PREDEFINED DAMAGE PATTERNS FOR LIMIT ANALYSIS ON NON-ENGINEERED MASONRY BUILDINGS

Cemal ICEL¹, Murat Altug ERBERIK², Mustafa Tolga YILMAZ³

ABSTRACT

Non-engineered masonry construction still constitutes a significant percentage of building stocks, especially in earthquake-prone Mediterranean, Asian and South American countries. It is not easy to quantify the seismic performance of this building type, because the analytical and numerical methods, which have been developed so far, generally work for engineered masonry buildings with specific design and construction practices. For such buildings, it is easy to define the load transfer paths through well-defined structural members. However, non-engineered masonry buildings generally do not have well-quantified material properties, rigid floor diaphragms and adequate floor-to-wall or wall-to-wall connections in order to ensure such a load path. Hence the use of conventional analysis tools become meaningless or even misleading since the seismic behavior of non-engineered buildings contradicts with the fundamentals of structural analysis and modeling, on which these analysis tools are based on. In such cases, the use of kinematical approach, which is mostly based on observed performance and damage on the considered building type, may provide a practical solution. This study aims to propose prescribed in-plane damage mechanisms and crack patterns for solid and perforated masonry walls by using the available post-earthquake field data obtained from damaged masonry buildings and experimental data obtained from masonry specimens. These predefined damage and crack patterns can be used as an input for limit analysis theorems in order to estimate the lateral load capacity of non-engineered masonry buildings.

Keywords: Non-engineered masonry; Kinematical analysis; In-plane wall damage; Crack pattern

1. INTRODUCTION

Masonry is still one of the most common construction types in the world due to the accessibility of materials in any environment conditions, ease of application, and low costs. Despite having many categories in masonry structures, one of the most critical types is unreinforced masonry (URM) structure. URM structures have high compressive strength under axial loads, yet have little or no tensile strength, which often leads to failure in a brittle manner. Types of which are especially common in rural areas, behavior under seismic actions are not accurately estimated due to the fact that there is no control in the construction process, material properties are not precisely known, and they are generally constructed with previous experiences in a traditional manner. Therefore, they can generally be considered as non-engineered structures.

This paper focuses on the development of pre-established rules regarding crack patterns and damage propagation for URM solid or perforated walls. In order to develop these rules, both observed data (either from field surveys or from laboratory tests) and numerical data (from parametric analysis) are employed. The developed set of rules is intended to be used to predict the failure surfaces for the façades of non-engineered URM buildings. Finally this information can assist the estimation of lateral failure load through limit analysis. Hence this approach provides a practical and reliable way to predict the lateral load capacity of non-engineered URM buildings without performing any detailed analysis.

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2. FIELD OBSERVATIONS FOR DAMAGED MASONRY WALLS

The main objective of this section is to comprehend the observed in-plane damage and failure modes of masonry walls by examining the effect of geometry, material properties, axial stress and perforations in the wall (i.e. the number and location of wall openings). Masonry wall damage is investigated in three different subsections, which focus on field observation of damage on perforated masonry walls, experimental observation of damage on solid masonry walls and experimental observation of damage on perforated masonry walls, respectively.

2.1 Field Observation of Damage on Perforated Masonry Walls

A vast number of post-earthquake field investigation reports have been studied and photos of damaged masonry structures have been collected for this purpose. After a thorough investigation, damaged walls are categorized into six types according to the number and type (either door or window) of wall openings as follows:

Wall Type =1 (PF1); Window Opening =1,
Wall Type =2 (PF2); Door Opening =1,
Wall Type =3 (PF3); Door Opening =1, Window Opening =1,
Wall Type =4 (PF4); Window Opening =2,
Wall Type =5 (PF5); Window Opening ≥2,
Wall Type =6 (PF6); Door Opening ≥1, Window Opening ≥2

The wall types are explained in Table 1 with some explanatory figures and related references. Although numerous field surveys have been investigated, only a typical reference with a single photo for each type has been presented due to page limitations.

