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Investigation on the behavior of brick-infilled steel frames with openings, experimental and analytical approaches

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ABSTRACT

This article deals with an experimental program to investigate the in-plane seismic behavior of steel frames with clay brick masonry infills having openings. Six large-scale, single-story, single-bay frame specimens were tested under in-plane cyclic loading applied at roof level. The infill panel specimens included masonry infills having central openings of various dimensions. The experimental results indicate that infill panels with and without openings can improve the seismic performance of steel frames and the amount of cumulative dissipated energy of the infill panels with openings, at ultimate state are almost identical. Furthermore, contrary to the literature, the results indicate that infilled frames with openings are not always more ductile than the ones with solid infill. It seems that the ductility of such frames depends on the failure mode of infill piers. This experimental investigation shows that infilled frames with openings experienced pier diagonal tension or toe crushing failure and have smaller ductility factors than those frames with solid infill. Furthermore, a simple analytical method is proposed to estimate the maximum shear capacity of masonry infilled steel frames with window and door openings.

1. Introduction

Steel and reinforced concrete framed structures in urban areas are usually infilled with masonry walls as interior and exterior walls. The resulting system is referred to as an infilled frame, which has high in-plane stiffness and strength. At low levels of lateral forces, the frame and infill wall act in a fully composite fashion. However, as the lateral force level increases, the frame attempts to deform in a flexural mode while the infill attempts to deform in a shear mode. Interaction between frame and infill panel significantly increases the infilled frame lateral stiffness and drastically alters the expected dynamic response of the structure. However, the effect of masonry-infill panels is often neglected in the analysis of infilled frames by structural engineers in current practice. Such an assumption may lead to substantial inaccuracy in predicting the lateral stiffness, strength, and ductility of the frame.

Since the 1950s extensive studies have been performed on lateral load behavior of masonry-infilled frames both experimentally and analytically. Stafford-Smith [1,2], has conducted experimental investigations on the lateral stiffness and strength of steel frames infilled with masonry panels. In order to model the infill frames, an equivalent diagonal strut was proposed by Stafford-Smith [2] to be substituted for the infill panel. A complete review of research studies on infilled frames through 1987 was reported by Moghadam and Dowling [3]. The results of the most intensive experimental program conducted on masonry-infilled steel frames were reported by Dawe and Seah [4]. Mosalam et al. [5] reported the results of a series of experiments on two-bay single-story concrete block masonry infilled steel frames tested under quasi-static loading. Moghadam presented the results of an experimental program on retrofitting brick masonry infilled steel frames [6]. El-Dakhakhni et al. conducted an experimental investigation to study the effect of retrofitting unreinforced concrete masonry-infilled steel frame structures using GFRP laminates [7]. Moghadam et al. [8] reported the results of an experimental investigation on small and medium scale masonry and concrete infilled frames with and without horizontal reinforcement as well as bond beams under in-plane cyclic loading. Doudoumis [9] proposed and used a precise linear finite element model to investigate the effects of interface conditions, mesh density, relative beam to column stiffness and orthotropy of the infill panels. Puglisi et al. [10,11] modified the conventional diagonal strut model (two independent struts in two opposite loading directions) by the inclusion of a new concept called "plastic concentrator". The plastic concentrator links the two diagonal struts and produces a transfer of effects from one strut to the other. They have shown that the use of plastic concentrators leads to a more realistic representation of

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the behavior of both steel and RC infilled frames than the conventional model with two independent struts. The effect of solid brick infill walls on a full-scale three-story reinforced concrete structure was experimentally investigated by Pujol and Fick [12]. The structure was subjected to a cyclic lateral load producing twenty displacement cycles with increasing amplitude. The added walls increased base shear strength and lateral stiffness by approximately 100% and 500%, respectively. They concluded that if the out-of-plane failure of the solid brick infill walls and shear failure of the columns are prevented, the drift capacity of the structures similar to the tested one, will reach to the level of 1.5%.

Based on nonlinear behavior of infill walls a 3D finite element method was used to investigate the effect of various parameters (building height, number of bays, ratio of area of shear walls to area of floor, ratio of infilled panels to total number of panels and type of frame) on the fundamental period of 189 computational models of RC buildings [13]. It was found that RC frames with infill walls had a shorter period, about 5%–10%, compared with RC frames without infill walls regardless of whether they had shear walls or not. A new equation, which was a function of the selected parameters, was also proposed for predicting the fundamental period of buildings, using multiple linear regression analysis.

Chaimoon and Attard [14] carried out an experimental and numerical investigation on full-scale masonry panels with two different mortar strengths under three-point bending (TPB). The material parameters were obtained from compression, TPB and shear tests on bricks and brick-mortar interfaces. For numerical study, a micro-model finite element formulation, in which masonry was modelled using expanded brick units with zero thickness brick-mortar interfaces, was used. The numerical results provided a good match to the experimental results even though the numerical formulation assumed a zero dilatancy.

