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Effect of masonry joints on the behavior of infilled frames

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HIGHLIGHTS

- Failure of a supporting column triggering a progressive collapse is analyzed.
- The effect of infill masonry wall interfaces on wall behavior is investigated.
- Three large-scale identical walls with different joints' properties are studied.
- Joint properties strongly affect the ultimate load and the energy dissipation.
- Contact zone size changes during loading and depends on joints characteristics.

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ABSTRACT

The present paper investigates the behavior of masonry infill walls and the effect of the interfaces between the masonry wall units (joints), on the global behavior and on the local infill-frame interaction. The investigation focuses on the case of failure of a supporting column that may trigger a progressive collapse of the building. Experimental results of a new testing method are presented. The experimental technique enables analysis of the contact zone and the contact tractions, and their variations during the loading process. The purpose of this study is to explore and quantify the effect of the joints on the global and local behavior of the composite infill-frame structure. The study examines the contact zone between the infill wall and the frame and its variation with loading, and compares the new data with available expressions that are found in the literature. A comparative experimental study that includes three large-scale unreinforced masonry infill walls with identical geometry and identical Autoclaved Aerated Concrete (AAC) masonry units, but different joints' properties is presented. The results show that the joint properties have a significant effect on the ultimate load, the initial stiffness and the energy dissipation with differences of about 50%, 85% and 70%, respectively. It is also shown that the length of the contact zone changes during loading in all three specimens and its size depends on the joints characteristics. The different contact lengths that are calculated by available simplified models are smaller than the experimentally measured contact region by more than 30%.

1. Introduction

Masonry infill walls are commonly used in public and residential buildings around the world. In past design practices, the contribution of the infill walls to the structural system was commonly neglected. However, when the structure is exposed to extreme loads as in the cases of earthquake, blast, car collision etc., it develops large deformations and the infill walls interact with the structural skeleton and affect its response. The behavior of the infill wall depends on the geometry of the wall including the layout of the masonry units and their dimensions, the mechanical properties of the masonry units and the interfaces between the units (the joints), and the geometrical and mechanical properties of the surrounding frame. It also depends on the interaction between the frame and the infill wall.

The characterization of the infill wall is commonly based on series of tests in which the stiffness, tensile strength, and compressive strength of the masonry units are determined, and friction coefficient as well as the shear, compressive and tensile strengths of the mortar-masonry unit interface are evaluated. The stiffness, compressive strength, and stress-strain relationship of the masonry units and mortar joints are usually assessed based on a masonry prism compressive test (e.g. [1]). Such mechanical properties tests are reported in many studies (e.g., [2–8]) and they

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provide an inclusive assessment of the main masonry material. However, along with the assessment of the masonry material properties, the characterization of the involved interface is of major importance. The assessment of the interface properties is commonly conducted by relative normal and tangential displacement tests. The shear behavior that characterizes the commonly used mortar joints is assessed by direct shear tests or by testing triplets made of three masonry units connected by two joints [9–13]. The normal behavior is assessed by means of compressive and tensile tests (e.g. [14–16]).

The aforementioned interface characterization tests naturally consider relatively small specimens that are composed of a small number of masonry units and mortar interfaces. The tests do not take into consideration the surrounding frame and particularly the interaction between that surrounding frame and the infill wall. This interaction is based on the contact regions between the infill wall and the frame and on the evolution of tractions along those contact regions. The formation of the contact regions directly affects the wall behavior, including its stiffness and load bearing capacity, which depend on the interaction. The complex behavior of the frame, the nonlinear behavior of the infill wall, and particularly, the nonlinear infill-frame interaction underline the complexity of the problem at hand and the need for experimental information regarding the contact phenomenon and its role in the infill wall's response. Such information, which is essential for understanding the response of the structural system as well as its assessment using analytical or numerical tolls is still missing.

