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Determination of initial stiffness modifiers for URM walls using a non-linear pushover methodology

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ABSTRACT

The development of an analytical model to help estimate seismic demand on key structural components is an important step in the seismic assessment of complex buildings. Analytical models of buildings with concrete or masonry structural walls typically use elastic finite area elements to represent the walls. It is accepted practice that the stiffness of these elastic elements should be modified to allow for the softening effects caused by existing or initial cracking. While many building codes and material standards provide guidance on the appropriate selection of initial stiffness modifiers for analytical models of reinforced concrete walls, there is significantly less guidance provided for unreinforced masonry walls. Eurocode 8 simply recommends applying a fixed modifier of 0.5 to the gross moment of inertia of the unreinforced masonry walls, while the current approach recommended in ASCE41-17 is to apply a fixed modifier to the gross moment of inertia, but does not provide guidance on an appropriate modifier to be used. Research has shown that the magnitude of gravity load present and the specific geometry of an unreinforced masonry wall may significantly affect its initial stiffness. Current simplified approaches to the selection of stiffness modifiers may therefore not be appropriate for all masonry wall configurations. This paper presents a generalized methodology, suitable for application in a design office environment, that allows appropriate initial stiffness modifiers for analytical models of unreinforced masonry wall structures to be determined. The proposed methodology uses the VecTor2 software suite to perform non-linear pushover analysis of individual unreinforced masonry wall segments and incorporates the gravity loads and geometry unique to each wall. An analytical study using the proposed methodology to determine initial stiffness modifiers for an extensive suite of historic masonry walls of various configurations is presented and general observations on the study are made.

Keywords: URM, historic, seismic, non-linear, stiffness

INTRODUCTION

The development of an analytical model to help estimate seismic demand on key structural components is an important step in the seismic assessment of complex buildings. Analytical models of buildings with concrete or masonry structural walls typically use elastic finite area elements to represent the walls. It is accepted practice that the stiffness of these elastic elements should be modified to allow for the softening effects caused by existing or initial cracking. While many building codes and material standards provide guidance on the appropriate selection of initial stiffness modifiers for analytical models of reinforced concrete walls, there is significantly less guidance provided for unreinforced masonry walls.

Eurocode 8 Cl.4.3.1(7) [1] recommends applying a fixed modifier of 0.5 to the gross section moment of inertia for cracked masonry walls and a modifier of 1.0 for uncracked masonry walls. ASCE41-17 Cl.11.3.12.1 [2] recommends that the stiffness of a cracked wall be "linear and proportional" with the properties of an uncracked wall, but does not provide guidance regarding the selection of an appropriate modifier. Previous research by Wilding and Beyer on unreinforced masonry walls has shown that the magnitude of gravity load present and the specific geometry of the wall may significantly affect its initial stiffness [3]. Applying a modifier that is independent of wall geometry and loading, such as the simplified approaches given in Eurocode 8 and ASCE41-17, is therefore not likely to be appropriate for all masonry wall configurations.

In addition, both Eurocode 8 and ASCE41-17 rely on a constant modulus of elasticity, E. The selection of this value, which varies with the level of axial stress, can also have a significant impact on the overall stiffness of a masonry wall.

This paper presents a generalized methodology, suitable for application in a design office environment, that allows appropriate initial stiffness modifiers for analytical models of unreinforced masonry wall structures to be determined. The VecTor2 software suite is used as part of this proposed methodology. It is a non-linear finite element analysis program that uses Modified Compression Field Theory for membrane structures. VecTor2 is effective in modeling in-plane masonry structures because it uses orthotropic compression properties, and although it uses a continuum membrane element, the software applies the Disturbed Stress Field Model to account for masonry shear slip [4]. Notably, VecTor2 allows the various failure modes of unreinforced masonry walls to be captured, i.e. diagonal tensile shear, sliding shear, rocking, and crushing.

An analytical study using the proposed methodology to determine initial stiffness modifiers for an extensive suite of historic masonry walls of various configurations has been completed. A selection of the examined walls and general observations on the analytical study are presented.

PROPOSED METHODOLOGY

The first two steps of the proposed methodology establish a non-linear stress-strain relationship for the masonry based on material properties. The VecTor2 software suite is then used to perform a non-linear pushover analysis of a discrete unreinforced masonry wall, incorporating the non-linear material properties, gravity loads and geometry unique to the wall. Next, a two-dimensional ETABS model containing the same discrete wall segment is created. The displacement profile of the ETABS model is calibrated to match the displacement profile from the VecTor2 results by varying the stiffness modifier. This stiffness modifier can then be used in the analytical model of the complete building.

