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Review article

Numerical modelling of out-of-plane response of infilled frames: State of the art and future challenges for the equivalent strut macromodels

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ABSTRACT

Infill-frame interaction constitutes a still open question both in research and in practicing engineering. Computational models used to predict this interaction are, in most cases, addressing the estimation of the response of the infilled frames when subjected to actions parallel to their plane. However, the observation of the post-earthquake damage has demonstrated that infills, weakened by the in-plane actions, may fail out-of-plane increasing the risks associated to the earthquake scenarios. In spite of this, different studies have shown that infills, if properly designed and supported by the frame, exhibit a significant strength and displacement capacity when called to resist to out-of-plane actions, offering the possibility to develop an arching mechanism in their deformed configuration. The prediction of the combined in-plane out-of-plane response prefigures the new goal of the seismic assessment of masonry infilled frames.

This paper presents an in-depth literature review of the capacity models developed for the prediction of the out-of-plane response of infilled frames, from the first flexural based computational models to the models implementing the arching action theory in their formulation. A comparison between the results obtainable is provided in order to compare the models reliability against the results of different experimental tests. A final discussion is devoted to the effectiveness the recent integrated in-plane/out-of-plane macromodels used in 3D structural models. A new promising approach, based on the use nonlinear fiber-section elements, is also outlined providing a numerical testing of the capacity of such elements to naturally account for the out-of-plane arching mechanism.

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1. Introduction

The interaction between masonry infills and framed structures (reinforced concrete or steel) has been studied for 60 years because of its recognized fundamental role in seismic performance of constructions. Predictive models are nowadays constantly updated as is their implementation in the most recent and powerful FE analysis programs. In this time frame, the majority of the studies concerning the behavior of infilled frames have regarded the in-plane (IP) interaction as of major relevance in the overall response. Infills produce a large increase of stiffness with respect to the one owned by the bare structures and substantially modify their dynamic response [1,2]. A simultaneous increase of strength is also recognized and is accompanied by a significant modification of the collapse modalities involving overall the structural complex [3–5].

Equivalent strut macromodels [6–13] comprise the most effective way to practically include in structural models the strengthening and stiffening effects provided by the infills, overcoming the large computational effort required by the refined FE micromodels [14–17]. Despite this, equivalent struts are purely phenomenological models. They don't reproduce exactly the physics of the original systems and, because of this, they may neglect important information such as the local shear transfer in contact regions [18,19].

The large number of experimental and analytical studies carried out to understand and predict the in-plane behavior of the infilled frames is not accompanied by as many studies investigating the out-of-plane (OOP) response of infills. However, this constitutes a quite relevant issue influencing seismic assessment of constructions and safety of people. During earthquakes, infills are in fact subjected to inertial forces normal to their plane which, in dependence of the infills characteristics and the damage produced by the simultaneous in-plane actions, may cause their collapse out of plane and constitute a further risk for the populations involved.

In other cases, the out-of-plane collapse may occur as a consequence of a prior in-plane damage experienced by the infills in previous earthquakes. Because of their in-plane stiffness, masonry infills attract a large amount of shear action. A typical x-pattern of cracks may occur even after moderate earthquakes, weakening infills and making them vulnerable to possible further shakings involving their out-of-plane capacity. Nevertheless, it is also true that if infills are not too slender and the boundary frame is adequately stiff, they can exhibit a significant strength and displacement capacity against actions normal to their plane.

Several studies have in fact demonstrated that masonry infills when subjected to OOP actions can resist even to large loads by the development of a resisting arching mechanism (Fig. 1a). Moreover the typical crack patterns observable after OOP experimental tests (Fig. 1b) suggest that the behavior of the infill, restrained by the surrounding frame, can be assimilated to that of a plate. The arching effect has therefore a 2-way generation.

Despite the fact that most theories agree in recognizing the aforementioned out-of-plane behavior for the infilled frames, their results are often conflicting. In most cases this may be justified by substantially different choices in the reference experimental programs.

With the scope to provide an outline of the literature models available for the prediction of the out-of-plane behavior of masonry infills, this paper presents a thorough state-of-the-art review highlighting from time to time the progress achieved in the characterization of the response. The literature review starts from the first computational models on the determination of the ultimate load, based on the simple flexural capacity of the panels, covering up to those including arching mechanism and two-way action.

A reliability comparison is also provided for the most prominent models presented, testing their capacity to predict the results obtained against different experimental tests. The issues related to reciprocal in-plane out-of-plane damaging are also discussed by presenting the results of massive experimental campaigns. The most recent developments provide the integration of interacting IP-OOP macromodels in 3D structural models. The features of the very recent 3D macromodels are presented, highlighting their qualities and limitations.

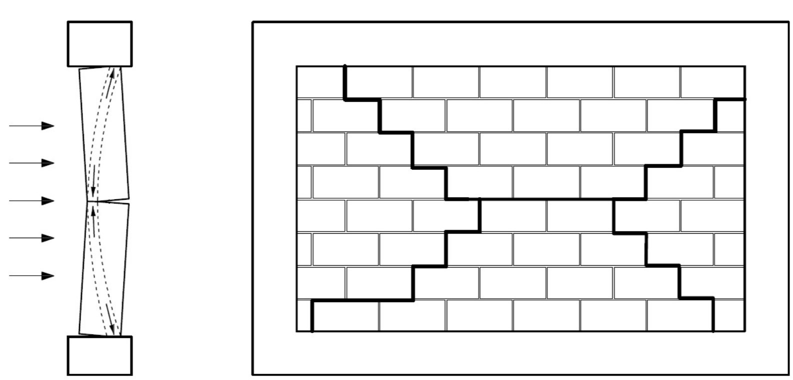
Considering the results of the experimental and analytical research works presented, the paper finally outlines the future perspectives in using macromodels for the simulation of the combined IP-OOP response. From the mathematical formulation of nonlinear fiber-section elements, a possible way to overcome the limits contradistinguishing the previous models is presented. The capacity of fiber elements to develop the out-of-plane arching mechanism is finally tested numerically on a reference infilled frame.

2. Models for prediction of the out-of-plane capacity

2.1. Flexural action based models

The out-of-plane capacity of the infills is generally measured by the maximum uniform lateral pressure causing the collapse of the panel. The majority of the analytical formulations appearing in the literature are devoted to the research of this value. The first solutions for the determination of the maximum lateral pressure were derived from Timoshenko theory [20]. Considering linearly elastic, isotropic, homogeneous material having a given tensile strength f_t, the maximum lateral pressure q_u could be calculated as

$$q_u = \frac{f_t}{6\beta_1 \left(\frac{h}{t}\right)^2} \tag{1}$$



(a) (b)

Fig. 1. Out-of-plane mechanism: (a) Development of the arching effect for OOP actions; (b) Typical OOP cracking pattern.