A critical aspect of the infill-frame interaction comes into effect in the failure mechanism of the structural assembly. The combination of a relatively strong infill with a relatively weak of poorly detailed reinforce concrete (RC) frame may lead to failure of the latter. Column failures have been widely observed in RC structures subjected to recent earthquakes in L'Aquila and Lorca reported by Verderame et al. [17] and Hermanns et al. [18]. The frame failure mechanism may become even more dominant when the RC infilled frame is subjected to relative vertical deformation. This observation has been investigated and highlighted by Brodsky and Yankelevsky [19] where the response of infilled RC frame to loss of a supporting column was investigated. The experimental investigation in [19] shows that the RC frame failure may determine the overall resistance of the infilled frame. In addition, it points at the relationship between the failure characteristics and the interaction effects along the infill-column interface. These observations, as well as the ones made in Brodsky et al. [20,21], where the interaction with a sensory surrounding frame made of hinged steel frame, further emphasizes the importance of the contact effects and the interfacial tractions that develop between the infill wall and the surrounding frame. Naturally, the evolution of the interfacial tractions and the critical role they play draw the attention to the question of the impact of the masonry material as a whole and the properties of the individual masonry units and the interfaces in between them on the interaction phenomena. This question is in the focus of the present paper.

In general, it is claimed that the strengths of the joints and the masonry units govern the cracking pattern of the infill wall. These parameters affect the response of the wall, dictate the interfacial behavior, govern the internal forces that develop along the frame elements, and influence the failure mechanism of the assembled wall. There is a broad spectrum of possible infill walls configurations, which differ in parameters such as the geometrical dimensions, the wall layout, type of masonry units, type of joints between the masonry units, properties of the joints, frame characteristics etc. The large number of possible combinations of different wall characteristics makes it difficult to determine the infill wall behavior and to come up with general concepts. Even for specific geometry, a given frame, and a well-defined type of masonry units there may be different layouts of joints. Within each layout, there may be different types of joints and different joint materials. The combined effect of the joints' layout and the joint properties plays a major role on the infill cracking and resistance. Commonly the wall construction is based on staggered laying a block on two blocks underneath, where its vertical centerline is aligned with the vertical joint between the blocks below. With about the same layout, these are the mechanical characteristics of the joint that are the key parameter that governs the behavior of a wall, and specifically the infill-frame interaction.

The effect of different masonry joints on the response to diagonal and vertical loadings has been widely investigated in the context of masonry walls without a confining frame (e.g. [22–24]). These studies showed that different joint parameters and particularly different mortar materials affect the masonry compressive strength. Sarangapani et al. [2] examined the brick-mortar bond effect on the masonry compressive strength. Four different mortars were examined consisting of different ratios of cement, sand, lime and soil (sand, silt and clay fractions). They found that an increase in bond strength, while keeping the mortar strength constant, leads to compressive strength increase of the masonry assembly. Alecci et al. [25] studied the effect of three different mortars (lime, cement and cement-lime based) on the shear strength of the masonry panel using a diagonal loading test. This study found that the mortar significantly affects the panel shear strength and the failure mode of the panel. Specimens with relatively lower mortar strength (the lime and the cement-lime based mortars) cracked along a non-diagonal direction (a step crack) while the crack in the cement based mortar specimen developed along the loaded diagonal.

Zahra and Dhanasekar [26] summarized the effects of the mortar properties based on the different experimental results taken from the literature. This include the mortar compressive strength (see [27–29]), the joint thickness, and the ratio between the joint thickness and the height of the masonry units [30]. Accordingly, the European Standard EN 1996-1-1 [31] defines the characteristic compressive strength of masonry, f_k, is expressed as function of the masonry unit's and mortar's strengths:

$$f_k = K f_b^{\alpha} f_m^{\beta} \tag{1}$$

where K, α, and β are constants, f_b is the mean masonry units compressive strength and f_m is the mortar compressive strength. However, for AAC units, the compressive strength depends on the masonry unit strength only and therefore $\beta = 0$ according to 3.6.1.2(2).

Despite the spectrum of studies on masonry without a confining frame, the effect of different mortar properties on the infilled frame behavior received considerably less attention. One of the few studies that addressed this question was presented by Gazic and Sigmund [32]. This investigation experimentally examined the effect of two different mortar types (made of lime and cement-lime) on the behavior of RC infilled frames during lateral cyclic loading. In both tests, hollow clay masonry units were used. It was found that the mortar type affects the strength, the energy dissipation capacity, and the mode of damage of the infilled frame. Sevil et al. [33] tested two stories infilled frames under reversed cyclic lateral loading with two different mortar mixtures, with and without steel fibers. It was found that the reinforced mortar dramatically changes the global load-displacement behavior. No further information is available on that aspect and the effect of different mortar properties on the infilled frame behavior remains an open question. This refers to the global (force-displacement) behavior of the infilled frame. With regard to the evolution of the contact effects between the infill and the frame no earlier works were found. Opposed to the case of lateral loading, which has gained