Table 1. Description of wall types due to post-earthquake field observations

<table>
<thead>
<tr>
<th>Damaged Wall Photo</th>
<th>Wall and Damage Description</th>
</tr>
</thead>
</table>
| ![Wall type 1 / PF1](image1) | **Wall type 1 / PF1**  
*Vertical stress:* Low  
*Material type:* Solid clay brick  
*Failure mode:* Diagonal tension failure is observed. Cracks were initiated from the corner points of the opening and propagated towards the edges of the masonry wall.  
*Reference:* Javed et al. (2006) |
| ![Wall type 2 / PF2](image2) | **Wall type 2 / PF2**  
*Vertical stress:* Low  
*Material type:* Hollow clay brick  
*Failure mode:* X-shaped diagonal tension failure is observed. Piers have an aspect ratio (λ) about 1.0.  
*Reference:* Javed et al. (2006) |
| ![Wall type 3 / PF3](image3) | **Wall type 3 / PF3**  
*Vertical stress:* Medium  
*Material type:* Clay brick  
*Failure mode:* Diagonal tension failure is observed. Cracks are initiated from the corner points of the openings and propagated towards the other openings corner points or edges of the wall. Rocking failure is also observed at middle pier.  
*Reference:* Javed et al. (2006) |
Table 1 (cont’d) Description of wall types due to post-earthquake field observations

<table>
<thead>
<tr>
<th>Damaged Wall Photo</th>
<th>Wall and Damage Description</th>
</tr>
</thead>
</table>
| ![Wall type 4 / PF4](image1) | **Wall type 4 / PF4**  
*Vertical stress:* Low  
*Material type:* Stone unit  
*Failure mode:* Diagonal tension failure is observed. Cracks are initiated from the corner points of the opening and propagated towards the adjacent openings’ corner point or to the edges of the wall.  
| ![Wall type 5 / PF5](image2) | **Wall type 5 / PF5**  
*Vertical stress:* Low  
*Material type:* Clay brick  
*Failure mode:* Diagonal tension failure is observed. Cracks are initiated from the corner points of the opening and propagated towards the adjacent openings’ corner points and to the edges of the wall. Sliding shear failure is observed at the bottom end of middle pier.  
*Reference:* Javed et al. (2006) |
| ![Wall type 6 / PF6](image3) | **Wall type 6 / PF6**  
*Vertical stress:* Low  
*Material type:* Adobe unit  
*Failure mode:* Diagonal tension failure is observed. Cracks are initiated from the corner points of the opening and propagated towards the adjacent openings’ corner point and to the edges of the wall.  

The above figures depict that the number and location of the openings have significant effect on determining the failure modes for URM walls. It may be possible to predict the type and propagation of cracks through this classification.

### 2.2 Experimental Observation of Damage on Solid Masonry Walls

It is essential to examine the in-plane behavior and the correlated damage modes of solid masonry walls since such walls exist in almost all of the masonry buildings. Moreover, in-plane behavior of piers in perforated walls has lots of similarities with the in-plane behavior of simple solid walls.

There exist different failure modes in solid URM walls. These failure modes depend on different parameters, most importantly, material type, aspect ratio, $\lambda$ (i.e. length / height ratio), vertical axial stress ($\sigma_y$) and compressive strength of masonry units ($f_m$). In order to relate the in-plane failure modes of solid masonry walls with the aforementioned parameters, 60 different solid URM wall experiments have been examined. In Table 2, only typical experiments that represent different failure modes of solid walls are given.

The in-plane failure models of solid masonry walls with their numbers that appear in Table 2 can be listed as follows:

1) Diagonal tension failure  
2) Sliding shear failure  
3) Rocking - flexural (toe crush) failure  
4) Mixed failure mode
In addition, the abbreviations used for the material types in Table 2 can be described as follows: SCB (solid clay brick with lime/cement mortar), HCB (hollow clay brick with lime/cement mortar).

