Out-of-Plane Seismic Behavior of Unreinforced Masonry In-filled Walls

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INTRODUCTION

In Taiwan, un-reinforced masonry (URM) was a common type of construction for low-rise buildings due to their low cost and ease of construction. At 1970s and 1980s, an improved type known as “confined masonry” became the mainstream. Confined masonry consists of pre-laid URM brick walls and post-constructed reinforced concrete (RC) boundary beams and columns. It is believed that the RC boundary elements provide confinement to the walls because of shrinkage of concrete. Usually the URM walls in confined masonry are 1-brick thick (24cm), but a confined masonry building is not allowed to exceed 3 stories or 10m high by the Taiwan Building Code. So after 1990s, URM walls are mostly used as pot-laid partition walls for RC buildings. However, there are still many existing confined masonry buildings, include residence, school, and public buildings in Taiwan. Former researches have confirmed the in-plane seismic capacity of URM walls. But in typical school and street side buildings that only have walls in one direction, the out-of-plane direction of the walls becomes the weak direction and the walls fail in their out-of-plane direction before the in-plane strength can fully contributed.

Therefore this paper presents an experimental investigation and an analytical approach for out-of-plane behavior and strength of URM walls in-filled in RC buildings subjected to lateral force. The experimental data comes from 2 in-site push over tests of typical school buildings by National Center for Research on Earthquake Engineering.

URM WALLS IN IN-SITE TESTS

Typical school buildings in Taiwan were found severe damaged in earthquakes. The main reason comes from the defects of their typical plan and structural system. As shown in Figure 1, usually a school building consists of classrooms along a corridor. Between classrooms are the URM partitions, mostly 1-brick thick. It makes the transverse direction much stronger than the longitudinal direction that has lots of openings. Therefore the typical school buildings usually collapse in the longitudinal direction and the URM walls fail in their out-of-plane direction.

Introduction of Tests

For research on seismic behavior of existing school buildings in Taiwan, 2 old school buildings about to be demolished were employed as specimens of in-site push over tests by NCREE [Tu, Hwang, and Chiou]. Both specimens are 2-floor typical school buildings, including a 3-
classroom unit of Hsin-Cheng junior high school, Hualien and 2-classroom original and reinforced units of Kouhu elementary school, Yunlin. The basic setup for each test is the same, as shown in Figure 2. Firstly the test unit was cut from building, then 6 hydraulic actuators were placed at each beam end of each floor to apply lateral load along the longitudinal direction. Steel bracings were placed in the spans behind actuators as reinforcement to provide reacting support. Lateral loads applied in the 1st floor and 2nd floor were controlled manually to remain the proportion 1:2 during the test to simulate earthquake load by fundamental mode of typical low-rise RC buildings.

![Typical School Building Structure](image1)

**FIGURE 1**
**TYPICAL SCHOOL BUILDING STRUCTURE**

![Basic Setup of In-Site Push Over Test](image2)

**FIGURE 2**
**BASIC SETUP OF IN-SITE PUSH OVER TEST**

(a) Hsin-Cheng specimen (roof drift 4%)
(b) Kouhu specimen (roof drift 6%)

**FIGURE 3**
**FINAL STAGE OF IN-SITE PUSH OVER TESTS.**

Figure 3 shows the 2 typical specimens at final stage of Hsin-Cheng and Kouhu test. Failure pattern similar to those happened in earthquake was found. Such like strong-beam-weak-column effect [Loh and Sheu] that causes prior failure of columns due to the rigid beams strengthened by slabs, and short-column effect by constraint of windowsills. Most damage and deformation happened at 1F since it carries larger lateral load than 2F does. Figure 4 shows the comparison between analytical and experimental push over curves. Although the analytical method has been verified by push over tests of plane structures, somehow it underestimates strength of both in-site specimens. So the difference between analytical and experimental curves is considered possibly
the out-of-plane contribution by URM walls. That is 507.0kN and 459.5kN for Hsin-Cheng and Kouhu test, respectively.

