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On the prediction of shear brittle collapse mechanisms due to the infill-frame interaction in RC buildings under pushover analysis

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ABSTRACT

A large number of research studies deal with the modeling and analysis of infilled reinforced concrete (RC) buildings under seismic actions, at the aim to understand the actual contribution given by masonry infills to the overall seismic resistance of a building. In this paper this aspect is investigated in the framework of pushover analyses, describing the theoretical and computational choices related to the involved parameters. Differently from the approaches available in literature and standards, the "double-strut model" is adopted to simulate the infill behavior, according to which an infill panel is represented by two equivalent non-parallel struts; the peculiarity is that the positions of the extremities of the two struts coincide with the points of application of the stress resultants on each side of the panel. The results show that, by adopting the double-strut model, it is possible to capture dangerous local shear failures which are usually neglected in pushover analysis and which can compromise the safety of the overall structure. By including in the analysis shear plastic hinges together with bending ones, it is evident how the additional shear forces, arising at the extremities of beams and columns, can substantially change the collapse mechanism of a structure under seismic action. The main features of the double-strut model are its low computational cost together with its accuracy, which make it particularly suitable for applications in the engineering practice. In fact it could be easily implemented in commercial calculation codes, representing a practical predictive tool able to enhance the safety level of infilled RC buildings.

1. Introduction

In Italy existing RC buildings are often characterized by the presence of infill panels which can interact with the primary structural elements under seismic action. A large number of research studies show that the presence of infilled panels in RC framed buildings can lead to conflicting effects on the structural response, depending on the mechanical properties, the geometrical distribution of infills and the interaction with the structural elements. Even if an increasing of structural stiffness and strength is expected, it is recognized that non-ductile damage mechanisms may be activated both at local (short column effect, brittle local failure, damages in joint region) and global scale (soft storey damage) [1–3].

With reference to a single frame, the increase in strength mentioned before is associated to an increase in the demand of shear capacity in some specific sections. Under lateral actions, the infill panel partially disconnects from the frame, remaining in contact with it only in correspondence of two opposite corners. RC frames (beams, columns and joints) can absorb the consequent increase of force, occurring in them due to their higher stiffness, only if they have sufficient shear overstrength. In the case of strong masonry infill, that is in the case of panels combined with frames having a low shear reinforcement, the activation of local brittle collapse mechanisms can become a major question and compromise the safety of the entire structure [4,5]. Fig. 1 shows the critical zones affected by the described local shear failure mechanisms due to the frame–infill interaction, while real case pictures can be found in [6].

This aspect of the frame-infill interaction constitutes the central issue of the present study, mainly referring for the previous considerations to existing buildings.

In the engineering practice, simplified macro-models approaches are often adopted to account for the influence of infills in structural analyses, also according to the specifications furnished by technical codes on this topic [7–9]. In particular the single equivalent strut method, based on the observation that the load path within the infill panel mainly follows the diagonal direction and introduced for the first time by Polyakov [10], is the most used one [11,12]. Such simplified approaches can be particularly

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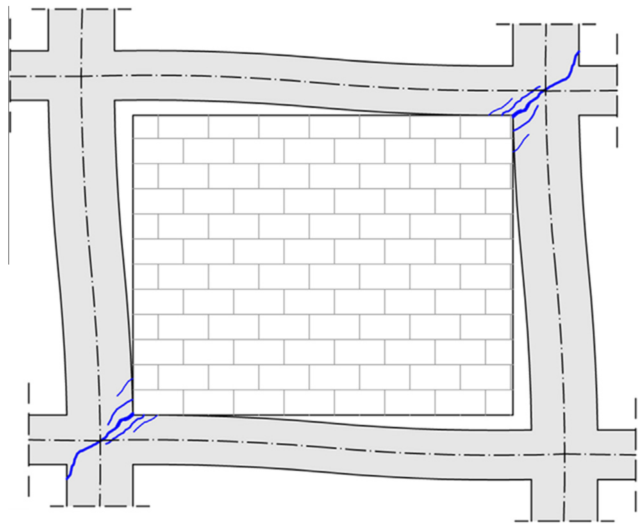

Fig. 1. Transmission of forces from the masonry panel to the surrounding reinforced concrete frame under seismic actions.

appropriate in the cases when the goal is the evaluation of the global structural displacement demand; on the contrary they are not able to capture the possible influence of infills on load-bearing structural elements due to local effects, as a consequence of which unexpected brittle collapse mechanisms can occur under seismic action [13]. More complex macro-models adopt multiple parallel diagonal struts (two or three) in the attempt to reproduce these effects [14–17]. In particular, among the studies carried out on this regard, El-Dakhakhni et al. [18] introduced a three -strut model at the aim to reproduce a reliable distribution of bending and shear forces on the frame elements. Chrysostomou et al. [19], in order to account also for the stiffness and strength degradation of infills, proposed a model with six compression inclined struts, i.e. three parallel struts for each diagonal direction, with the off-diagonal ones positioned at critical zones along the frame elements.