Table 2. Summary table for failure modes of different solid wall experiments

<table>
<thead>
<tr>
<th>Specimen no</th>
<th>Masonry Material</th>
<th>Aspect Ratio (λ)</th>
<th>Length (m)</th>
<th>Height (m)</th>
<th>Thickness (mm)</th>
<th>Unit Compress. Strength (MPa)</th>
<th>Vertical Axial Stress (MPa)</th>
<th>Lateral Load (kN)</th>
<th>Failure Mode</th>
<th>Reference Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>SCB</td>
<td>1.0</td>
<td>0.6</td>
<td>0.6</td>
<td>90</td>
<td>8.44</td>
<td>0.42</td>
<td>54</td>
<td>1</td>
<td>Basoenondo (2008)</td>
</tr>
<tr>
<td>S2</td>
<td>SCB</td>
<td>1.0</td>
<td>0.6</td>
<td>0.6</td>
<td>90</td>
<td>8.44</td>
<td>0.17</td>
<td>74</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>HCB</td>
<td>1.1</td>
<td>2.0</td>
<td>2.25</td>
<td>195</td>
<td>8.99</td>
<td>1.07</td>
<td>187</td>
<td>1</td>
<td>Petry and Beyer (2015)</td>
</tr>
<tr>
<td>S4</td>
<td>HCB</td>
<td>1.1</td>
<td>2.0</td>
<td>2.25</td>
<td>195</td>
<td>9.75</td>
<td>1.07</td>
<td>178</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>HCB</td>
<td>1.1</td>
<td>2.0</td>
<td>2.25</td>
<td>195</td>
<td>12.00</td>
<td>1.07</td>
<td>121</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>HCB</td>
<td>1.1</td>
<td>2.0</td>
<td>2.25</td>
<td>195</td>
<td>11.70</td>
<td>1.58</td>
<td>145</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>S7</td>
<td>HCB</td>
<td>1.1</td>
<td>2.0</td>
<td>2.25</td>
<td>195</td>
<td>9.02</td>
<td>1.58</td>
<td>132</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>S8</td>
<td>HCB</td>
<td>1.5</td>
<td>1.0</td>
<td>1.5</td>
<td>300</td>
<td>4.00</td>
<td>0.60</td>
<td>-</td>
<td>3</td>
<td>Petry and Beyer (2014)</td>
</tr>
<tr>
<td>S9</td>
<td>HCB</td>
<td>1.5</td>
<td>1.0</td>
<td>1.5</td>
<td>300</td>
<td>4.10</td>
<td>1.19</td>
<td>-</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

The gathered experimental data provides some information regarding the effect of the considered parameters on the in-plane behavior of tested walls. For instance, it is observed that as the axial load increases, the failure mode turns to diagonal cracking whereas for low levels of axial load, sliding shear and rocking mode is more common. In addition, as the aspect ratio increases (i.e. slender wall), rocking behavior becomes pronounced when compared to other behavior modes. Hence it seems to be possible to develop practical rules from the experimental database regarding cracking pattern and propagation of solid masonry walls.

2.3 Experimental Observation of Damage on Perforated Masonry Walls

In order to verify the observed damage patterns and failure modes from post-earthquake field surveys, failure modes and crack propagations of perforated masonry wall specimens in experimental studies are also investigated by considering the same wall types explained in Section 2.1. Among numerous experimental studies considered, six of them are presented in the Table 3.

The experimental results on perforated masonry walls provide valuable insight regarding crack patterns and crack propagation around the openings. It is observed that in most of the cases cracks initiate from the corners of the openings and propagate towards the adjacent corner of the opening or the wall. Depending on the location and size of the openings, the cracks can be vertical, horizontal or inclined. Due to rocking motion, corner of piers generally exhibit horizontal cracking whereas if the pier is subjected to severe horizontal and vertical loads, diagonal cracks exist on the wall. In some of the cases, it is possible to observe a mixed type of damage where there are more than one crack pattern.
Table 3. Damaged perforated wall types in experimental studies

