Institute of Structural Engineering (IKI)

Advanced Structures

Special Project 2.1.

Bauhaus-Universität Weimar

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Equivalent-Frame models for irregular masonry walls

What is the Equivalent-Frame method?

The equivalent frame method (EFM) is a structural modelling approach that simplifies a masonry wall into macro-elements to predict the wall in-plane behavior.

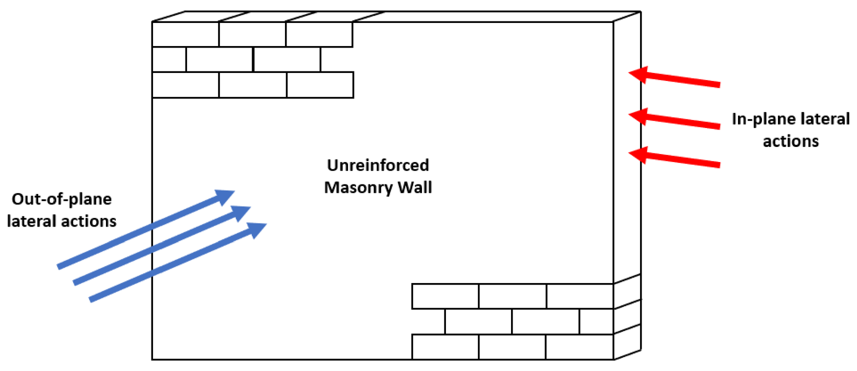

Figure 1. In-plane and out-of-plane actions.

How does it work?

The wall is divided in three different elements maintaining a configuration that will ensure a wall will have a "frame-like" behaviour. Elements are enlisted as follows:

Piers
- Main vertcal elements
- Carry the loads to foundations

Spandrels
- Secondary loads
- Transfer loads to piers
- Located betweeen consecutively vertical openings

Rigid nodes
- Infinitely rigid
- Connection between spandrels and piers

What is the problem?

The EFM is considered efficient as long as the analyzed walls have a regular configuration of openings, but when it comes to existing masonry buildings with irregular geometries or irregular distribution of openings, the effectiveness of the method becomes questionable. Literature indicates such irregularities can be measured by irregularity indexes (Berti, et al. 2017) and can be a measure that indicates how accurately the EFM will predict a wall's behaviour (Siano et al., 2017).

What was done?

A hundred cases of Unreinforced Masonry Walls with irregular configuration of openings and subjected to different seismic events were compiled. All walls were digitized and equivalent frame definitions were obtained by applying Dolce's criteria with some adaptations depending on the presence of beams, gable roofs and observed damages.

Each one of the cases was then classified according to type of use of the building, number of storeys, moment magnitude of the occurred event, location, maximum Modified Mercalli Intensity, observed failure mechanisms (flexural or shear), type of diaphragm and observed irregularities.

Irregularity indexes were calculated for ten cases. A push over analysis was performed in SAP2000 for two cases to compare the capacity curves of the original walls and the idealized regular wall (Berti et al., 2017), using Dolce's criteria to define the equivalent frames. Lastly, non-linear quasi-static analysis was performed for two cases to compare de capacity curves of different equivalent frame definitions.

What is next?

In this study several topics were identified with the need of further investigation, examples that can be considered extensions of this project are:

- Influence of effective height of ground floor piers in Equivalent frame models using SAP2000;
- Compilation of URM material properties for each of the countries included in the research;
- Performance points of walls considering the earthquake registered for each URM wall;
- Global irregularity indexes for walls with more than one irregular openings.

Equivalent-Frame definition criteria independent of load direction

Lagomarsino's criteria.

For **regular walls**, the effective height of interior piers becomes equal to the height of the consecutive opening and for the exterior piers it becomes the average between the height of the opening and the consecutive storey.

For **irregular walls**, the effective height of interior piers becomes equal to the average between the two lateral openings. The effective height of exterior piers becomes the average between the height of the opening and the consecutive storey.

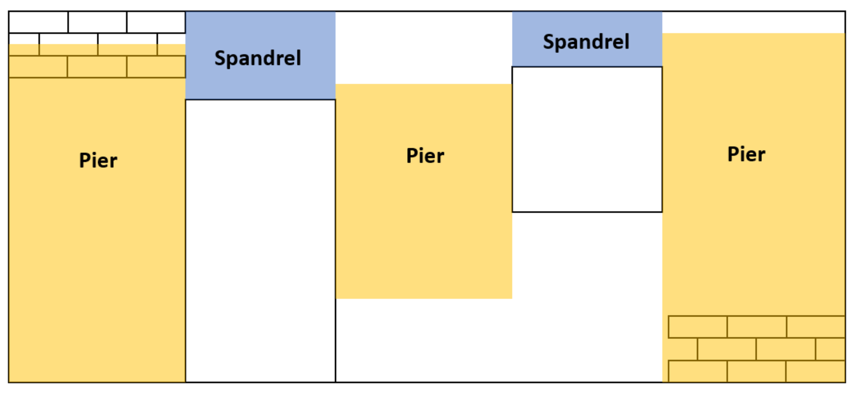

Figure 2. Graphical representation of Lagomarsino's EF definition.

