# Seismic Performance Evaluation of Reinforced Concrete Structures with Infill Masonry Walls Containing Various Opening Locations

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## ABSTRACT

The seismic performance of reinforced concrete (RC) structures with infill masonry walls (UMW) is significantly influenced by the presence and various locations of openings within the walls. This research evaluates the effects of different opening locations on the strength and stiffness of RC frame structures. UMW, commonly used in Afghanistan, is typically neglected in structural design despite their substantial contribution to the overall stability of RC buildings. This study focuses on introducing a reduction factor based on the net area of the UMW and the average strut angle to estimate the force-deformation curve of UMW with various opening locations. The proposed method is validated by comparing it with experimental test results and analytical method results, demonstrating its accuracy and applicability. The results indicate that the new reduction factor effectively predicts the seismic performance of RC structures with UMW containing different opening locations, providing a practical tool for engineers and researchers. This study underscores the importance of considering UMW in structural analysis to enhance the seismic resilience of RC buildings. Furthermore, implementing the reduction factor into existing design codes can significantly improve the safety margins of RC structures in seismic regions. A parametric study conducted as part of this research highlights the critical influence of opening size and location on the seismic behaviour of UMW. In addition, this research has applied nonlinear dynamic analysis to evaluate the structure's response, confirming the robustness of the proposed reduction factor.

# 1 INTRODUCTION

Unreinforced masonry walls (UMWs) have been the preferred choice for partitioning in reinforced concrete (RC) structures across nearly all regions of Afghanistan for the past three decades. Burned bricks, commonly used for both interior and exterior walls, are readily available and help reduce construction costs compared to alternative materials. From a structural perspective, UMWs contribute to the overall strength, stiffness, and durability of buildings. However, their effect on structural stability depends on detailing, reinforcement, and connection to the RC frame. Despite their influence on structural behavior, UMWs are often overlooked as structural components during the analysis and design phases.

Large earthquakes have posed a significant threat to building structures over the past decades, resulting in human casualties and economic losses. One recent example in Afghanistan is the October 2015 Hindu Kush earthquake, which resulted in 117 deaths and 544 injuries, according to the United States Geological Survey (USGS) (USGS, 2016). Afghanistan is situated within the Alpine-Himalayan belt, which was formed by the collision of the Indian, Eurasian, and Arabian tectonic plates (Shnizai, 2020). This study reveals that 22 active faults have been identified across Afghanistan. Among these, the Chaman Fault is a significant concern. This fault extends for approximately 650 kilometers within Afghanistan and passes through the Kabul region, exhibiting a northward movement of 3 centimeters per year. Research conducted by Riaz et al. indicates that the Chaman Fault can generate potent ground motions with the potential for considerable destruction .

Even though considerable research, experiments, and studies have been conducted on RC structures with UMWs, there is less emphasis on how variations in opening sizes and locations within these walls affect a structure’s seismic performance. The International Building Code (IBC), the American Society of Civil Engineers (ASCE), the Federal Emergency Management Agency (FEMA), and various other standards primarily focus on estimation procedures to assess the impact of UMWs on RC structures. According to these guidelines, UMWs contribute to the lateral strength and rigidity of RC frames, depending on their configuration, attachment, and detailing.

Maidiawati et al. have done a series of experiments on a one-bay, single-story RC frame with brick masonry walls containing different opening ratios (Maidiawati *et al.*, 2019). The considered models were ¼ scale RC frames containing a bare frame (BF), an RC frame with a brick-masonry wall, and two RC frames with infill masonry of 25% and 40% central openings. The first experiment focused on the seismic performance of reinforced concrete frames with brick masonry walls containing different central opening sizes. The second showed single openings had less stiffness reduction than two openings, significantly reducing lateral strength. In the third experiment, the sample remained identical to that in the first experiment, with the sole exception being the inclusion of two horizontal rebars placed at the bottom and top of the opening. The outcome of this third test closely resembled that of the first experiment.

