonry blocks and cohesive interface model for simulation of mortar behaviour and shear failure of concrete. Stavridis and Shing [15] proposed a 2D simplified micro-model for analysis of masonry infilled RC frames adopting the cohesive crack interface elements developed by Lotfi and Shing [22] to consider mortar effect. Mohyeddin et al. [16] used a 3D simplified micro-model in which the mortar at joints was halved and an elastic interaction model was defined between the two mortar layers. Minaie et al. [23] used Concrete Damaged Plasticity (CDP) model in ABAQUS to investigate bi-directional loading behaviour of fully and partially grouted masonry shear walls. Despite that previous numerical studies have shown capability of FE models in simulation of masonry infills or masonry shear walls, some limitations of these models are noted as follows. Although simple to use, the 2D models were not adequate to capture many aspects of infilled frames such as non-typical geometric properties, stress concentration, local reinforcement effects, and out-of-plane behaviour. For the existing 3D model studies, there is commonly a lack of information provided on the input material parameters, which makes it difficult for others to reproduce the model and associated results. Moreover, these models were calibrated against test results of a specific type of masonry infill and bounding frame, their effectiveness for a wide range of material and geometric parameters was not investigated.

In view of the above, this study was then motivated to develop a 3D finite element model to study the in-plane behaviour of masonry infilled RC frames. Encoded in ABAQUS software, the model development, analysis procedure, and input parameters were described in detail in this paper. Concurrent with the finite element modeling, ten masonry infilled RC frames were tested and experimental parameters included interfacial gaps and infill openings. Detailed validation of the model against experimental results was discussed. Once verified, the model was used in a sensitivity study of several critical material input parameters on the behaviour and strength of infilled RC frames. Recommendations were provided on the efficacy of the model in simulation of infilled RC frames covering a wide range of these parameters.

2. Experimental program

The experimental program, conducted by the same research team, involved the testing of ten masonry infilled RC frames subjected to a monotonically increased lateral load to failure. The objectives of the experimental program were to provide test results to 1) investigate the behaviour of masonry infilled RC frames as affected by infill openings and infill-to-frame interfacial gaps; and 2) validate the numerical model. Information on test specimens, test setup, and results deemed relevant to this paper is provided in the following section. A detailed description of the test program and discussion of results can be found elsewhere [24].

Ten specimens included one bare frame (BF), one infilled frame control specimen (IFNG), four infilled frame specimens with interfacial gaps between either the top frame beam and the infill (IFTG) or the frame columns and the infill (IFSG), and four infilled frame specimens with window or door openings (IFW and IFD). Table 1 presents a detailed description of the test specimens.

All infilled frame specimens had the same dimension as shown in Fig. 1, yielding a height-to-length aspect ratio of about 0.73. The masonry infill was constructed using the custom-made, half-scale 200 mm standard concrete masonry units laying in the running bond. The interfacial gaps for those four specimens were achieved by adjusting the thickness of the mortar joints. The RC frame was designed according to CSA A23.3 2004 [25] and reinforcement detailing including size, spacing, arrangement of longitudinal bars and stirrups complied with requirements to provide ductility and avoid brittle shear failure.

2.1. Test setup and instrumentation

The experimental set-up is illustrated in Fig. 2. The specimens were connected to the strong floor through high strength bolts and the lateral load was applied at the top beam level using a hydraulic actuator with a capacity of 250 kN. Two linear variable differential transformers (LVDTs) (LVDT 1 and 2) were mounted at the centerline of the top and bottom beam respectively to measure the in-plane lateral displacements. Another two LVDTs (not shown) were positioned at the half height of the masonry infill wall and at the central point of the top beam respectively, both on the back side, to monitor any possible out-of-plane movements of the infill wall and the concrete frame, respectively.

2.2. Material properties

The mechanical properties of CMUs, mortar, and masonry prisms for the infill and those of concrete and reinforcement for the frame were obtained experimentally in accordance with ASTM specifications. A summary of the material properties is presented in Table 2.

3. Finite element model

In this study, the so-called simplified micro-modeling approach [17] was adopted and the key characteristic of this approach is that the mortar joints are not physically modeled, rather, they are replaced with zero-thickness interface elements. The geometry and the meshing of the model is shown in Fig. 3. The ABAQUS software was used in the model development. The concrete masonry units (CMU) as well as RC frame members were modeled using solid elements. The CMU dimensions were increased by the half thickness of the mortar joint in both horizontal and vertical directions so that the discrete CMUs were connected and interact with each other through zero-thickness interface elements. The simplified micro-model was shown to provide desired accuracy [2,4,15,17] and is considered as a more computing efficient modeling technique than a detailed micro-modeling approach where mortar joints are modeled. The following sections describe modeling details of each component of the infilled frame. It is noted that while ABAQUS provides the general material constitutive and interfacial behaviour models for different structural applications, the contribution of this study lies in the determination of appropriate models and critical material parameters, and conducting computationally efficient and accurate simulation of masonry infilled RC frames.

3.1. Nonlinear behaviour of concrete and CMUs

Different from ideal brittle materials such as glass, concrete and CMUs are considered as quasi-brittle materials with high toughness after subcritical cracking [26]. The Concrete Damaged Plasticity (CDP) model for quasi-brittle materials in ABAQUS [28] was used to simulate the behaviour of concrete and CMUs in this study.

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