Step 1: Determine key masonry material properties

The non-linear pushover analysis requires masonry material properties to be determined. Ideally, these would be obtained from a testing program with samples from the building being analysed. In the absence of building-specific values, regionally and historically appropriate material properties can be determined from literature.

The material properties required to develop a non-linear stress-strain curve are:

- The compressive and tensile strengths of the masonry assemblage, and
- The compressive and tensile strains at peak stress.

Step 2: Define a non-linear stress-strain relationship

The material properties listed above can be used in the VecTor2 software suite to specify a stress-strain curve for masonry. A curve generated by VecTor2 for a sample wall is presented in Figure 1 below. Many material models defining parts of the stress-strain curve for masonry have been developed, most of which have been implemented in the VecTor2 software [4]. Some commonly adopted models are illustrated below.

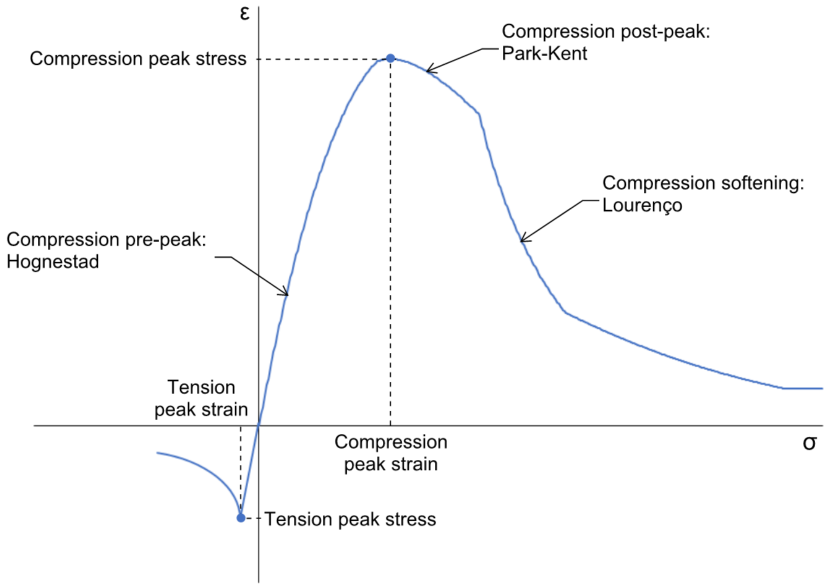


Figure 1. Masonry stress-strain curve

Step 3: VecTor2 analysis using non-linear material properties

The stiffness and capacity of the discrete wall is determined by performing a non-linear pushover analysis in VecTor2. This procedure subjects a non-linear analytical model of the wall to a monotonically increasing lateral load to develop an analytical force-displacement curve.

A VecTor2 model is created for the discrete wall segment. The wall geometry, wall thickness, material properties, gravity loads, seismic forces and analysis parameters are all defined in the VecTor2 software suite. The seismic forces are calculated using a reasonable load vector and applied to the model as monotonic loads.

Following the completion of the model, the VecTor2 processor is run and the pushover analysis results are obtained. The program allows for the failure mode to be visually reviewed and for a force-displacement curve to be plotted with the force-displacement data from each load step. Figure 2 below presents the procedure for a sample wall.