Tanjung et al. conducted experimental research on a one-bay, single-story RC frame with full brick masonry walls (Tanjung *et al.*, 2019). The experiments included one specimen of an RC frame infilled with brick masonry, one with brick masonry strengthened using chicken wire mesh, and another infilled with brick masonry anchored to the columns with plain steel rebars. The results showed that strengthening with chicken wire mesh increased the lateral strength of the RC frame by about 22%, while using plain steel rebar anchors decreased it by about 1.8%. Similarly, Ahani et al. conducted experimental research involving a one-bay, single-story RC frame with an UMW featuring a central opening that constituted 19% of the wall's area (Ahani *et al.*, 2019a). Following the experimental findings, numerical models were developed to incorporate various central opening ratios and were compared with other numerical research. The goal was to propose a strength reduction factor for estimating the effect of central openings on the seismic performance of UMWs.

Following the findings derived from the finite element method, Asteris P. G. et al. suggested an equation to estimate the initial lateral stiffness of UMWs containing openings (Asteris *et al.*, 2011). Naqi and Saito assessed the performance of RC low-rise buildings with reinforced masonry infill and proposed a damage index to examine the vulnerability of these structures (Naqi and Saito, 2017). Similarly, Sharafi et al. (Sharafi and Saito, 2023) investigated the impact of brick masonry walls on the seismic performance of a RC school building. They observed that brick masonry walls could reduce the building's vulnerability and enhance its seismic performance.

The primary objective of this research is to introduce a new reduction factor that utilizes the net area of the UMW and the average strut angle to estimate the force-deformation curve of UMWs containing openings in various locations. This method expands on the research conducted by Sharafi and Saito (Sharafi and Saito, 2023). The analysis is performed using the nonlinear frame analysis program, STERA 3D, which was developed by one of the authors (Saito, 2024). In this program, the backbone curve of the masonry element is defined, including the deterioration of the bearing capacity after yielding.

## 2 MODELS FOR OPENING LOCATIONS IN INFILL MASONRY WALLS

The opening, usually used for doors and windows, can be in any position of the UMWs. This research considers the opening location in various scenarios, including central opening, top-left or top-right opening, upper-middle opening, middle left or middle right opening, and door opening. In the suggested method, the UMWs with the opening is divided into segments that are around the opening, as shown in Figure 1. Equation 1 calculates the net area of the UMWs. Each segment around the opening has a different diagonal strut angle, so the average strut angle is calculated as Equation 2. Equations 3 and 4 obtain the width and height of the new UMWs with net area.

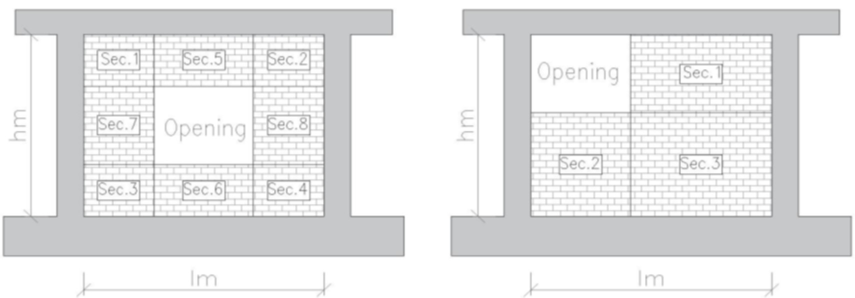
$$A_m - A_{op} = A_{net} \tag{1}$$

$$\theta_{(avg)} = \frac{\sum_{i=1}^{n=8} (A_i \times \theta_i)}{\sum_{i=1}^{n=8} (A_i)} \tag{2}$$

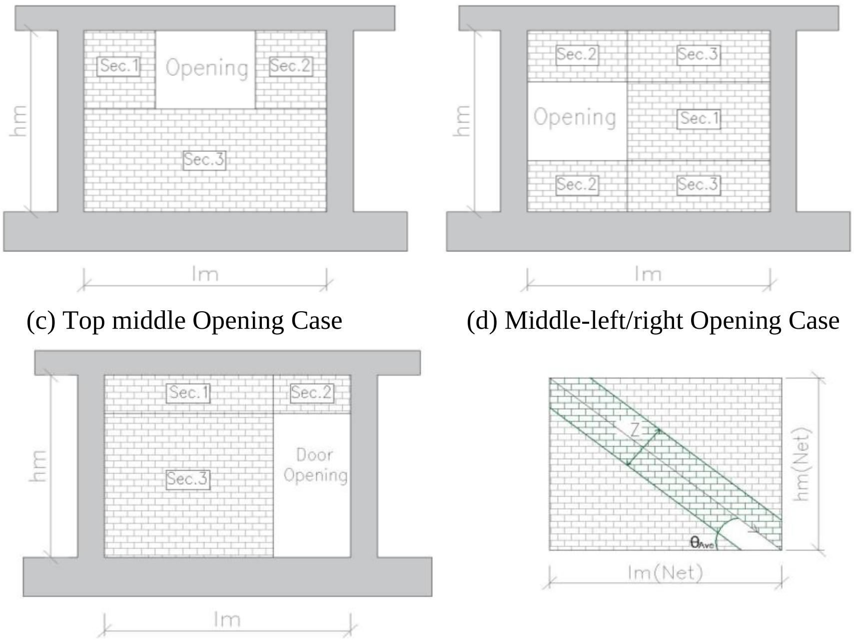
$$l_{(m)} = \sqrt{\frac{A_{net}}{\tan(\theta_{avg})}} \tag{3}$$