<table>
<thead>
<tr>
<th>Damaged Wall Photo</th>
<th>Wall and Damage Description</th>
</tr>
</thead>
</table>
| ![Wall type 1 PE1](image) | **Wall type 1 / PE1**  
  *Vertical Stress:* Low  
  *Material type:* Solid clay brick  
  *Failure Mode:* Diagonal tension failure is observed. Cracks are initiated at the corners of the openings and propagated towards the edges of the wall.  
  *Experimental campaign:* Static cyclic.  
  *Reference:* Kalali and Kabir (2012) |
| ![Wall type 2 PE2](image) | **Wall type 2 / PE2**  
  *Vertical Stress:* Low  
  *Material type:* Adobe unit  
  *Failure mode:* Diagonal tension failure is observed. Cracks are initiated at the corners of the openings and propagated towards the edges of the wall.  
  *Experimental campaign:* Shaking table.  
  *Reference:* Elvin and Uzoegbo (2011) |
| ![Wall type 3 PE3](image) | **Wall type 3 / PE3**  
  *Vertical Stress:* Low  
  *Material:* Clay brick  
  *Failure Mode:* Diagonal Tension Failure is dominant in all piers. Cracks were initiated from the corners of the openings and propagated to the adjacent openings’ corner point and to the edges of the wall.  
  *Experimental campaign:* Static cyclic.  
| ![Wall type 4 PE4](image) | **Wall type 4 / PE4**  
  *Vertical Stress:* Low  
  *Material type:* Hollow clay brick  
  *Failure Mode:* Diagonal Tension Failure is dominant in outer piers. Rocking failure is observed at the bottom of middle pier.  
  *Experimental campaign:* Static cyclic.  
  *Reference:* Irimes and Bia (2000) |
| ![Wall type 5 PE5](image) | **Wall type 5 / PE5**  
  *Vertical Stress:* Low  
  *Material type:* Solid clay brick  
  *Failure Mode:* Sliding shear failure is observed at the lowest part of the ground floor wall. Rocking and diagonal tension failure is observed at piers.  
  *Experimental campaign:* Static cyclic.  
  *Reference:* Moon et al. (2007) |
| ![Wall type 6 PE6](image) | **Wall type 6 / PE6**  
  *Vertical Stress:* Low  
  *Material type:* Solid clay brick  
  *Failure Mode:* Diagonal tension failure the dominant failure mode at all piers. Cracks were initiated from the corner points of the opening and propagated towards the adjacent openings’ corner point and to the edges of the wall  
  *Experimental campaign:* Static cyclic.  

The experimental results on perforated masonry walls provide valuable insight regarding crack patterns and crack propagation around the openings. It is observed that in most of the cases cracks
initiate from the corners of the openings and propagate towards the adjacent corner of the opening or the wall. Depending on the location and size of the openings, the cracks can be vertical, horizontal or inclined. Due to rocking motion, corner of piers generally exhibit horizontal cracking whereas if the pier is subjected to severe horizontal and vertical loads, diagonal cracks exist on the wall. In some of the cases, it is possible to observe a mixed type of damage where there are more than one crack pattern.

If observed damage data is compared with experimentally obtained data, it seems that these two databases can be used together to propose common rules regarding damage and crack mechanics of different types of masonry walls.

3. NUMERICAL MODELING OF URM WALLS

Field or experimental observations provide invaluable data to develop predefined damage and failure mechanisms for URM walls. However obtained data is never a complete set due to either limited observations in the field or economical constraints in laboratory studies. Therefore, numerical analysis always fills the gap for required missing data to have a complete parametric set. Accordingly, in this study, numerical analyses are employed together with observational data in order to predict the failure patterns of solid or perforated URM walls.

In this section, crack initializing locations and failure modes of masonry walls are determined for 6 different cases (PE1~PE6) that are selected in Section 2.3 by using numerical analysis. Numerical models developed for these cases are analyzed in two steps by using the SAP2000 (CSI, 2009) software.

In the first step, non-linear pushover analysis is performed. Lateral force vs. top displacement curves are developed for URM wall models and these curves are compared with the experimental results. First step of analysis can be regarded as a verification step for the URM wall models by comparing the experimental and numerical curves.

In the second step, simplified failure analysis is performed for the same wall models. Under ultimate lateral loading, stress distributions of the walls are developed. By employing the Coulomb-Mohr failure criteria, crack initializing locations are determined. Thus, predominant stress states in different wall regions are obtained.

3.1 Nonlinear Pushover Analysis of URM Wall Models

Displacement controlled nonlinear static pushover analysis is performed and top joint displacements are monitored for each selected specimen (PE1~PE6) in Table 4. Material properties are taken from the related experimental studies.

