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Quasi-static cyclic tests of two mixed reinforced concrete–unreinforced masonry wall structures

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A B S T R A C T

In several seismic countries, residential buildings are constructed using both reinforced concrete (RC) and unreinforced masonry (URM) walls. Despite their popularity, there is a general lack of knowledge concerning the seismic behaviour of such mixed systems and they are often designed using oversimplifying assumptions. For this reason, a research programme was initiated at EPFL with the objective of contributing to the understanding of the seismic behaviour of such structures. This paper presents two quasi-static cyclic tests on two-third scale models of a prototype structure. The two specimens are composed of a two-storey RC wall coupled to a two-storey URM wall by means of RC beams. The horizontal forces were applied at the two floor levels. The main difference between the two test units was the axial load applied at the top of the walls. A particular test set-up allowed measuring the reaction forces (axial force, shear force and bending moment) at the base of the URM wall. From the applied horizontal and vertical loads the reaction forces at the base of the RC wall were computed. It was hence possible to back-calculate the distribution of the reaction forces between the two walls. The article describes the design of the test units, the test set-up and the damage evolution during testing. The main results are summarised and behaviour patterns of mixed RC–URM wall structures identified.

1. Introduction

Existing unreinforced masonry (URM) buildings, which do not pass the seismic design check, are often strengthened by adding RC walls to the existing structure or by replacing selected URM walls with RC ones. The RC walls herein considered are designed for developing a stable flexural response and failing for larger displacement demands than the URM walls. In Switzerland, such mixed construction technique is also adopted for new residential buildings of 3–6 storeys. Despite the popularity of these mixed constructions, very little is known about their seismic behaviour, as only few studies were carried out in the past [1]. As a consequence, codes do not provide guidelines for mixed RC–URM wall structures and design engineers, when conceiving such structures, often adopt oversimplified assumptions. As an example, in Switzerland typically only the lateral stiffness and strength of the RC walls is taken into account for the seismic design of mixed RC–URM wall buildings. In most building configurations the URM walls outnumber, however, the RC walls and, as the paper will show, influence therefore significantly the lateral stiffness and strength of the building.

Numerical studies on mixed RC–URM wall structures [2–6] confirmed that URM walls have to be considered when realistic estimates of the structure's stiffness and strength are sought. For example, since the global response of mixed RC–URM wall structures is influenced by both types of walls, the displacement profiles of mixed RC–URM wall structures differ from those of buildings with RC or URM walls only. At the same time, numerical results are very sensitive to the modelling assumptions [2,3] but the models could not be validated since experimental evidence on the seismic behaviour of mixed RC–URM wall structures was lacking [1]. Non-linear static analyses on mixed RC–URM structures were carried out by Cattari and Lagomarsino [4]. However, their analyses focused on mixed structures with RC walls designed for vertical loads only. As a consequence, the RC walls failed before the URM ones and decreased the displacement ductility capacity of the mixed structure when compared to a regular URM building.

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Only two experimental campaigns on mixed RC–URM structures were conducted in the past (apart from RC frames with URM infills). The first study consisted of shake table tests on a URM wall building with one RC column [7]. Nevertheless, the latter had no influence on the behaviour of the structure under lateral loads since the URM walls were considerably stiffer than the RC column. Therefore these tests cannot be used as benchmark for the seismic evaluation of mixed RC–URM wall structures. An additional study dealt with the behaviour of a mixed structure composed of URM walls and one RC frame on the ground floor [8–14]. Coupling the two systems vertically addresses, however, very different issues then the horizontal coupling. The authors of this study also investigated different strengthening solutions including one which consisted in adding a RC central core wall connected to the foundation by means of a rubber plate [13,14]. Hence, none of the experimental studies addressed the seismic behaviour of mixed RC–URM wall structures where RC and URM walls are continuous over the height and the RC walls fixed to the foundation. Moreover, existing studies only addressed the global behaviour and not the contribution of the individual components. For this reason, an experimental campaign was initiated at the École Polytechnique Fédérale de Lausanne (EPFL) in which both dynamic and quasi-static cyclic tests on mixed RC–URM wall structures were performed.

This paper describes the results of the quasi-static cyclic tests on two units representing two-third scale models of a prototype structure. The two-storey test units are composed of a RC wall and a URM wall which are coupled by means of RC beams. The test setup is particular as it allows measuring the reaction forces at the base of the URM wall. The objective of the test is to provide high quality experimental data for (i) calibrating and evaluating numerical and analytical models and (ii) investigating the contribution of the URM and RC walls to the system's strength, stiffness, deformed shape and displacement capacity. Following this introduction, Section 2 describes the design of the test units and the test set-up. Section 3 continues with the presentation of the test results and their discussion. A summary of the most important features of the behaviour of mixed RC–URM wall structures when subjected to lateral loading is presented in Section 4, which concludes with an outlook on future research activities.

