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Resistance of reinforced concrete frames with masonry infill walls to in-plane gravity loading due to loss of a supporting column

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ABSTRACT

This paper focuses on typical infilled masonry reinforced concrete (RC) frame buildings, and their action in the course of an extreme event. An extreme event (i.e. local impact, blast or earthquake) may severely damage a supporting frame column and lead to a full or partial progressive collapse of the frame (or building). The increasing frame deflection at the point of the missing column support under the action of gravity loading may be restrained due to the structural resistance of the masonry infill wall and its composite action with the surrounding RC frame. In this study the composite action of masonry infilled walls is examined through laboratory experiments of simplified specimens comprising of a masonry wall surrounded by a RC frame. It aims at evaluating the contributions of infill masonry walls, in an attempt to examine the infill masonry wall added resistance to the bare frame and its possible contribution to prevent progressive collapse. Results of laboratory tests that have been conducted on half scale seven reinforced concrete infilled frames without a supporting column, under monotonic vertical loading along that column axis, are presented. The results indicate that masonry infill walls considerably increase the frame resistance to a vertical load action, compared to the resistance of a bare frame (around 280% on average and up to 500%). Masonry block type and column shear connectors have a major effect on the mode of failure. Reinforcement details have a pronounced effect on the frame performance; the proposed improved reinforcement details increase the resistance by almost 100%.

1. Introduction

Reinforced concrete frames with unreinforced masonry infill walls are commonly used worldwide in residential and public buildings. In recent years more attention is given to extreme loads on structures such as impact and blast, and to other resulting modes of damage including progressive collapse. The latter may result from a local severe damage of a supporting column of the RC frame at the ground story level. The local severe column failure is responsible for a support loss the effect of which may affect the entire frame or structure or a major part of it and cause partial or full collapse. A resulting downward displacement of the damaged column may distort a bare RC frame that is supported on that column thus producing bending that exceeds its capacity and cause failure. In the case of an infilled frame, the infill masonry may interact with the RC frame, restrain its deformation, increase its stiffness and capacity and help redistributing the loads to neighbouring spans thus inhibiting the possible collapse with an alternative stable load path. Despite its importance this problem has hardly been addressed and most of the attention has been given to infilled masonry walls subjected to lateral loads, with relevance to earthquake loading. The few experimental studies aiming at investigating the RC infilled frame behaviour were related to interior column loss [1–3]. There are no experimental studies on the composite wall behaviour in the case of peripheral column loss, although the peripheral column is more likely to be damaged, in case of car collision or a nearby explosion in proximity to the building façade.

1.1. Masonry infill wall modelling in column loss analysis

Usually the unreinforced masonry infill walls are considered by the designer as non-structural and are not taken into account in the structural design. Several experimental and numerical analysis studies aiming at evaluation of the RC building resistance to progressive collapse have been carried out and reported in the literature. These studies may be subdivided into two main groups that differ with regard to the infill wall model. In the first group the infill wall is modelled with a continuum linear shell element [4]. This model cannot account for cracking and is suitable for the linear infill wall behaviour only. The second group uses strut

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elements to model the infill wall. Usually a single strut is used that is connected to the beam-column joints [4–6]; in several studies multiple struts are used as well [7]. The single strut approach does not allow evaluating the real bending moment and shear forces in the RC frame as they do not simulate the interaction between the infill wall and the surrounding frame. The multiple struts with off-diagonal struts introduce discrete contacts with the RC frame however these are simplified models with a pre-determined contact with the frame that is not related to the variable continuous contact pressure distribution between the masonry infill and the RC frame. In all these studies the infill wall properties are taken on the basis of earlier experimental, analytical and numerical studies of the frame-infill wall composite behaviour under the action of a lateral load rather than of a vertical load. This is mainly due the lack of knowledge regarding the composite wall behaviour under the action of a vertical load that the present paper aims at investigating. A brief overview at the case of a lateral force action is given in the following.