$$h_{(m)} = \sqrt{A_{net} \times \tan(\theta_{avg})} \tag{4}$$

where $A_m$ is the area of masonry wall, $A_{op}$ is the area of the opening, $A_{net}$ is the net area of masonry wall, $\theta_{avg}$ is the average strut angle, $l_{(m)}$ is the length of the masonry wall, $h_{(m)}$ is the height of masonry, $\theta_i$ is the strut angle of $i_{th}$ segments and $A_i$ is the area of $i_{th}$ segments.




(a) Central Opening Case (b) Top-left/right Opening Case



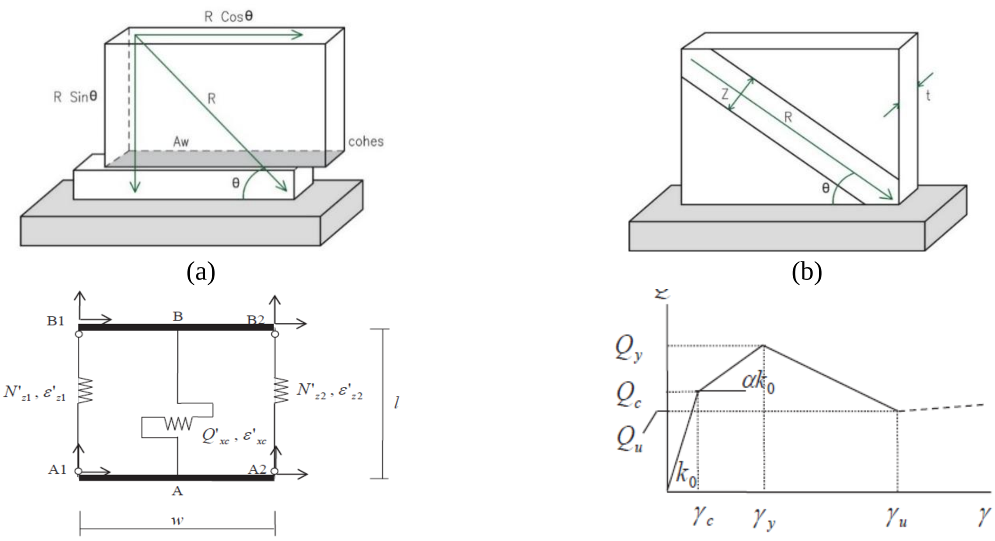

(c) Top middle Opening Case (d) Middle-left/right Opening Case

(e) Door Opening Case (f) Masonry wall with net area

*Figure 1. Proposal of the model of the infill masonry wall with a central opening*

## 3 INFILL MASONRY WALL BACKBONE CURVE

In this study, STERA 3D was used to analyze the UMWs within the RC frame. The element model for the UMW is defined in STERA 3D as comprising a nonlinear shear spring located in the middle of the wall panel and two vertical springs, as illustrated in Figure 2c. The force-deformation curve of the shear spring is modeled with a tri-linear backbone curve, depicted in Figure 2d. The shear resistance at the yielding point is calculated as the minimum value between the shear strength from sliding shear failure (Figure 2a) and the shear strength from diagonal compression failure (Figure 2b), according to Equations 5 to 7. The methodology for determining the forces and deformations at the crack point ($Q_c$ and $\gamma_u$) and the ultimate point (($Q_u$ and $\gamma_u$) is based on the STERA_3D manual (Saito, 2024).




