1. Introduction

Out-of-plane wall failures most commonly occur due to inadequate anchorage of the wall to the floor diaphragms. In such cases, the wall behaves as a cantilever and collapses if the inertia forces on the wall push it beyond the point of instability. Given sufficient anchorage to the diaphragms, out-of-plane walls will respond as vertical “beams” in bending as the inertia forces on the walls are distributed to the attached diaphragms. Due to limited tensile strength of the mortar, anchored URM walls will frequently crack just above mid-height. This results in rocking of the top and bottom wall segments in the out-of-plane direction. If the displacements induced by the ground motion are large enough (i.e. exceeding the wall width at the crack location) the wall can become unstable and collapse. Considering the improvement in behaviour for the relatively modest cost of anchoring the walls to the diaphragms, it is assumed in this study that the walls are sufficiently anchored to the floor diaphragm to develop the beam bending mode of failure.

For out-of-plane walls with sufficient anchorage to the diaphragms, FEMA 356 (ASCE 2000), specifies acceptance criteria based on the height to thickness ratio ($h/t$) of the wall. For walls at the top of a multi-story building, FEMA 356 limits the $h/t$ ratio to less than 14 for a spectral acceleration at a structural period of 1.0 second, $S_a(1.0)$, less or equal to 0.37g. For $S_a(1.0)$ greater than 0.37g, $h/t$ is limited to less than 9. These are the most stringent $h/t$ limits provided since the walls at the top story are the most vulnerable to failure due to the low axial loads.

This study focuses on the out-of-plane response of clay-brick multi-wythe URM walls typically used in turn-of-the-century school buildings in southwest British Columbia. These buildings are located on very dense or stiff soil sites. The quality of construction, including the ability of the collar joints between the wythes to maintain composite action during out-of-plane response, is very difficult to assess for the existing structures. Given the limited number of tests on clay-brick multi-wythe walls discussed in the literature, it is not possible to determine the sensitivity of the out-of-plane response to soil conditions, local seismic hazard, and wall construction quality. The following reports on shake table tests on URM walls designed to address these issues and assess the need for retrofit measures for walls adequately anchored to the diaphragms. Further details are provided in Meisl et al. 2005.

2. Out-of-plane Response Analysis

A nonlinear-elastic SDOF model developed by Doherty et al. (2002) was used to estimate the post-cracking out-of-plane rocking behaviour of the URM wall specimens and select the ground motions for the shake table tests. The SDOF model provides an estimate of the mid-height displacement for a wall that is assumed to be cracked at mid-height. The wall is assumed to reach its instability limit when the mid-height displacement exceeds the width of the wall.
Analyses were conducted with a suite of 80 ground motion records from various site conditions, all scaled to the Uniform Hazard Spectrum (UHS) for Vancouver from the proposed 2005 National Building Code of Canada (Adams and Atkinson, 2003) (The UHS has a probability of exceedance of 2% in 50 years). The ground motions were scaled up (or down) from the UHS level until instability was detected by the SDOF analysis. The Instability Factor was defined as the scaling factor (relative to the UHS level) required to first detect instability. The distribution of Instability Factors for the suite of ground motions is shown in Figure 1. These results from the SDOF model suggest that the soil conditions play a significant role in determining the stability of the wall. With the increased level of displacements seen in softer soil conditions, the average Instability Factor decreased from 2.09 for site class B (rock) to 0.98 for site class E (soft soil). The ground motion selected for the shake table tests described below was recorded on firm ground (site class C) in Gilroy, California during the 1989 Loma Prieta Earthquake and has an instability factor of 1.52. When scaled to the UHS, this record has a PGA of 0.63g and a PGD of 8.9cm and $\text{Sa}(1.0) = 0.4g$. Given this seismic demand, the FEMA 356 $h/t$ limit is 9.

![Figure 1. Distribution of Instability Factors](image)

### 3. Shake table Tests

Wall specimens were designed to represent a wall from the top story of an early 1900’s URM school building in British Columbia, including mortar quality and construction methods. Two types of collar joints were used to provide bounds on construction variability:

1. **Poor Collar Joint** - Light mortar bed, collar joints not slushed
2. **Good Collar Joint** - Heavy mortar bed, collar joints slushed

Four three-wythe wall specimens were constructed; two with poor collar joints and two with good collar joints. American bond, with a header coarse at every sixth coarse, was used for all specimens. The walls had...
a total height of 4250 mm and a thickness of 355 mm, resulting in an $h/t$ ratio of 12, thereby exceeding the FEMA $356 \, h/t$ limit of 9. The walls were held in place on the shake table by angles on either side of bottom course of bricks with rubber spacers to allow for rotation. The top support was designed to restrain movement in the out-of-plane direction, but allow for rotation and vertical movement of the top of the wall.

Due to space constraints, only test results from two walls will be discussed below; one with good collar joints, the other with poor collar joints. Both were subjected to the site class C ground motion discussed above. The ground motion was applied at increasing amplitudes with the following scale factors (relative to the UHS level): 0.21, 0.42, 0.53, 1.0, 1.25, 1.52, and 1.75.

At a scale factor of 0.42 (corresponding to a return period of 475 years), both walls experienced cracking at the base and at header 6 (i.e. approximately 2750 mm from the base of the wall). Rigid body rocking, where the wall acted as two rigid blocks pivoting about the top restraint, header 6, and the base, was observed for the remainder of the tests. At the UHS level (1.0 scaling), two bricks were dislodged from the good quality wall at header 6, and crushing of the outside bricks was also evident. For the good quality wall, at scaling levels above 1.25, slight bearing between the wall and the top restraint was noted. This interference may have resulted in limiting mid-height displacements for these tests. For the poor quality wall at a scaling of 1.25, cracks formed at the first header above the base of the wall. Further damage also occurred at header 6 with crushing of the outside brick corners and daylight was observed through the crack. At 1.75 times the UHS, the outer wythe of bricks at the first header were lost, thereby changing the walls rocking behaviour and apparently decreasing the mid-height displacements. Due to the significant damage, the wall was considered to be unstable and all instruments were removed. Figure 2 shows the final collapsed profile of the wall.

The maximum header 6 displacements vs. scale factor for the two walls are compared against the analytical SDOF results in Figure 3. The observed peak displacements of the poor quality wall compare very well to the analytical results until significant damage occurs at the first header during the final test. The good quality wall compares reasonably well with the analytical results up to a scale factor of 1.25. Applied ground motions above this level resulted in limited moment resistance at the top of the wall due to interference of the top restraint. As shown by the dashed line in Figure 3, this interference appears to decrease the peak displacement. Further investigation of this applied moment and its effect on wall stability is required.
4. Conclusions

The study presented here has investigated the sensitivity of the out-of-plane response of multi-wythe URM walls to the type of ground motion and the quality of the wall construction. Analyses based on a SDOF model indicate that, given sufficient anchorage of the walls to the diaphragms, URM buildings located on soft soil sites are more likely to experience out-of-plane wall failures than buildings located on firm ground. Based on the shake table test results, the quality of the collar joints did not appear to have a significant impact on the level of damage or the response of the walls up to the code level ground motion for Vancouver, Canada. Since the wall specimens with \( h/t = 12 \) remained stable well beyond the code level ground motion, the \( h/t \) limit of 9 from FEMA 356 appears conservative for the evaluation of URM walls on firm ground sites. Although the walls cracked at 2/3 of their height, they still remain stable, dissipating energy through rigid body rocking.

References


Keywords: unreinforced masonry walls; out-of-plane response; rocking; shake table tests; construction quality