1.2. Frames and infill masonry wall behaviour under lateral load

The behaviour of RC infilled frame buildings under a strong earthquake is very much dependent on the composite action of the frames and the infill masonry walls that provide considerably larger shear resistance. Therefore, over the last decades extensive efforts have been made to investigate its behaviour. Many of these studies focused on a typical single bay, single story wall in a building, with commonly locally used types of masonry blocks. Extensive studies examined several major governing parameters such as: the wall geometry, window opening in the wall, type of the masonry blocks and their geometry, frame's beam and column stiffness, reinforcement details in the RC frame, construction method of the wall, effect of vertical load, etc. [8–14]. Some of the studies were extended to include the overall building parameters such as the number of stories and number of bays [10,15,16]. Buildings in Israel are built mainly with hollow concrete masonry blocks or with lightweight autoclave-cured aerated concrete (AAC) masonry blocks. They differ from other types of bricks that are being used in many other countries and are the typical masonry infill that had been used in many of the above mentioned experimental studies. Therefore, there was a need to investigate the composite wall behaviour to lateral loads with RC frames that were infilled with these Israeli typical masonry blocks as well [17].

1.3. Masonry infill wall failure modes

Review of accumulated experimental test results of typical walls subjected to, mostly static or quasi-static, lateral loads, identifies different modes of damage depending on combinations of the different parameters; the major identified damage and failure mechanisms are [18]: corner crushing, shear sliding, diagonal compression, diagonal cracking and frame failure (Fig. 1).

1.4. Masonry infill wall modelling based on lateral loading behaviour

These observations motivated development of analytical methods to model the composite wall behaviour. A most common model represents the infill wall by a compressed diagonal strut. The properties of this equivalent strut have been widely investigated [19–21] and the Federal Emergency Management Agency (FEMA) adopts this single equivalent strut approach as the recommended design model [22–24]. The strut approach has been extended to include several adjacent struts [18,25,26]; nevertheless, there are rather different recommendations for the equivalent strut parameters the implementation of which yields different results. Comparison of these models predictions, including different strut parameters, with experimental results shows a wide scatter. This also indicates that the strut model oversimplifies the complex composite wall behaviour. Indeed, careful observations of experimental results show that many times a combination of several modes of damage is developed throughout the loading process. The single equivalent strut approach cannot represent any of the modes and of their combinations, and, in fact, may model only the primary building's stiffness to the action of the horizontal loading, and has inherent deficiencies in attempting to represent the entire wall behaviour until reaching failure.

Beyond the simplified analytical models there exist advanced modelling attempts, mainly using Finite Element formulations, suggesting detailed description and modelling of the infill wall by using micro-models [27], where modelling of every block and mortar interface are required. The analytical and numerical models support the experimental observations that the masonry infill walls have an undoubtedly significant effect on the structural performance of composite walls. Elaboration and discussion of these models is beyond the scope of this paper.

1.5. Differences between the behaviour to lateral and vertical loading

It should be noted that there are considerable differences between the behaviour of the same typical wall to lateral and to vertical loading, among which one could mention the wall geometry (aspect ratio), the relative position of the load line of action with respect to the direction of the masonry infill wall mortar beds, the relative location of columns and beams with their different stiffnesses and reinforcement details, different location of wall construction details (e.g. shear keys, cast stops), etc. Therefore the use of masonry wall well-known models that are based on lateral loading studies raises doubts with regard to their suitability in the case of vertical load.

1.6. Summary and gaps of knowledge

The above review describes the lack of knowledge regarding the role of the masonry infill walls in the structure response to vertical loading due to the loss of a supporting column. Attempt to simulate the evolution of a progressive collapse mechanism and its analysis are commonly based on knowledge and data borrowed

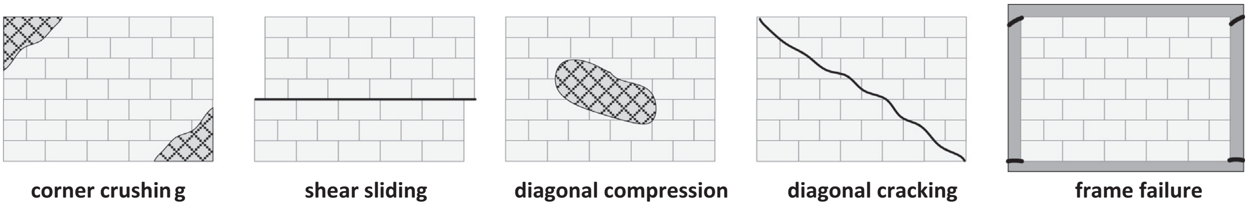

Fig. 1. Typical failure modes of masonry infilled frames subjected to lateral loading.