(a) (b)

(c) (d)

*Figure 2. STERA 3D models for infill masonry wall*

$$Q_y = \min(V_f, V_c) \tag{5}$$

$$V_f = \frac{\tau_0 \times A_w}{1-\mu \tan\theta} \tag{6}$$

$$V_C = Z \times t \times f'_m \times \cos\theta \tag{7}$$

Where $\tau_0$ is the cohesive capacity of the mortar beds (= $0.04 f'_m$, Paulay and Priestley (1992) ), $A_w$ is the cross-sectional area of the masonry wall, $\mu$ is the sliding friction coefficient along the bed joint, $Z$ is the width of the diagonal strut ( $Z = 0.25d$ ), $f'_m$ is the compressive strength of a masonry prism. Parameter d and t are the diagonal length of the masonry wall and the thickness of the masonry, respectively.

## 4 EARTHQUAKE RESPONSE ANALYSIS OF MODEL WITH STERA 3D

The STERA 3D software was employed to conduct earthquake response analysis for UMW within the RC frames. STERA 3D is a finite element-based software developed by one of the authors (Saito, 2024) and takes into account the nonlinear behaviour of materials and cross-sectional geometry. The line element model represents the RC beam element with two nonlinear flexural springs at both ends and one shear spring in the middle, as shown in Figure 3. It also represents the column element, incorporating nonlinear axial springs distributed at both ends and two nonlinear shear springs in the middle to capture the element's directional characteristics. For both beams and columns, the reinforcing steel strength is modified to be 1.1 times the nominal strength, and the ratio of post-yield stiffness to initial stiffness is set at 0.001. The beam-column connections are assumed to be rigid in the current research. The hysteresis model of the nonlinear spring is defined as a poly-linear slip model. The STERA_3D technical manual by Saito (2021) provides detailed illustrations of the model.

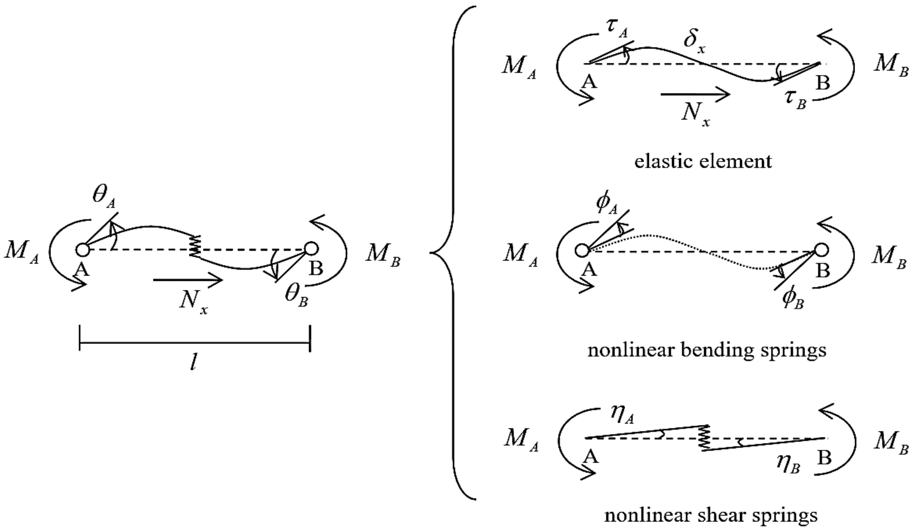



*Figure 3. Nonlinear model of beam element in STERA_3D*

## 5 VALIDATION OF THE NEW PROPOSED REDUCTION FACTOR

The new method was compared to several experimental tests and analytical models for validation to propose a new reduction factor for UMWs containing different opening locations. The comparison result shows a similar value to that of experimental tests and other related methods. The newly proposed reduction factor can make it easier for engineers and researchers to analyse RC structures with UMWs and openings in different locations. The result of the comparison is detailed below.

## 5.1 Ahani et al. conducted an experimental test.

Ahani et al. (2019) experimentally researched a single-bay, single-story RC frame with a clay brick masonry wall. The specimen was a half-scale RC frame with a masonry wall with a 19 % central opening. The height and length of the RC frame were 1,800 mm and 2,845 mm, respectively. The RC frame featured rectangular columns measuring 250 by 250 mm and rectangular beams measuring 250 by 300 mm. The specimen details of the experiment are explained in Figure 4.