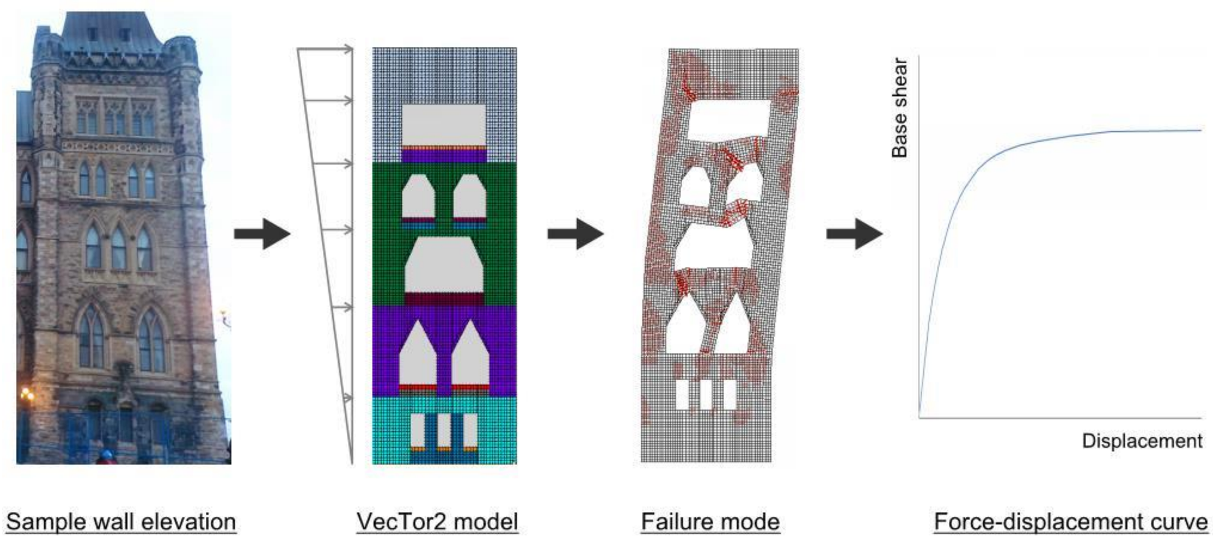


Figure 2. Procedure for determining force-displacement curve for a wall using the VecTor2 software suite

Step 4: Idealized force-displacement curve

The yield capacity and deformation of the discrete wall is determined using the ASCE41-17 non-linear static procedure (Cl.7.4.3.2.4). An idealized force-displacement curve is fit to the analytical force-displacement curve generated from the pushover analysis, with points at peak (V_d, Δ_d), yield (V_y, Δ_y) and 60% of yield ($0.6V_y$).

The idealized force-displacement curve is developed by identifying the peak base shear, defining V_y as a function of $0.6V_y$ (a point on the analytical curve) and using an iterative graphical procedure to equate the areas below the analytical and idealized curves up to peak. Figure 3 below presents the analytical and the idealized force-displacement curves.

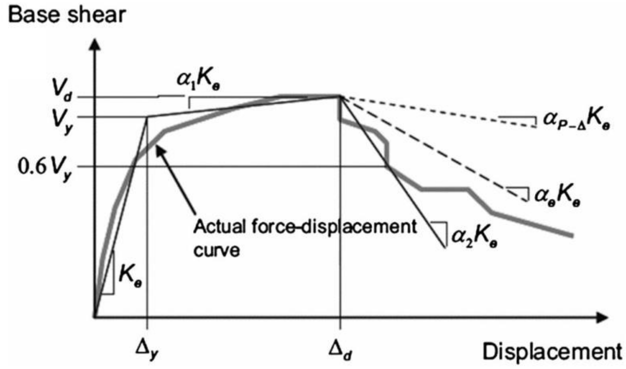


Figure 3. Idealized force-displacement curve [2]

The ASCE41-17 procedure applied to the sample wall shown in Step 3 results in the idealized bi-linear curve presented in Figure 4 below.

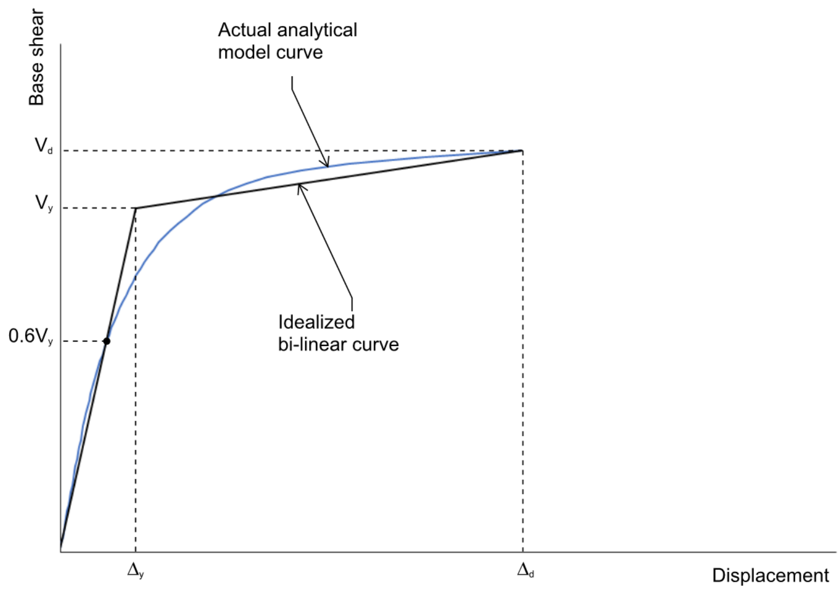


Figure 4. Analytical and idealized force-displacement curves for sample wall

The key thresholds on the force-displacement curve may be described as follows:

- 60% of yield corresponds to the onset of non-linear action and is the threshold at which damage (cracking) begins. Up to this point, the wall is essentially elastic.
- Between 60% of yield and yield there is a modest amount of non-linear action. Damage in the form of cracks is present, but global stability of the wall is maintained.
- Peak is identified by a rapid increase in displacement, indicating excessive cracking, instability and global failure.