FIGURE 4
COMPARISON BETWEEN ANALYTICAL AND EXPERIMENTAL PUSH OVER CURVES.

Damage of URM Walls

Since the URM partition walls were pre-laid and well confined, they stayed within the RC boundary frames during the test, as shown in Figure 5. The main damage was horizontal cracks along the top and near bottom edges of the wall. It’s apparent that when the URM wall was subjected to a lateral load came from the slab above it, largest bending moment happened on its top and bottom edges. So cracks appeared at the tensile side of the edges since both brick and mortar are weak in tension. When loading increased, the main cracks became wider and wider in company with surface mortar spalling at the compressive side of wall. The final width of main cracks was about 8~10mm in both specimens.

FIGURE 5
DAMAGE OF URM WALLS IN IN-SITE PUSH OVER TESTS.

The main cracks of walls actually connected with the critical cracks of boundary columns. When the short-column effect made the critical section of column raised to top of windowsill, the bottom crack of wall was not really horizontal but formed gently ascent between the wall base and the top of windowsills, as shown in Figure 6. It indicates that the pre-laid URM walls might share partial stress of boundary columns.

Eight displacement gauges per wall were set on the elevation of 1 wall in Kouhu specimen and 2 walls in Hsin-Cheng specimen to measure out-of-plane deflection. Figure 7 shows the
relationship between height and out-of-plane deflection at the center line of walls. The vertical axis represents the height of URM walls and square marks show where the gauges were placed and the deflection they recorded. Disregarding a measuring error of Hsin-Cheng-1, all the walls showed rigid body rotation, like two-force members with both ends as hinges. The relationship between height and deflection keeps linear until the gauges were removed when the specimens were severe damaged. An approximate pivot can be found by extending the height-deflection lines to the vertical axis. The position of pivots is about 15~30cm, which agree with the position of bottom cracks.

FIGURE 6
HEIGHT AND FORM OF THE BOTTOM CRACKS CHANGED BY BOUNDARY CONDITION.

FIGURE 7
RELATIONSHIP BETWEEN HEIGHT AND OUT-OF-PLANE DEFORMATION OF URM WALLS.

FIGURE 8.
COMPRESSION TESTS FOR URM WALLS.
Material Property

Because bricks might behave differently when they become masonry, both bricks and URM walls were sampled for compression tests after the in-site tests. The bricks were cut into 2 halves and lapped into specimens according to CNS (Chinese National Standard), as shown in Figure 8(a).

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Analytical Model for Out-of-Plane Strength of URM Walls

For URM walls subjected to out-of-plane lateral load, former researches suggested that cracked sections can be considered as hinges. An URM wall has no resistance to overturning so it can only keep stable by its own weight [Doherty] or carry the lateral load by arching mechanism [Angel].

The in-site test result confirmed the concept. Therefore an analytical model for URM walls in-filled in RC frames subjected to out-of-plane lateral load is developed in this paper. As shown in Figure 9, conservatively assuming the tensile strength is nearly zero and the tensile zone is all cracked. Therefore the lateral load is carried by arching mechanism, which is a compressive strut from the loading point to the support end.

\[ P = T \cdot \sin \gamma \]  \hspace{1cm} (1)

where \( \gamma \) is the angle between strut and vertical axis. An essential in the equilibrium is the constraint force from the top beam and the base. Because of the thickness of wall, the constraint in vertical direction causes compression at 2 diagonal corners and forms the strut when the wall...
is trying to rotate. Without the constraint, such like an independent masonry wall, the wall would have to keep stable by its own weight. Axial load and weight of the wall is conservatively neglected in this model. Therefore the strut force can be calculated by integrating the compressive stress at the constrained zone. As shown in Figure 10, when the wall has rigid body rotation, 2 diagonal corners are compressed from their original shape to the height constraining line. Shadowed area in Figure 10(b) shows the compressed zone at one of the top corner. Assuming the boundary condition at top and bottom of wall is the same, the strut is formed between 2 reverse symmetrical compressed zones, as shown in Figure 10(a). Because of the reverse symmetry, compressive deformation of almost every fiber of the strut is the same and equal to the maximum deformation of one corner. So with the maximum compressive deformation $\delta$, compressive strain, compressive stress, and strut force can be derived.