In most cases, door or window openings are provided in masonry infill panels because of the functional and ventilation requirements of buildings. Introducing openings in an infill wall alters its behavior and adds complexity in behavior. Furthermore, due to the presence of openings in infill panels, the lateral strength and effective stiffness of infilled frames is reduced. Although there have been many experimental activities on lateral load behavior of solid masonry-infilled steel frames, few tests have been conducted on infilled frames with openings. Teeuwen et al. [15], studied the behavior of one-storey, one-bay steel frames and precast concrete infill panels with window openings subjected to experimental and numerical analyses. Their experimental results show that discretely connected precast concrete panels with window openings can significantly improve the performance of steel frames. The tangent stiffnesses corresponding to the deflection of 1/300 of the height of the structure range between 4 and 13 times the bare frame stiffness, depending on the size of window opening. A comparison between their experiments and finite element simulations indicated that the FE model is able to predict the lateral load versus deflection relationship of the hybrid lateral load resisting infilled frame, and the ultimate lateral load carrying capacity for all failure mechanisms.

Mallick and Garge experimentally investigated the effect of opening position on lateral stiffness of infilled frames with and without shear connectors [16]. The conclusion was that if an opening is provided at either end of the loaded diagonal of an infilled frame without shear connectors, the strength and stiffness are reduced by about 75 and 85%–90%, respectively when compared to those of a similar infilled frame with solid infill panel. Also, it has been recommended that the best location for a window or door opening is at the center of the infill panel [4,16]. Mosalam et al. reported that the presence of openings reduces solid infill panel stiffness values by about 40% for lateral loads below the cracking load level [5]. Also, openings in infill walls lead to a more ductile behavior while ultimate load capacities of solid infills and infills with windows are similar. Schneider et al. investigated the in-plane behavior of steel frames with masonry infills having large window openings [17]. Test parameters included the masonry pier width and the number of wythe. The conclusion was that narrow piers and double wythe infills tend to be more ductile than wide piers. Kakaletsis and Karayannis [18] conducted an experimental program to find the effect of window and door openings on the hysteretic characteristics of infilled RC frames and studied the relative merits and demerits of different positions for windows and doors. They found that the location of the opening as near to the edge of the infill as possible provides an improvement on the performance of the infilled frame [18]. Also, it was observed that the energy dissipation is more significant in the case of the larger piers where a better distribution of cracks in the wall is developed. Kakaletsis and Karayannis [19] experimentally investigated the effect of masonry infill compressive strength and openings on failure modes, strength, stiffness and energy dissipation of infilled RC frames under cyclic loading. They found that infills with openings and strong masonry can significantly improve the performance of RC frames. In addition they presented an analytical approach based on the equivalent diagonal strut to predict the lateral resistance of the studied infilled RC frames with openings. In another article they reported the results of an experimental study on eight infilled RC frames investigating the influence of masonry opening shape and size on the seismic performance of such frames. The results show the significance of various forms of openings on reduction of stiffness, strength and energy dissipation capability of the tested infilled frames [20]. Furthermore, they proposed a continuous force–deformation model for nonlinear analysis of masonry infill panels with openings.

Due to the lack of extensive knowledge on the seismic behavior of masonry-infilled frames with openings, most of the proposed macro-models (equivalent strut or truss type models) have been verified for solid infill panels only. Therefore, many structural engineers ignore such infills when assessing the seismic vulnerability of these frames. Consequently, more research is needed to evaluate the strength and stiffness of masonry-infilled frames with openings.

This article reports on an experimental program to investigate the in-plane, cyclic deformation behavior of steel frames with clay brick masonry infills having a central window and door openings. Six large-scale frame specimens were tested by applying in-plane cyclic lateral deformations at the roof level, to determine the masonry infill behavior from elastic to ultimate state. The main test parameters were the pier width with respect to spandrel beam depth of the infill panel and opening type.

2. Experimental work

2.1. Description of test specimens

Six large-scale single-story single-bay steel frames were constructed and tested under cyclic quasi-static lateral in-plane loading. All specimens were 2400 mm long by 1870 mm high. Infill panels consisted of 219 × 110 × 66 mm solid clay bricks (with no voids) placed in running bond with 22 courses within a surrounding moment–resistant steel frame fabricated using IPE140 sections ($A = 16.4$ cm^2, $I_{xx} = 541$ cm^4, $d = 14$, $b_f = 7.3$, $t_f = 0.69$, $t_w = 0.47$ cm). The single wythe infill panel thickness in all specimens was 110 mm. One frame was tested without an infill panel (bare frame), one had a solid infill panel, and the others had infill panels with symmetrical window or door openings. Table 1 summarizes the properties of each specimen and Fig. 1 illustrates the geometry and dimensions of the test specimens. None of the specimens (except PW4) had steel bar ties.