Examples of these thresholds for the sample unreinforced masonry wall are illustrated below. The analysis was performed using the VecTor2 software suite. The red lines represent cracks. Displacements have been magnified for visual emphasis.

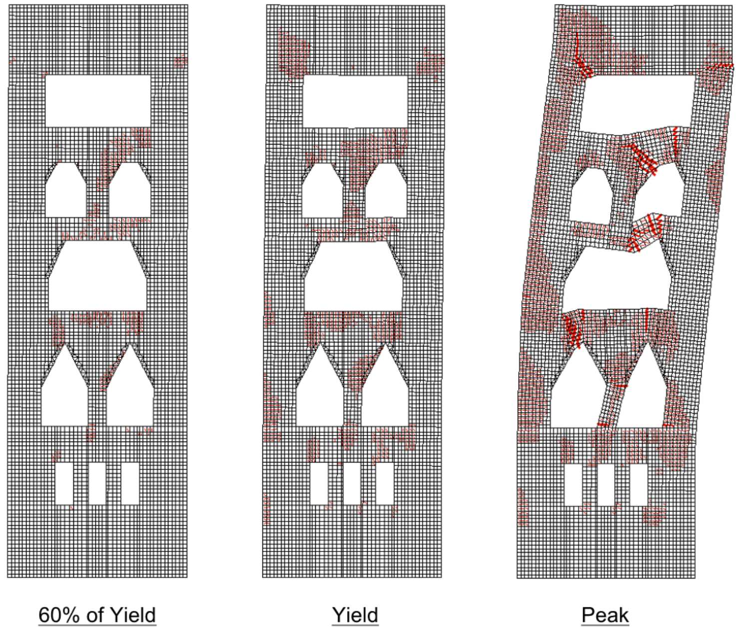


Figure 5. Crack and displacement patterns of a sample wall

Step 5: Stiffness modifier calibration

The final step is to determine a stiffness modifier for the discrete masonry wall. This is achieved by calibrating the displacement profile of an ETABS model of the wall (with linear material properties) to match the displacement profile obtained from the non-linear VecTor2 analysis.

A two-dimensional ETABS model containing the same discrete wall segment as the VecTor2 model is created. The wall geometry, wall thickness, gravity loads and seismic forces in the ETABS model are identical to those in the VecTor2 model. A value for the masonry modulus of elasticity (E_m) is also required to complete the analysis. This value is typically calculated as the chord modulus of the masonry compression stress-strain curve between $0.05f'_m$ and $0.33f'_m$. Recommended values for the masonry modulus of elasticity vary greatly. The Masonry Standards Joint Committee code [5] recommends $550f'_m$ for existing masonry, CAN/CSA S304 [6] recommends $850f'_m$ for modern masonry, and Eurocode 6 [7] recommends $1000f'_m$ for masonry. The New Zealand Technical Guidelines for Engineering Assessments [8] recommend $300f'_m$ as an appropriate value for seismic analyses of existing masonry. This value is lower than other recommendations and due in part to the modulus being calculated using the stress-strain curve between $0.05f'_m$ and $0.70f'_m$. For the purpose of this evaluation, a value of $300f'_m$ was used.

It should be noted that because the overall stiffness of the wall in ETABS is calibrated to the non-linear VecTor2 model using stiffness modifiers, the specific value used for E_m is not critical. Selecting a higher value for E_m in ETABS will result in a stiffer unmodified ETABS model and a smaller stiffness modifier to achieve the right calibration. Similarly, a lower value of E_m will result in higher stiffness modifiers, but achieve the same overall stiffness. The magnitude of the stiffness modifiers will vary with the selection of E_m, however, the final displacement profile will be the same.

The displacement profile of the ETABS model is calibrated to match the displacement profile from the VecTor2 results by varying the stiffness modifiers. The two models were calibrated at the top of the wall at 60% of yield (i.e. the non-linear threshold of the wall). Calibrating all walls in a full building model to this performance point provides an appropriate global stiffness upon which the fundamental period and resulting seismic base shear may be based.