2. Experimental investigations

Two large scale specimens were constructed and tested at the structural engineering laboratory of EPFL. In the following, the geometry of the test units, their relationship with a fictitious four storey mixed reference structure, the material properties, the test set-up and the loading history are described.

2.1. Test units and reference structure

Each of the two test units comprised a two-storey URM wall coupled to a two-storey RC wall by two RC beams. The main difference between the two systems was the axial load applied at the top of the walls. For the first system (TU1), an axial load of 400 kN was applied at the top of the URM wall leading to a behaviour of the latter controlled by shear deformations; for the second test (TU2) the axial load was reduced to 200 kN in order to achieve a prevalent rocking behaviour of the URM wall. The RC walls of TU1 and TU2 were subjected to axial loads of 125 kN and 0 kN, respectively.

Each test unit aimed at representing the most critical elements of a mixed RC–URM wall structure. The reference structure is a four storey building (Fig. 1) with three URM walls and one RC wall. The walls are coupled at the floor levels by means of RC slabs. Due to the shear forces transferred by the RC slabs, the axial forces in the external walls vary when the building is subjected to lateral loading, whereas it is almost constant in the internal walls since RC slabs of equal strength and length frame into these walls from both sides.

The most interesting part of the reference structure comprises the two lower storeys of the two external walls: the walls are expected to fail in the lower storeys and, since the behaviour of URM and RC walls is sensitive to the variation of axial force, the outer walls are of particular concern. The test units represented therefore the two lower storeys of the outer walls of the reference structure. The storey height of the specimens was 1.61 m, which corresponds approximately to two thirds of the storey height of a full-scale structure. The length of the URM and RC wall were 2.1 m and 0.8 m, respectively; the width of both walls was 0.15 m.

The length of the URM walls was not scaled by a factor of 2/3 in order to increase their influence on the overall behaviour of the test units, as the number of URM walls from the reference structure to the specimens was reduced from 3 to 1. The RC beams, connecting the two walls, had a cross section of 0.45×0.2 m (width $\times$ height) and represented the effective width of the slabs in the reference structure. According to Priestley et al. [15], the effective width of slabs coupling internal walls can be estimated as three times the wall thickness. The two RC beams were designed to provide approximately the same variation of axial force at the wall base as in the reference structure. Pushover analyses of the reference structure and the test unit showed that the behaviour of the test unit is representative of the behaviour of the reference structure with regard to the failure mechanism of the URM wall and the redistribution of axial force between the two walls.

The URM walls were constructed using hollow clay bricks which, according to EN 1996-1 [16], belong to "*Group 2*". Furthermore, the selected brick type has continuous longitudinal webs (Fig. 3), which are necessary for carrying the in-plane shear forces of the masonry walls. The thickness of the bed joints was 1 cm with dry vertical joints. The RC walls are "model" capacity-designed ductile walls and the RC beams are designed to develop a stable flexural mechanism. The reinforcement layouts of RC walls and RC beams are shown in Fig. 2a and b, respectively.

2.2. Material properties of the test units

In addition to the two quasi-static experiments, material tests on bricks, mortar, masonry wallets, concrete and reinforcing bars were carried out. In the following, the most important material properties are summarised. The masonry walls were constructed using hollow-core tongue-and-groove clay bricks with standard dimensions of $300 \times 190 \times 150$ mm (length $\times$ height $\times$ thickness, Fig. 3). E-moduli and strength of the bricks were determined according to EN 772-1 [17] and the results are summarised in Table 1. The mortar was a standard cement mortar (Weber Mur 720). The bed joints had an average thickness of 1 cm; the head joints were not filled. The E-modulus, compressive strength and Poisson's ratio of the masonry were determined according to EN 1052-1 [18] and are summarised in Table 2. Triplet tests according to EN 1052-3 [19] were used to determine the interface strength between mortar and bricks. Table 3 summarises the Mohr–Coulomb relationships characterising the peak and residual shear strength of the bed joints.

The mechanical properties of the concrete are given in Table 4. Each test unit was cast with two batches of concrete: the first batch was used to construct the foundation and the first storey wall, the second one to build the second storey wall and the two beams. Table 5 summarises the mechanical properties (yield and tensile strength) of the reinforcing steel in beams and walls.