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Designing infilled reinforced concrete frames with the 'strong frame-weak infill' principle

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ABSTRACT

This paper presents an experimental study of the seismic performance of a category of reinforced concrete (RC) frame with weak infill panel and the complicated interaction between bounding frame and infill panel at different loading stages. Large-scale infilled RC frame specimens, which were fabricated to simulate those in as-built RC frame buildings designed in accordance with the provisions of Chinese seismic code (GB50011-2001), were tested under reversed cyclic loading. Particular emphasis was placed on the influence of the masonry materials and aspect ratio of infill walls on the hysteretic characteristics of the infilled frames. Three types of masonry infill were used, which included solid clay bricks (SCB), hollow concrete blocks (HCB) and aerated concrete blocks (ACB). The test results indicated that the bounding frames of infilled frame specimens had the same failure mode as the bare frame. These infilled frames exhibited superior seismic performance to the bare frame in terms of strength and energy dissipation capacity. The experiment showed the complicated interaction between bounding frame and infill panel as well as the failure mechanism of frames with weak infill. Moreover, HCB infill panels incurred the most serious damage amongst the infills, which may jeopardise the in-plane and out-plane stability of infill walls. Bounding frame bore a greater internal force than bare frame, especially at the end of columns, which affected the failure mode of the bounding frame. It is proposed to enlarge the moment and shear design values of columns to consider the local effect of infill on bounding frames in design practice. Based on the concept of the multi-line defence against earthquakes, it is suggested that infilled frames should be designed with the 'strong frame-weak infill' principle, in which frame and weak infill will form a two-line system of defence against earthquakes.

1. Introduction

Due to the high architectural efficiency, the infilled frame structure is a main structural form commonly used for low- to medium-rise buildings in the world. In this structural form, masonry infill panels are frequently used as partitions or cladding. In design practice, infill panels are usually regarded as non-structural elements, and the interaction between bounding frame and infilled panels is ignored in structural models established by engineers. Nevertheless, their strengths and bracing actions are not negligible, and they will interact with the bounding frame when the structure is subjected to strong lateral loads induced by seismic actions. The complicated interaction may be either beneficial or detrimental to the seismic performance of infilled frame structures, while this is largely dependent upon how to design reasonably the structures.

During the past three decades, extensive research has been carried out on the seismic performance of infilled reinforced concrete or steel frames. The previous experiments [1–8] mainly focused on the in-plane seismic behaviour of single-storey, single-bay infilled frames and reached the conclusion that infilled steel or reinforced concrete frames show superior lateral load capacity and energy dissipation capacity compared with bare frames, which even led to the misconception in engineering that masonry infill in steel or reinforced concrete frames would always be beneficial to the seismic performance of structures [9].

However, the numerous examples of catastrophic structural failures of and damage to infilled RC frame buildings, reported in nearly all destructive earthquake events, including the Mexico City earthquake in 1985, the Turkey Kocaeli earthquake in 1999 [10], the Taiwan Chi-Chi earthquake in 1999 [11], the China Wenchuan

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earthquake in 2008 [12] and the Emilia earthquake in 2012 [13], indicate that the interaction between bounding frame and infill panel is more complicated than expected. The strength and bracing action of infills not only alter the local mechanical characteristics but also the overall dynamic characteristics of structures [14–22]. These structural action modifications can be detrimental to the seismic performance of the buildings resulting in unexpected damage, such as weak- and soft-storey failures, torsion failure and short-column failure [23–26].

As research continued, a consensus was reached that the strength and bracing action of infills should not be ignored in design practice. However, numerous factors influence the infilled frame behaviour. Studies have shown that infilled frames could develop a number of possible failure mechanisms, to a great extent, depending on the relative strength and stiffness of the bounding frames to infill panels and the configuration of infill panels in the frame system. Based on the previous experimental observations, five main failure modes of infilled frames are summarised and the respective failure mechanisms are analysed [27]. However, no analytical models are reasonably applicable to different types of infilled frame structures. They only focus on one type of mechanism or another. So far there are still neither well-developed design recommendations nor well-accepted analytical methods for infilled RC frames. The main bottleneck in design practice and evaluation performance of infilled structures is to determine the resistance mechanism and failure modes of infilled frames. Hence, it is important to develop a distinguishing criterion of failure mechanism and design recommendation to improve design practice.