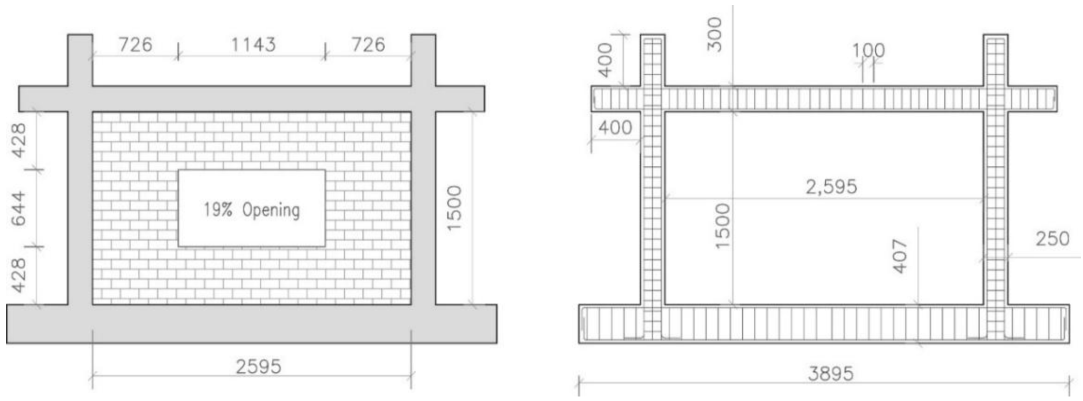



*Figure 4. Ahani et al. experimental model (2019)*

According to the experimental result, Ahani et al. (2019) proposed a strength reduction factor as follows:

$$
\begin{aligned}
S &= 1 - 0.01 \times OP & \quad 0 \le OP < 15 \\
S &= 0.858 - 0.0387 \times OP & \quad 15 \le OP < 100
\end{aligned}
\tag{8}
$$

Where S is the strength reduction coefficient, OP is the opening ratio in percentage. This study also considers another reduction factor from the Seismic Assessment of Existing Buildings (SAEB): Technical Guidelines for Engineering Assessments, July 2017, Version 1, Ministry of Business, Innovation and Employment (Ministry of Business, Innovation and Employment, 2017) as:

$$
q_{n,\inf} = q_{n,\inf}^{solid}\left(1 - \frac{A_{OP}}{A_{wtot}}\right) \tag{9}
$$

Where, $q_{n,\inf}$ is the probable uniformly distributed lateral load capacity, $A_{op}$ is the area of the opening in the UMW, and $A_{w,tot}$ is the gross area of an equivalent infill panel with no openings.

The new proposed reduction factor estimates the shear strength of the UMW in Figure 4 with central opening ratios and compares it with those by the other two methods (and SAEB) in Table 1 and Figure 5.

*Table 1. Shear Strength of RC Frame with Masonry Wall containing different Opening.*

| **Methods** | **Specimen.1 9.5% Opening** | **Specimen.2 19% Opening** | **Specimen.3 29% Opening** | **Specimen.4 39% Opening** |
|---|---|---|---|---|
| Elshan Ahani | 0.81 | 0.794 | 0.719 | 0.680 |
| New reduction Fa. | 0.911 | 0.83 | 0.756 | 0.680 |
| New Zealand T. M | 0.905 | 0.81 | 0.71 | 0.61 |

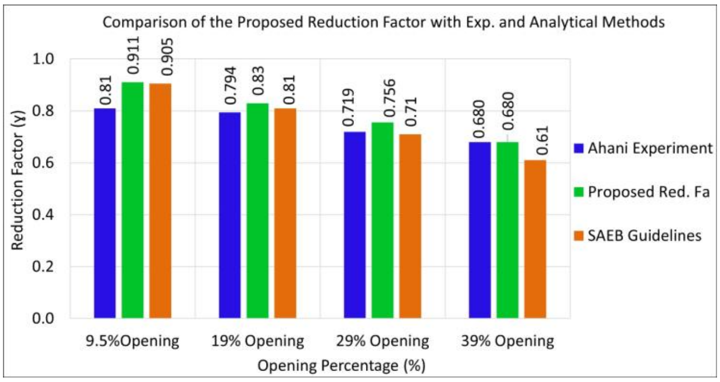



*Figure 5. Comparison of shear strength of UMW with central opening*

## 5.2 Maidiawati experimental tests.

Maidiawati et al. (Maidiawati *et al.*, 2019) experimented on single-story RC frames with BMW containing different openings. The height of the RC frame is 950 mm, and the section sizes of RC elements are 125x125 mm for the column and 200 x 200 mm for the beam. The specimens were ¼ scale RC frames consisting of a BF, an RC frame with solid brick, and two RC frames with BMW of 25% and 40%. Figure 6 presents the specifics of the test.