For stress-strain characteristics of the walls, compression model of masonry in Figure 1 that proposed by Kaushik et al. (2007) is used. Tension behavior of masonry is modeled based on Dhanasekar et al. (2007) study as presented in Figure 2. Elasticity modulus of masonry is determined based on study of Kaushik et al. (2007) and presented in Equation 1. Poisson’s ratio (ν) of masonry is taken as 0.2 as per Mosalam et al. (2009) in case it is not mentioned in related study. Internal friction angle (θ) for clay bricks is taken as 30°~40° based on Kawa et al. (2007) in case the internal friction angle is not mentioned in the referred study.

\[ E_m = 250 \sim 1100 \times f_m \] (1)
The comparison reveals that numerical and experimental curves are generally close to each other. Hence this modeling strategy can be used in a parametric study to investigate the influence of different structural parameters on damage and crack mechanics of URM walls.

Table 4. Comparison graphs of the experimental results and non-linear analysis results.

<table>
<thead>
<tr>
<th>Spec. No</th>
<th>Wall Model View</th>
<th>Comparison Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE1</td>
<td><img src="image1.png" alt="Wall Model View" /></td>
<td><img src="image2.png" alt="Comparison Graph" /></td>
</tr>
</tbody>
</table>

![Figure 1. Compression material model of masonry](image3.png)

![Figure 2. Tension material model of masonry](image4.png)
Table 4 (cont’d). Comparison graphs of the experimental results and non-linear analysis results.

<table>
<thead>
<tr>
<th>Spec. No</th>
<th>Wall Model View</th>
<th>Comparison Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE2</td>
<td><img src="image1" alt="Wall Model View" /></td>
<td><img src="image2" alt="Comparison Graph" /></td>
</tr>
<tr>
<td>PE3</td>
<td><img src="image3" alt="Wall Model View" /></td>
<td><img src="image4" alt="Comparison Graph" /></td>
</tr>
<tr>
<td>PE4</td>
<td><img src="image5" alt="Wall Model View" /></td>
<td><img src="image6" alt="Comparison Graph" /></td>
</tr>
</tbody>
</table>
Table 4 (cont’d). Comparison graphs of the experimental results and non-linear analysis results.

<table>
<thead>
<tr>
<th>Spec. No</th>
<th>Wall Model View</th>
<th>Comparison Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE5</td>
<td>![PE5 Image]</td>
<td>![Comparison Graph PE5]</td>
</tr>
<tr>
<td>PE6</td>
<td>![PE6 Image]</td>
<td>![Comparison Graph PE6]</td>
</tr>
</tbody>
</table>

For the modeled specimens; calculated ultimate strengths for PE1, PE5 and PE6 considerably match with the experimental results. Furthermore, initial stiffness values for modeled specimens PE1, PE3, PE4 and PE6 match with the experimental curves. But, as it can be seen from the Table 4, there are differences regarding initial stiffness and ultimate strength values for some specimens. These differences are believed to occur from the gross assumptions about mechanical properties of the specimens as mentioned in Chapter 3.1 since it is very difficult to adopt the exact mechanical properties of masonry material. However, from the general point of view, non-linear analysis for perforated masonry walls can provide reasonable results compared with the experimental studies and it can be stated that this modeling approach can be used to estimate the behavior of URM walls.

3.2 Determination of Crack Initializing Locations

In simplified failure analysis, stresses in shell elements of URM wall models are obtained under ultimate loading conditions. By using these shell stresses, Coulomb-Mohr stresses are calculated. Then, calculated Coulomb-Mohr stresses are normalized by ultimate material capacities for individual shell elements as shown in Table 6. The same table also includes the color codes used to demonstrate the stress distribution in shell elements in Table 5.

As observed in Table 5, colored shells are categorized into six cases. The first classification represents the stress states of related cell such as, “Pure Tension, Pure Compression and Tension / Compression”. The second classification represents whether the shell element reaches its failure limit capacity or it is still below this limiting stress value. This is achieved by calculating the stress ratio of each shell (i.e. calculated stress/Coulomb-Mohr failure stress). If this ratio exceeds 1.0, this means failure is reached or exceeded (F) whereas if it is a lower value than 1.0, the failure limit is not reached or exceeded (NF).
Figure 3 is a more detailed explanation of Table 5, where stress states are presented in stress space with Coulomb-Mohr failure criterion also given in the same figure.