Liauw and Lee [20] investigated the efficacy of the diagonal strut model for masonry infills with and without openings, showing that the position of openings can significantly affect the strength and stiffness of panels.

Crisafulli and Carr [17] proposed a detailed multi-strut macro-model including both the classical diagonal truss elements and a special shear frictional strut aimed at reproducing the effect of vertical loads on the overall strength of the masonry infill. Recently the influence of vertical loads and openings has been further investigated by Campione et al. [21] and Asteris et al. [22].

Nevertheless the process of definition of the mechanical properties to attribute to the equivalent struts, as well as in which way taking into account the frame-infill stiffness ratios, are not clear yet, above all within nonlinear analyses [23–25].

The present paper focuses on the above aspects, underlining how a careful definition of the equivalent strut properties is of exceptional significance for achieving a realistic building response.

At this purpose two different panel macro-models are considered, the single equivalent strut model [11,12] and the double strut model proposed in [26], with the objective to point out how the collapse mechanisms can substantially change in the two configurations. Suitable nonlinear static analyses are thus carried out on a significant framed RC building, selected as case study and modeled in 3D, at the aim of appraising the influence of infill panels over the global and local collapse mechanisms under seismic action. In order to allow a critical comparison and deduce some observations about the infill modeling, three configurations are considered: the bare frame, the infilled frame and the frame with infills in correspondence of all storeys except for the first one (soft storey).

The theoretical and computational choices related to all the steps of the pushover analysis are accurately described in the paper. The final goal of the proposed study is in fact to provide a practical tool for the prediction of the real distribution of shear demand in frame critical sections when a macro-modeling approach is used within non linear static analyses. A first strategy in this direction is proposed in [6], where the local shear forces acting on beam and column ends is expressed as a fraction of the axial load experienced by the equivalent single strut. However the method, tested exclusively for specimens having two different aspect ratios, could result rather onerous to be implemented in commercial calculation codes. In this framework the double-strut approach may represent an effective predictive tool for the accurate evaluation of frame-infill interaction effects in pushover analysis, since it could be easily implemented in commercial codes and could be applied for each dimension of panel frames. These topics are of crucial importance considering that the correct simulation of local brittle failures represents a major question in order to guarantee a proper safety level of infilled RC buildings.

2. Masonry infill model parameters

Based on the analytical and experimental studies carried out in the last decades, five different failure modes of masonry infilled frames can be recognized: Corner Crushing mode (CC mode), representing crushing of the infill in at least one of its loaded corners; Sliding Shear mode (SS mode), representing horizontal shear failure through bed joints at mid-height of a panel causing the cracking for sliding; Diagonal Compression mode (DC mode), representing crushing of the infill in the middle; Diagonal Cracking mode (DK mode), representing cracking across the compressed diagonal of the infill panel; Frame Failure mode (FF mode), in the form of plastic hinges in the columns or in the beam-column connection [14,27].

Mixed collapse modes can also occur. It is worth noting that only the CC and SS modes are of practical interest. In fact the DC mode is very rare and can just occur in presence of a high slenderness ratio of the infill that could cause out-of plane buckling under in-plane loading. Similarly the DK mode and the FF have not particular interest since the first one does not represent a real failure mode, due to the circumstance that the panel still carries significant load after cracking, and the second one hardly occurs.

So the study herein carried out focuses on the CC mode, which first of all is coherent with the failure mode reproduced by both the single-strut model and the proposed double strut model [26] and also represents the most common modality of cracking of infills.

The fundamental parameters governing an equivalent strut model are: the number and position of struts; the width of the strut; the constitutive relationship of the panel, reproducing the failure mode. Due to the uncertainties and the extreme variability characterizing the mechanical properties of the infill, the definition of the above parameters presents some critical aspects that if not properly managed can compromise the reliability of the results.

The following sections provide some specific comments on the calibration of the panel macro-models to be used in pushover analyses.

2.1. Choice of the macro-model

In the research study herein presented two macro-models are adopted to simulate the behavior of infill panels: the single equivalent strut model (Fig. 2a) [11,12] and the double-strut model [26] (Fig. 2b).