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Experimental structural behavior of wall-diaphragm connections for older masonry buildings

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ABSTRACT

Wall-diaphragm connections can affect overall seismic performance of older unreinforced masonry buildings, but there is little test data available about the structural behavior of such connections. Results are presented of an experimental study designed to evaluate the behavior of typical brick wall to wood joist/diaphragm connections. Tests were conducted on two different types of component specimens (with and without nailed strap anchors), using three different loading methods (static monotonic, as well as static and dynamic cyclic). Contributions of friction (activated at brick joist supports to represent gravity load normal force effects) and of strap anchor nails loaded in shear have been considered separately and together in the testing matrix. Force vs. displacement envelope and hysteresis curves have been developed from the experimental data. Also from these data, simplified average multi-linear plots derived from all the experiments can be compared based on different test specimen and loading types, leading to aggregate findings about various distinctive structural behaviors exhibited. These findings include typical strengths and failure modes, as well as stiffness and/or friction coefficient values as a function of displacement, for all the test specimens. Results obtained from these masonry connection tests can be used in numerical analyses of whole building systems.

1. Introduction

Brick masonry can be an esthetically pleasing, durable, and strong building material with good resistance to sound and thermal transmission. For these reasons, it has been a popular choice as a construction material for a variety of low-rise structural applications. However, unreinforced masonry (URM) structures can be relatively more vulnerable to earthquake excitations than steel, reinforced concrete, or even timber structures.

During severe earthquakes, older URM buildings can exhibit a variety of damage mechanisms. In-plane and/or out-of-plane failures are the most likely damage modes for masonry walls. Local wall-diaphragm connection behavior may contribute to overall wall behavior, especially in the out-of-plane direction, depending on the nature of these connections. Early wall-diaphragm connections were often either star anchors or masonry anchors providing a positive attachment between the end of a wood floor joist and the brick masonry pocket in which it rested. One end of the steel anchor would be nailed to the web of a joist, with the other end embedded through the masonry wall to an external anchor plate. These types of anchors were typically only placed when a joist was perpendicular to and supported on a wall (at some of the pocket connections), but not for joists parallel to a wall. For global continuity of lateral load resistance in such structures, adequate overall connection is needed between the masonry walls and wooden floor diaphragms, which is typically provided by a mixture of the sort of connections described above along with other locations, where the joists simply rest in brick masonry wall pockets.

In the literature, the global behavior of URM structures has been investigated by various researchers. Doherty et al. [1] conducted research on out-of-plane bending of multi-story URM walls. A simplified (linearized) displacement-based procedure was presented, along with recommendations for selection of an appropriate substitute structure to provide the most representative analytical results. Tri-linear force vs. displacement relationships were used to characterize nonlinear wall behavior of unreinforced brick masonry as rigid and semi-rigid blocks. A substitute structure concept was applied to further simplify single-degree-of-freedom (SDOF) models so the behavior of URM walls could be predicted using displacement response spectra. Simsir et al. [2] summarized research on out-of-plane behavior of URM bearing walls in buildings subjected to earthquake motions. Results from a set of shake-table tests revealed that such walls can perform quite well even if moderately intense base motions are applied to fairly slender walls. Experimental results were compared with those simulated using SDOF and multi-degree-of-freedom (MDOF) computational models, which were then used to establish that permissible limits on wall slenderness, as prescribed by some seismic design guidelines, could be increased.

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In-plane shear behavior of masonry walls has also generated significant interest in development of appropriate assessment and analysis methods. Sutcliffe et al. [3] proposed a lower-bound limit analysis technique for URM shear walls, treating the masonry as an anisotropic, inhomogeneous, and perfectly plastic material. A simple seismic assessment approach for in-plane response of brick masonry walls was outlined by Magenes and Calvi [4]. Strength, deformability, and energy dissipation capacity of unreinforced brick masonry walls were evaluated, with shear failure mechanisms and shear strength formulae identified and formed, respectively, based on experimental results from Calvi et al. [5]. Peralta et al. [6] conducted an experimental testing program on the lateral in-plane behavior of pre-1950s existing and rehabilitated wood floor and roof diaphragms representative of URM buildings found in the central and eastern regions of the United States. They found that FEMA 273 tended to overpredict the stiffness and significantly underpredict yield displacement and ultimate deformation levels, while FEMA 356 tended to underpredict stiffness and overpredict yield displacement.