Figure 6 below shows the deflected profile of the sample wall. It can be observed that the displacement profiles from the VecTor2 software suite and ETABS closely match at 60% of yield.

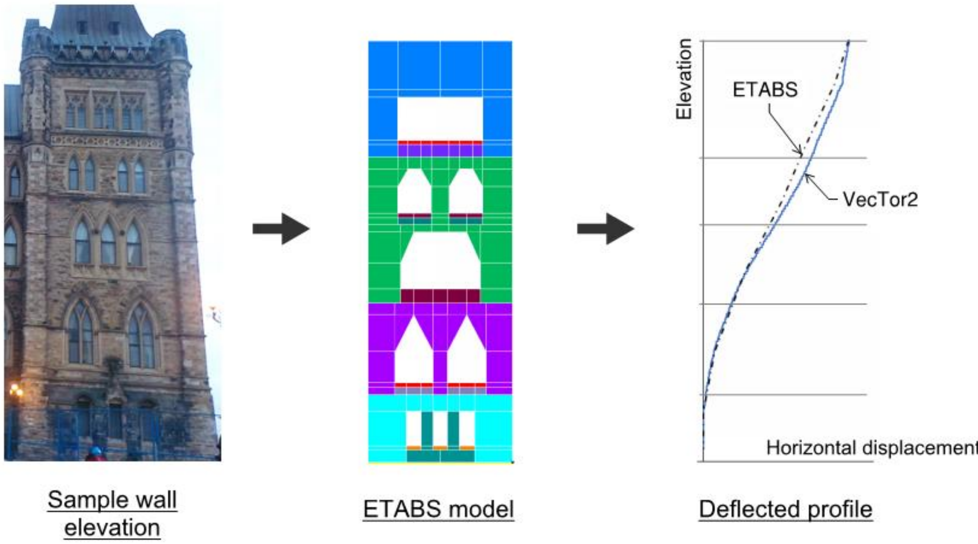


Figure 6. Procedure for determining wall stiffness using the VecTor2 software suite and ETABS

The calibrated stiffness modifier determined using this procedure is then used in the analytical model of the complete building. In an elastic finite element ETABS model with calibrated stiffness modifiers unique to each discrete wall, the displacements are accurate up to the onset of non-linearity, i.e. up to 60% of yield.

ANALYTICAL STUDY OBSERVATIONS

The methodology proposed in the section above was used in an analytical study to determine initial stiffness modifiers for an extensive suite of historic masonry walls. Approximately 80 walls with different thicknesses, aspect ratios, opening configurations, gravity loads and seismic loads were evaluated. A selection of the examined walls is presented in the tables below and general observations on the analytical study are made.

Table 1. Summary of walls from analytical study (Walls A & B)

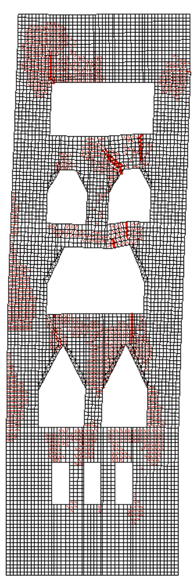
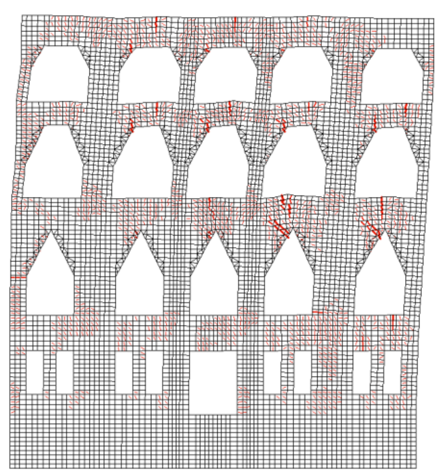
Wall name	A	B
Wall at peak displacement		
Stiffness modifier	0.73	0.71

Table 2. Summary of walls from analytical study (Walls C & D)