![Diagram](image)

**FIGURE 10**
**DERIVATION OF THE STRUT FORCE T.**

The maximum compressive deformation $\delta$ is geometrically related to $b$, the compressive zone depth, and $\theta$, the out-of-plane drift angle of the wall, as shown in (2). The compressive zone depth $b$ can also be derived by geometrical relation as shown in (3). Then $\varepsilon_s$, the compressive strain of strut can be calculated by dividing $\delta$ by the length of strut, which is very close to the height of wall since $\gamma$ is usually very small, as shown in (4). The angle $\gamma$ between strut and vertical axis can also be found by geometrical relation in Figure 10, as shown in (5).

$$\delta = b \cdot \tan \theta \quad \text{(in cm)}$$

$$b = \frac{t}{2} \left( \frac{H}{2\sin \theta} + \frac{H}{2\tan \theta} \right) \quad \text{(in cm)}$$

$$\varepsilon_s = \frac{1}{2} \left( \frac{1}{2\cos \theta} + \frac{t}{2H} \right) \cdot \tan \theta$$

$$\tan \gamma = \frac{\varepsilon_s + \cos \theta - 1}{\sin \theta}$$

where $H$ is the efficient height between top and bottom cracks, $t$ is the thickness of the wall, respectively. Compressive stress $f_b$ is calculated by Angel’s equation [Angel], as shown in (6).
\[ f_b = \frac{27 f_m' (250 \varepsilon_{cr} - 1)}{4 \varepsilon_{cr}^3} \cdot \varepsilon^3 + \frac{27 f_m' (1 - 333 \varepsilon_{cr})}{4 \varepsilon_{cr}^2} \cdot \varepsilon^2 + E_0 \cdot \varepsilon \text{ (in kgf/cm}^2) \] (6)

where \( f_m' \) is the compressive strength and \( \varepsilon_{cr} \) is the crushing strain of masonry block, respectively. \( E_0 \) is elastic modulus of masonry block. By Angel’s suggestion, \( E_0 = 750 f_m' \) and 0.004 is used for \( \varepsilon_{cr} \) here.

Strut force then can be obtained by multiplying \( f_b \) by the strut area as shown in (7).

\[ A_T = \frac{b}{\cos \theta} \cdot \cos \gamma \cdot W \text{ (in cm}^2) \] (7)

where \( W \) is the width of wall. Finally by substituting (7) to (1), the lateral load \( P \) that corresponds to certain drift angle \( \theta \) can be obtained by (8).

\[ P = f_b \left( \frac{b}{\cos \theta} \cdot \cos \gamma \cdot W \right) \cdot \sin \gamma \text{ (in kgf)} \] (8)

In (8), both \( b \) and \( \gamma \) can be expressed by \( \theta \), so an out-of-plane lateral load-drift curve can be found. The maximum load \( P_{max} \) appears in the curve therefore means the out-of-plane strength of the wall.

**Comparison between Analytical and Experimental Result**

By substituting the efficient height, thickness, width, and compressive strength of masonry block of URM walls in Hsin-Cheng and Kouhu tests, relating curves between the variables above and out-of-plane drift \( \theta \) can be obtained as shown in Figure 11 and Figure 12.

The left graph in the upper row of Figures 11 and 12 shows that compressive zone depth \( b \) starts at 12cm, the center of section since there is no drift at all. Then it decreases due to cracks becomes larger with the increasing drift. Finally when \( b \) decreases to zero, it means all the section is cracked by tension and the wall can be considered collapse.

However, the maximum out-of-plane strength appears far before it. The compressive strain \( \varepsilon_s \) (middle one in the upper row) and stress \( f_b \) (middle one in the lower row) show trigonometric or polynomial but not linear relationships with the drift. Therefore the strut force \( T \) (middle one in the lower row) shows a nonlinear relationship with drift as well. Although the extreme values of all the 3 curves shows before \( b \) decreases to zero, they do not correspond to the same drift. So unlike usually expected for ordinary structural behavior, when the maximum compressive stress or strut force shows does not stand for when the maximum out-of-plane strength appears.