Table 5. Stress States and Color Codes

<table>
<thead>
<tr>
<th>Color Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT, NF</td>
<td>Pure Tension. Failure is not expected</td>
</tr>
<tr>
<td>PT, F</td>
<td>Pure Tension. Failure is expected</td>
</tr>
<tr>
<td>PC, NF</td>
<td>Pure Compression. Failure is not expected</td>
</tr>
<tr>
<td>PC, F</td>
<td>Pure Compression. Failure is expected</td>
</tr>
<tr>
<td>CT, NF</td>
<td>Tension and Compression. Failure is not expected</td>
</tr>
<tr>
<td>CT, F</td>
<td>Tension and Compression. Failure is expected</td>
</tr>
</tbody>
</table>

Table 6. Color categorized stress distribution of wall models

<table>
<thead>
<tr>
<th>Spec. No</th>
<th>Wall Model View</th>
<th>Expected Crack Pattern</th>
<th>Description of Stress Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE1</td>
<td><img src="image1.png" alt="Wall Model View" /></td>
<td><img src="image2.png" alt="Expected Crack Pattern" /></td>
<td>Two cross corners of the opening and corners of the walls have exceeded their stress limits.</td>
</tr>
<tr>
<td>PE2</td>
<td><img src="image3.png" alt="Wall Model View" /></td>
<td><img src="image4.png" alt="Expected Crack Pattern" /></td>
<td>Top left corner of the opening and lowest left corners of the wall piers have exceeded their stress limits.</td>
</tr>
</tbody>
</table>
Table 6 (cont’d). Color categorized stress distribution of wall models

<table>
<thead>
<tr>
<th>Spec. No</th>
<th>Wall Model View</th>
<th>Expected Crack Pattern</th>
<th>Description of Stress Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE3</td>
<td>![Wall Model View](Image 275x627 to 398x715)</td>
<td>![Expected Crack Pattern](Image 293x309 to 380x393)</td>
<td>Bottom right corner of window opening and top left of the door opening have exceeded their stress limits.</td>
</tr>
<tr>
<td>PE4</td>
<td><img src="292x56" alt="Wall Model View" /></td>
<td><img src="409x483" alt="Expected Crack Pattern" /></td>
<td>Cross corners of the openings and mid height of the all piers have exceeded their stress limits.</td>
</tr>
<tr>
<td>PE5</td>
<td><img src="292x56" alt="Wall Model View" /></td>
<td><img src="409x483" alt="Expected Crack Pattern" /></td>
<td>Cross corners of the openings have exceeded their stress limits.</td>
</tr>
<tr>
<td>PE6</td>
<td><img src="292x56" alt="Wall Model View" /></td>
<td><img src="409x483" alt="Expected Crack Pattern" /></td>
<td>Cross corners of window openings and lowest left corners of the first and third piers have exceeded their stress limits.</td>
</tr>
</tbody>
</table>

By examining the shell elements with maximum stress, crack initializing locations of the walls can be determined. Furthermore, when the stress distribution on the wall model is investigated, crack propagation of the walls can be estimated. Expected crack patterns for each specimen are marked in Table 6.

4. CONCLUSIONS

According to the recently conducted and ongoing work in this research, the following conclusions can be stated regarding the development of predefined damage patterns for limit analysis on non-engineered masonry buildings:

1) Axial stress ratio, aspect ratio and brick/mortar quality seem to play an important role on failure type of solid and perforated walls. Diagonal tension failure is observed rather than rocking failure for URM walls with low axial load. Sliding shear failure commonly occurs for low quality of mortar/brick. Diagonal tension failure is mostly observed when λ is equal to or
smaller than 1.0. Rocking failure is mostly observed when $\lambda$ is larger than 1.5. Sliding shear failure is observed when $\lambda$ is smaller than 1.0.

2) In perforated URM walls, most failures are initiated from the corners of the openings. Crack propagations tend to find the shortest way to another stress concentrated location such as corners of walls or edges of the wall. Also, it is observed that the expected crack patterns in Table 6 match with the experimental results in Table 3.

3) Nonlinear analysis results are compatible with the experimental results. This shows that experiments are accurately established and nonlinear analysis give reasonable results for URM wall calculations.

4) Overall, damage data gathered from the field and experimental observations together with numerical modeling output seems to be encouraging for the development of predefined rules regarding crack patterns and failure lines in limit analysis of non-engineered masonry buildings.

5. REFERENCES