Furthermore, in numerous experiments in the past years, most of the test frames infilled with solid clay masonry constituted the experimental foundation of the current design codes considering the influence of infill panels. In the last decade, due to good properties of lightweight, thermal insulation, sound insulation and higher construction efficiency, some new masonry material was widely used in new-built frame buildings, such as hollow concrete blocks and aerated concrete blocks. Previous studies mainly focused on the mechanical, sound insulation performance and thermal performance of masonry units, while studies on the structural performance of new masonry infill were relatively few. Considering the distinguished difference between clay masonry infill and new masonry infill, it is necessary to carry out research on the seismic performance of frame infilled with new masonry infill.

Based on the aforementioned issues, the objective of this study was to investigate experimentally the seismic behaviour of a category of RC frame with weak infill panel and to reveal the complicated interaction between bounding frame and infill panel at different loading stages. Large-scale, single-storey and single-bay infilled RC frame specimens, which were fabricated to simulate those in as-built RC frame buildings designed in accordance with the provisions of the Chinese seismic code [28], were tested under reversed cyclic loading. The variables investigated included masonry infill materials and the aspect ratio of infill walls. Particular emphasis was placed on the influence of two new lightweight wall-materials on the hysteretic characteristics of infilled RC frames. Including solid clay bricks as a traditional masonry material, two new types of lightweight wall-material, namely hollow concrete blocks and aerated concrete blocks, were examined. Furthermore, based on the concept of the multi-line defence against earthquakes, it is suggested that infilled frames should be designed with the 'strong frame-weak infill' principle', in which frame and weak infill form a two-line system of defence against earthquakes. Meanwhile, a simple macro model for frames with weak infill is proposed to predict the lateral strength and stiffness.

2. Experimental programme

2.1. Test specimens

A typical four-storey, three-bay, residential, reinforced concrete frame building in China was selected as a prototype structure. The frame building was designed in accordance with the provisions of the Chinese seismic code [28] with the seismic fortification intensity of 7 in Category 1 and design PGA of 0.15 g, which represents a very large number of existing RC frame buildings in China. In design practice, the load resistance contributed by infill panels was ignored, while the stiffness contributed by infill panels was considered by reducing the fundamental period of the structure with a reduction factor of 0.7. The prototype substructure was selected as the central bay of the first storey of the prototype frame building. Test specimens were designed and fabricated to represent the prototype substructure.

In the experimental programme, five 1/2-scale, single-storey and single-bay RC frame specimens were tested, as shown in Fig. 1, under simulated seismic loading and a constant axial compression. The variables investigated included the aspect ratio (width/height) of infill panels and masonry-infill materials. Two common infill-panel aspect ratios were considered, which were approximately 1.5 and 2.0. A summary of panel aspect ratios and infill materials of test specimens is presented in Table 1. All test specimens have the same storey height of 1375 mm with spans of 2250 mm and 3000 mm, thus achieving the panel aspect ratios of 1.5 and 2.0, respectively. Columns have a 250 × 250 mm square section and beam cross-sections are 200 mm wide and 250 mm deep. A reinforced concrete base with a cross-section of 300 × 400 mm was cast as the foundation of columns. Details of test specimens and steel reinforcement are illustrated in Fig. 1.

Specimen BF was a bare frame and tested as a control specimen without any infills, while the other four specimens were fully infilled with an infill wall. Three different types of masonry units used in specimens are solid clay brick (SCB), hollow concrete block (HCB) and aerated concrete block (ACB). Solid clay bricks are the traditional masonry units with a modular size of 240 × 115 × 53 mm. Hollow concrete blocks and aerated concrete blocks are the new lightweight infill-wall materials, which are now commonly used in China with a modular size of 280 × 180 × 180 mm and 600 × 240 × 120 mm, respectively. The hollow concrete block has a solid top surface and hollow bottom surface, as shown in Fig. 2, and the shell thickness of a hollow concrete block is 18 mm. They are widely adopted as an infill-wall material due to convenient construction and high construction quality. All the specimens were cast vertically in the laboratory to simulate the condition of practical construction. The infill wall was constructed after the frame had been completed. The bed and head joints were approximately 10 mm thick. No shear connectors were provided between bounding frame and infill panel.

2.2. Material strengths and reinforcement details

All test specimens were constructed using normal weight and ready mixed concrete with a mean 28-day concrete compressive strength of 34.5 MPa obtained from standard tests on 150-mm cube specimens. The mechanical properties of steel reinforcement used for 6 mm, 12 mm and 16 mm diameters are shown in Table 2. The compressive strengths of SCB, HCB, and ACB infill units were 12.6 MPa, 7.8 MPa, and 7.2 MPa, respectively. The compressive strength of mixed mortar used for SCB infill and HCB infills was 4.4 MPa obtained from standard tests on a 70.7-mm long cube specimen at 28 days, while the compressive strength of special