The relationship between \( \theta \) and the angle \( \gamma \) between strut and vertical axis (right one in the upper row) shows similar tendency with \( b \) does. They both look linear but actually are very flat trigonometric curves. The angle \( \gamma \) starts with very small value (2~3 degrees) and turns to negative quickly. It means the strut force can not provide balance component for lateral load when \( \gamma \) becomes zero. So the strut becomes useless when \( \gamma \) becomes negative.

Finally the relationship between out-of-plane lateral load \( P \) and corresponding drift shows approximately trigonometric curve with part of it being negative due to \( \gamma \). The positive maximum value of the curve is considered the out-of-plane lateral strength \( P_u \) of the walls. That is 59.4kN and 120.5kN for per URM wall in Hsin-Cheng and Kouhu test, respectively. The dotted lines in Figures 11 and 12 show the drift when maximum \( P \) happens, for most variables, such like the compressive strength of masonry block, it is not when their maximum happens.
FIGURE 11
RELATIONSHIPS BETWEEN VARIABLES AND DRIFT ANGLE $\theta$ OF THE URM WALL IN HSIN-CHENG TEST.

FIGURE 12
RELATIONSHIPS BETWEEN VARIABLES AND DRIFT ANGLE $\theta$ OF THE URM WALL IN KOUHU TEST.
The comparison between the analytical out-of-plane strength multiplied by number of URM walls and the experimental strength obtained from Figure 4 is shown in Table 1. It shows that the analytical model is too conservative for Hsin-Cheng specimen yet acceptable for Kouhu specimen. It is possibly due to the error at determination of experimental values and the conservative assumptions for analytical model.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Analytical strength (per wall)</th>
<th>Number of URM walls</th>
<th>Analytical strength (total)</th>
<th>Experimental strength</th>
<th>Error (Analytical to Experimental)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hsin-Cheng</td>
<td>59.4</td>
<td>4</td>
<td>237.6</td>
<td>507.0</td>
<td>-53.2%</td>
</tr>
<tr>
<td>Kouhu</td>
<td>120.5</td>
<td>3</td>
<td>361.5</td>
<td>459.5</td>
<td>-21.3%</td>
</tr>
</tbody>
</table>

TABLE 1
COMPARISON BETWEEN ANALYTICAL AND EXPERIMENTAL OUT-OF-PLANE STRENGTH OF URM WALLS

Figure 13 shows the main factors that affect the out-of-plane strength $P_u$ of URM walls. It can also be seen from the equations that $P_u$ is directly proportional to the compressive strength $f_m'$ of masonry block. The ratio of height to thickness ($H/t$) is found to be about inversely proportional to $P_u$. It means according to this model, higher or thinner URM walls are weaker in out-of-plane load as expected.

![Graph](a) $P_u$ vs. $f_m'$

![Graph](b) $P_u$ vs. $H/t$

FIGURE 13
MAIN FACTORS FOR OUT-OF-PLANE STRENGTH OF URM WALLS

CONCLUSIONS

From in-site tests of RC school buildings, failing and deforming behaviors of URM in-filled walls subjected to out-of-plane lateral load at the top are introduced generalized in this paper. Cracks appeared at the top and almost as soon as tensile stress happened in the walls. After cracking, the URM walls act like two-force members with hinged ends. It agrees with former researches.

Basic on the behavior of URM walls in in-site tests, an analytical model with arching mechanism concept is presented in this paper. It consists of some conservative assumptions and a theoretical derivation. The model shows that out-of-plane lateral strength if URM walls is directly proportional to compressive strength of masonry block, inversely proportional to the
ratio of height to thickness, and has nearly trigonometric relationship with out-of-plane lateral drift.

Comparison between analytical and experimental results shows that the analytical model is acceptable and conservative. Future researches on both static and dynamic out-of-plane behavior of in-filled URM walls is still needed.

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REFERENCES