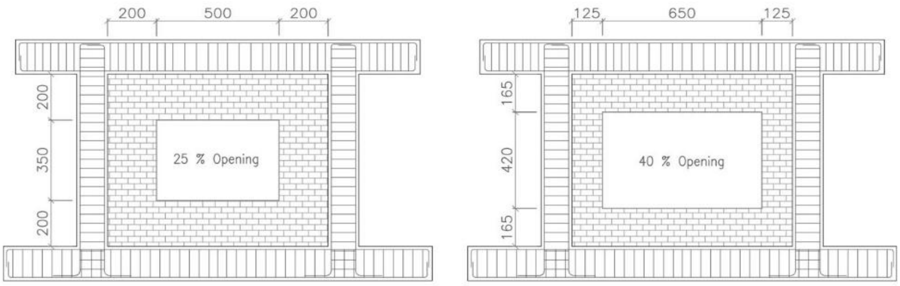



*Figure 6. Maidiawati experimental model (2019)*

The shear strengths of the RC frames are estimated using the new reduction factor and reduction ratio of the NTM and compared with the test results, as illustrated in Table 2 and Figure 7. The newly proposed reduction factor shows results that are in good agreement with the experimental results.

*Table 2. Shear Strength of RC Frame with Masonry Wall containing different Opening.*

| Methods | Specimen 1 (25 % Opening) | Specimen 2 (40 % Opening) |
|---|---|---|
| Maidiawati experiments | 0.719 | 0.680 |
| New proposed method | 0.790 | 0.670 |
| New Zealand Technical M. | 0.75 | 0.60 |

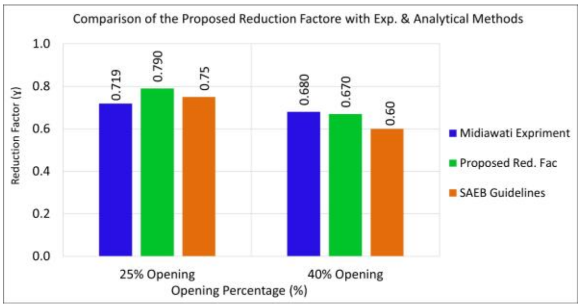



*Figure 7 Force-displacement curve of RC Frame with UMW containing opening.*

### 5.3 Hayasaki et al. experimental research.

Hayasaki et al. (Hayasaki *et al.*, 2007) conducted experimental tests on a set of single-story RC frames with UMWs containing different opening shapes and opening positions. The internal dimensions of the UMWs are 1750 × 1050 mm², the cross-sectional dimensions of the side columns are 100 × 225 mm², and there are RC beam stubs on the top and bottom. Figure 8 presents the test specimen details. Since there is not enough space in this research paper, only one of the experimental test figures is shown.

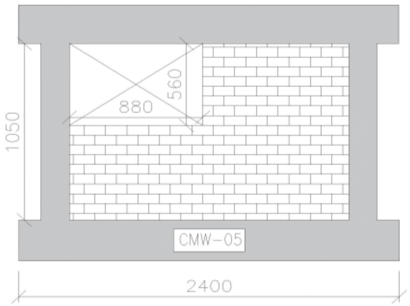



*Figure 8. Hayasaki experimental model (2007)*

The shear strengths of the RC frames are estimated using the new reduction factor and the reduction ratio of the SAEB and compared with the test results, as illustrated in Table 3 and Figure 9. The newly proposed reduction factor results agree with the experimental results.