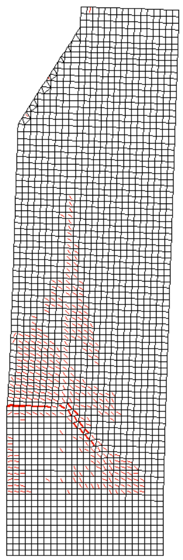
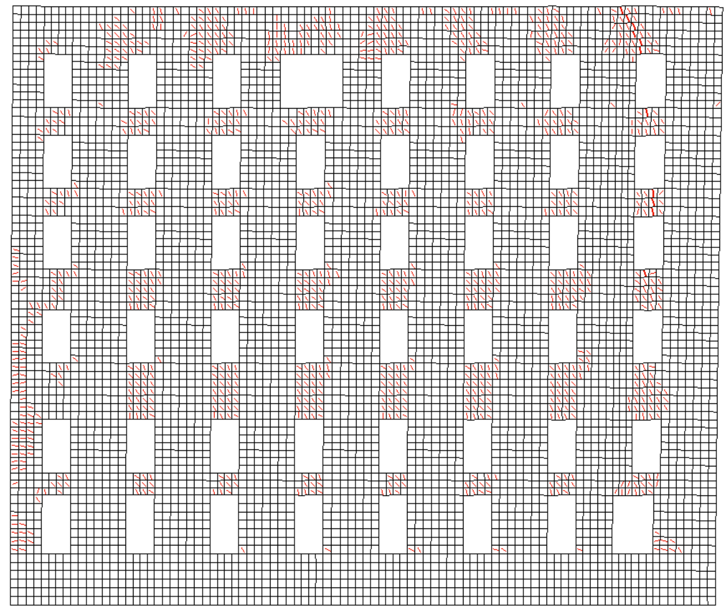
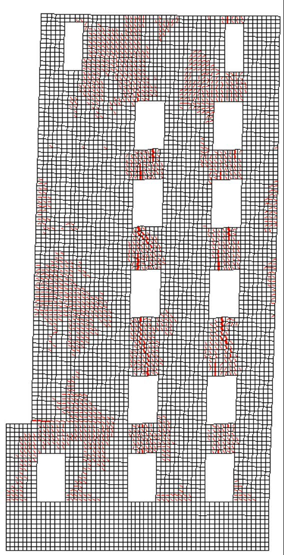
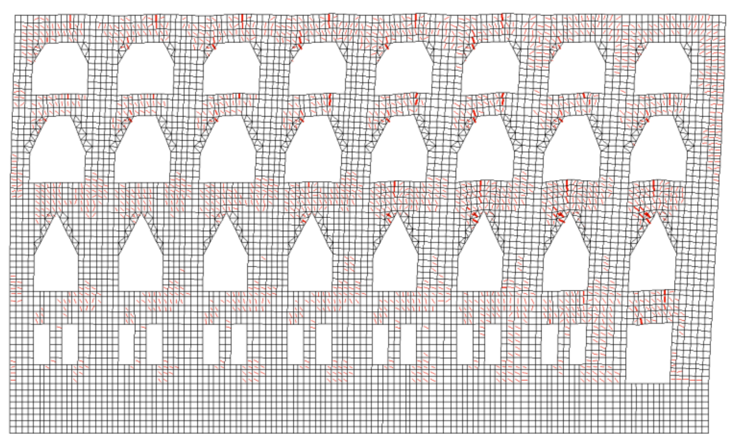
Wall name	C	D
Wall at peak displacement		
Stiffness modifier	1.54	1.00

Table 3. Summary of walls from analytical study (Walls E & F)

Wall name	E	F
Wall at peak displacement		
Stiffness modifier	1.31	0.48

From the walls shown above, the following observations can be made:

- The stiffness modifiers vary from 0.48 to 1.54.
- Walls A and B have similar stiffness modifiers (0.73 and 0.71, respectively) despite their different aspect ratios.

- Walls C and E, which both exhibit a rocking failure mode, have higher stiffness modifiers (above 1.3).
- Walls B, D and F are similar in that they all have squat aspect ratios, significant openings, and are governed by spandrel failures. However, their stiffness modifiers vary significantly, from 0.48 to 1.0.
- The stiffness modifier of an unreinforced masonry wall is not easily estimated, as it varies significantly with geometry and opening configurations.

CONCLUSIONS

The proposed methodology to determine stiffness modifiers for unreinforced masonry walls considers all the factors that contribute to wall in-plane stiffness: wall geometry, openings, non-linear material properties and gravity loading. The analytical study presented shows that the stiffness modifiers vary significantly with these factors. The simplified approach suggested by building codes and material standards with a constant modifier for all walls may not be appropriate, as it does not capture these potential variations. A comprehensive study to evaluate a unique stiffness modifier for each wall in a building is therefore recommended, as it will help produce an analytical model that is calibrated to a more appropriate fundamental period and result in more accurate estimations of wall shears and displacements.

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