An experimental investigation on the dynamic behavior of reduced-scale URM buildings, including both in- and out-of-plane walls with flexible diaphragms, was conducted by Costley and Abrams [7]. Experimental parameters included the relative lateral strengths of the two parallel shear walls and the aspect ratios of piers between window and door openings. According to their test results, measured frequencies were much lower (longer periods) than those determined using design codes. Substantial strength and deformation capacity still existed after the walls cracked (and rocked) during the experiments, indicating that there was some ductility within the structure. It was suggested that story drift can be used to define different performance levels for URM buildings in performance-based design approaches. Yi et al. [8,9] conducted full-scale tests and finite element model (FEM) simulations for a two-story URM building. Their test structure exhibited large initial stiffness, and its damage was characterized by sizeable discrete cracks that developed in the masonry walls. Global rocking of an entire wall and local response such as rocking and sliding of each individual pier were observed in masonry walls with different configurations. Elastic and inelastic FEMs included different degrees of complexity – rigid body analyses and nonlinear pushover analyses were conducted. It was concluded that interactions between masonry walls and flexible roof/floor diaphragms are in part determined by relative stiffness values of the basic components (like the in-plane wall, out-of-plane walls, and flexible diaphragms) of a URM building. Their tests also revealed that connection details in general between masonry walls and diaphragms can influence response of the wall-diaphragm system.

Most research done investigating masonry buildings has emphasized structural components such as masonry walls or diaphragms, without much attention being given to the connections between brick masonry walls and the wood joists/diaphragms. Cross and Jones [10,11] outlined the development of a technique for examining seismic performance of joist and beam bearing connections in URM structures. They stipulated that an understanding of the connections can allow for better estimation of the overall structural behavior of brick buildings, and provide a useful tool for the design of seismic retrofit details. An FEM that accounts for friction and impact behavior at the diaphragm-to-wall interface was developed. Some MDOF systems of portal frames and cantilever beams illustrated the method and demonstrated its ability to capture sliding and impact behavior at the connection detail. Applying this approach, a historic brick building shaken during the Loma Prieta earthquake of 1989 was modeled.

A review of the literature has indicated that wall-diaphragm connections can have a significant influence on the seismic performance of URM buildings. Failure of the connections could lead to total structural collapse, and connection flexibility could significantly affect overall structural response. However, relatively little research has been conducted on the structural behavior of wall-diaphragm connections for URM buildings under various loadings, such as to even determine their basic force vs. displacement relationships. Due to this lack of data on inelastic force–displacement behavior of wall-diaphragm connections, an experimental study of representative wood joist and brick masonry connections has been undertaken. The experimental data, such as overall force–displacement curves or even approximate stiffness values of connections, can then be used in developing numerical models of entire structures to better determine their response to ground motions.

2. Background

In this section, a brief description is given about certain construction details that are typically found in older URM buildings in the US (commonly constructed for example from the 1920s until the 1960s). A series of editions of Architectural Graphic Standards [12] consistently indicates a method by which wooden floor joists were connected to brick masonry walls that supported them (including the type of nailed anchors used at some of these connections). The International Library of Technology [13] also shows similar wall-diaphragm connection details, where wood joists rest on brick masonry walls in pocketed connections (with some of them having a metal strap nailed to the joist that also goes into/through the wall). Such connections, as shown in Fig. 1, are quite similar to the connection subassemblies constructed, tested, and reported on as part of the experimental program that is the subject of this paper.

Floor diaphragms and wall-diaphragm connections in typical older URM buildings also have some other common characteristics: sheathing was typically made of straight members (nailed onto the framing), and the steel wall anchors used to connect the diaphragm to the wall were at most present at every 4th floor joist (and were often even less prevalent than that) [14]. The joists themselves were supported in pockets of the URM wall, with a modest bearing area. Sometimes joists or beams were simply supported on special corbels, but most often the URM wall was constructed around the supported beams, either with bricks tightly fitting around them or with a weak grout used to fill oversized cavities housing their supports [15]. Fig. 2a and b shows floor joists connected to a supporting masonry wall in an actual URM building, and of a floor joist that has a metal strap nailed to it that is also connected through the masonry wall. Most of the floor joists, however, had no such strap. While all of these components appear to be in fairly good condition in this particular older URM building, condition assessments of certain of such structures can reveal some wood deterioration and/or steel corrosion. The effect of that deterioration on structural performance is unknown and is outside the scope of the experimental work presented in this paper.

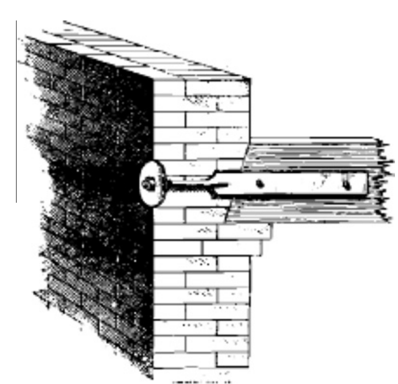

Fig. 1. Image of wall-diaphragm connection (International Library of Technology, 1923 [13]).