*Table 3. Shear Strength of RC Frame with Masonry Wall containing different Opening.*

| Methods | CMW-05 Reduction Fa. | CMW-06 Reduction Fa. | CMW-07 Reduction Fa. |
|---|---|---|---|
| Noboru Hayasaki | 0.84 | 0.91 | 0.65 |
| New reduction Fa. | 0.86 | 0.93 | 0.76 |
| SAEB | 0.728 | 0.935 | 0.72 |

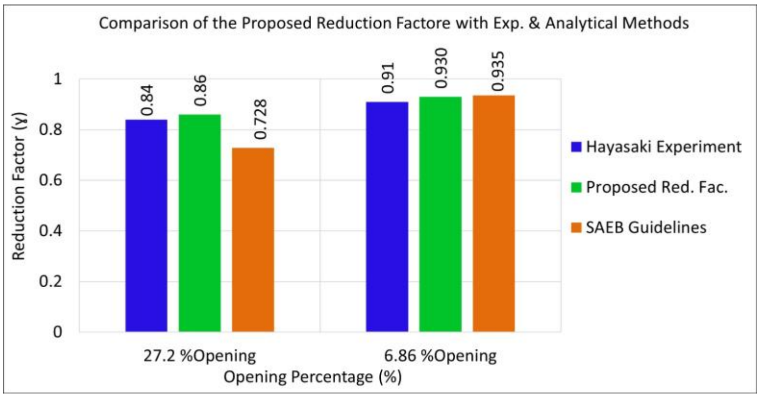



*Figure 9. The force-displacement curve of the RC frame contains an opening in the UMW.*

#### 5.3.1 Sigmund and Penava experimental research.

Sigmund and Penava (Sigmund and Penava, 2012) conducted experimental studies on RC frames infilled with UMW with openings. The experimental models were built on a scale of 1:2.5 and infilled with UMWs. Specimens Type I, Type II, and Type III of the experiment were selected for the current research to validate the new proposed reduction factor. The specimen details of the experiment are illustrated in Figure 10.

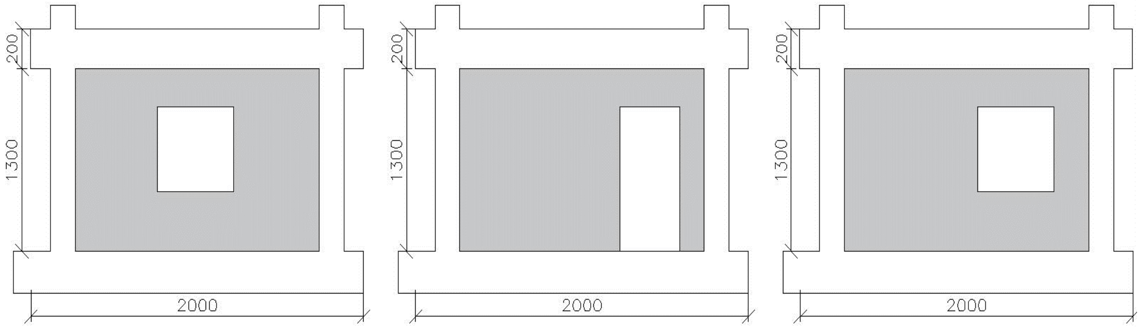



*Figure 10: Sigmund and Penava tested specimens, a) Central opening (Type I/2), b) Door opening, C) Right side opening*

*Table 4. Shear Strength of RC Frame with Masonry Wall containing different Openings.*

| Methods | Type I/2<br>Reduction Fa. | Type I/3<br>Reduction Fa. | Type I/4<br>Reduction Fa. |
|---|---|---|---|
| Sigmund and Penava | 0.89 | 0.88 | 0.885 |
| New proposed method | 0.908 | 0.897 | 0.88 |
| SAEB | 0.870 | 0.870 | 0.870 |

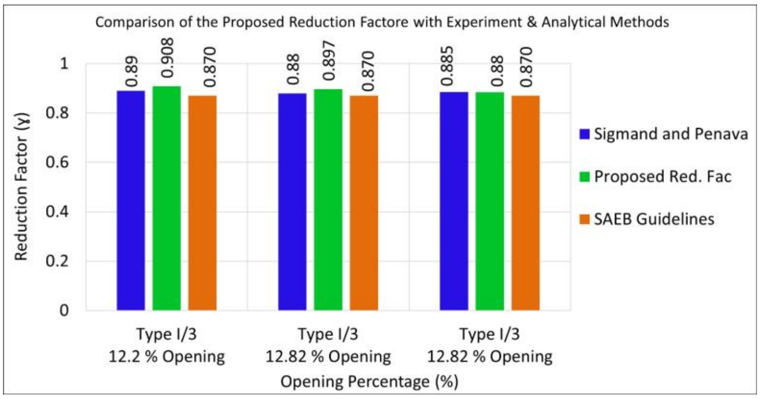



*Figure 11. The force-displacement curve of the RC frame contains an opening in the URW.*

## 6 PROPOSED REDUCTION FACTOR

n this study, the effect of different opening positions in URWs within RC frames is evaluated.

The opening locations were considered in different scenarios:a central opening case, left or right upper side opening case, middle left or right-side opening case, and left or right-side door opening case. To determine the reduction factor, first, the UMW can be divided into segments around the opening. Then, based on Equation 1 and Equation 2, the average strut angle can be calculated. The new proposed reduction factor was compared to experimental research and analytical methods with similar results. The proposed reduction factor is an easy way to consider the effectiveness of an infill masonry wall in an RC structure containing UMWs. Figure 12 shows the results of the different experiments and the presented reduction factor, showing good agreement between the test data and the proposed expression, with consideration of the opening location.

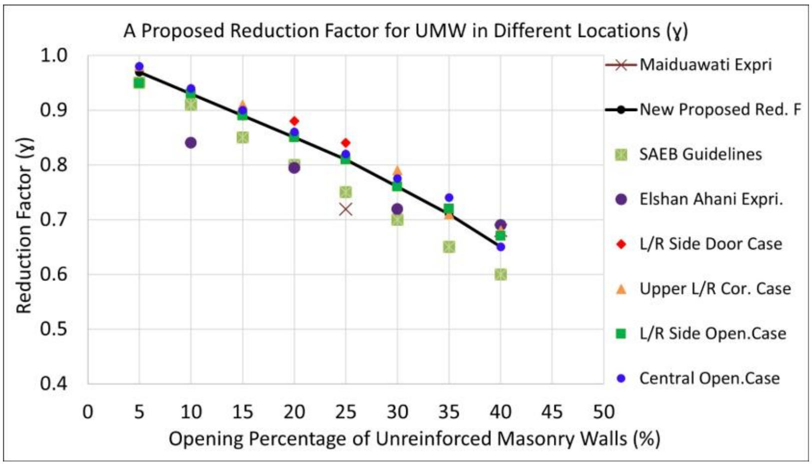



*Figure 12 Force-displacement curve of RC Frame with UMW containing openings.*

## 7 CONCLUSION

UMW structures are commonly used in nearly all regions of Afghanistan. Burnt Clay bricks, used in interior and exterior walls, are easily accessible for construction projects in various areas and can significantly decrease budget costs compared to other alternative materials. Although UMWs demonstrate greater strength, durability, and stiffness that increase the stability of RC structures under applied loads, the effect of UMWs has always been neglected as a non-structural component in local practice. The seismic vulnerability of RC structures with UMWs is a critical concern, especially in regions prone to significant seismic activity, such as Afghanistan. Historical seismic events, such as the 2015 Hindu Kush earthquake, highlight the substantial role of UMWs in enhancing buildings' seismic resilience.

This study suggests a new reduction factor based on the net area of the UMW and the average strut angle for the RC structures with UMWs containing different opening locations. By incorporating the net area and average strut angles, this method comprehensively analyzes how different opening placements affect the structural integrity of UMWs under seismic loading. The accuracy of the proposed reduction factor was confirmed by comparing the capacity of UMWs specimens with experimental and analytical results published earlier. The findings of the current research can be summarized as follows:

- The proposed reduction factor simplifies assessing UMW effectiveness in RC structures by considering the net area and average strut angle, allowing researchers and engineers to evaluate seismic vulnerability efficiently.
- Openings can be located anywhere in UMWs, and the proposed reduction factor is a versatile calculation method that can be applied to a wide range of UMW structures.
- This research has shown that openings in UMWs have an extremely large impact on the seismic performance of the RC structure. Therefore, highly recommend using the proposed reduction factor and calculating the effectiveness of UMWs in the RC structure.
- The results of comparing the newly proposed reduction factor are almost the same and acceptable as those from experiments and other numerical analyses.

In conclusion, this study introduces a robust and validated approach for assessing the seismic performance of RC buildings with UMWs, proposing a novel method. This method serves as a practical and reliable tool for engineers and researchers, aiding in the design of safer, more resilient structures in earthquake-prone areas. Future studies should aim to refine this model further by exploring additional configurations and investigating the effects of various materials, thereby deepening our understanding of how UMWs influence seismic performance.

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