Rigid offset criteria.

The effective height of the pier is equal to the minimum clear height between openings.

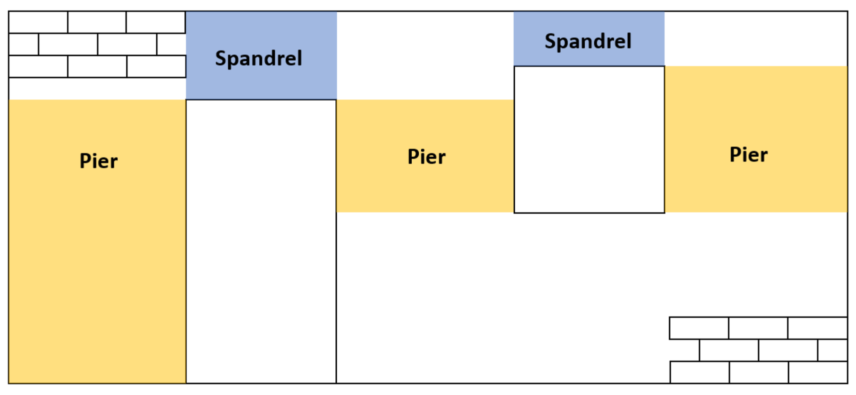

Figure 3. Graphical representation of EF definition with rigid offset criteria.

Dolce's criteria.

The effective height of piers is defined by the prolongation of a line from the corners of an opening to the end of the wall or to the consecutive opening, with an inclination limited to 30 degrees. Such angle indicates the maximum expected inclination of cracks in case of shear failure.

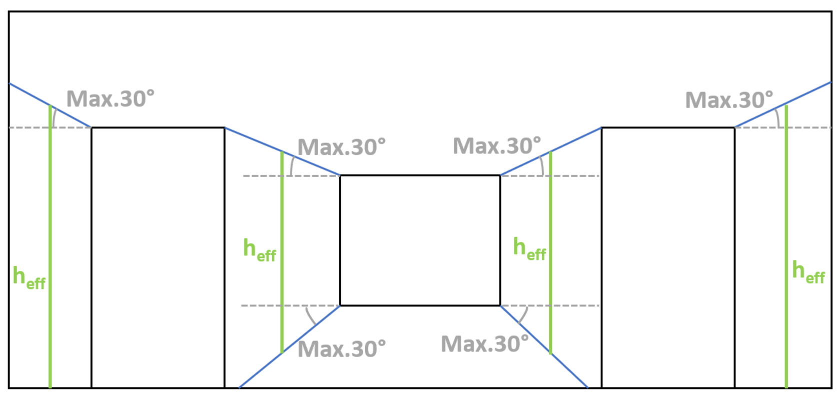

Figure 4. Graphical representation of Dolce's EF definition.

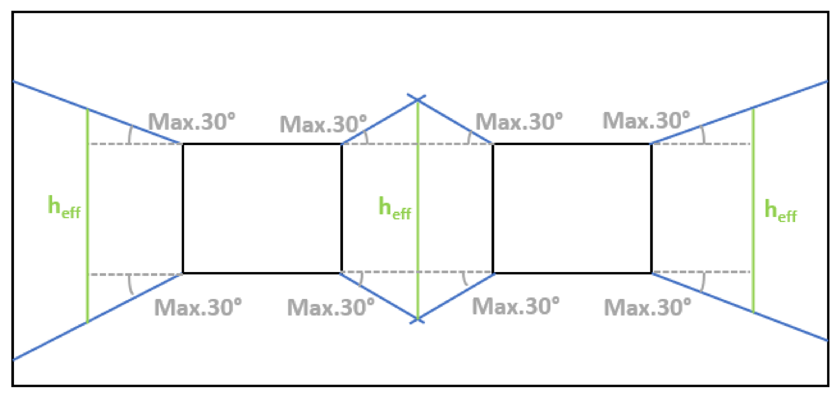

Figure 5. Graphical representation of EF definition with an adaptation of Dolces's criteria.

Equivalent-Frame definition criteria dependent of load direction

Augenti's criteria.

The effective height of the piers is considered to be equal to the height of the consecutive opening in the orientation of the load. The use of this criteria has been proof to be better to predict the force distribution among piers, it gives less differences in the evaluation of strength when the results are compared to those of finite element models (Siano et al., 2017).

Moon's criteria.

This criterion considers the most frequent failure mechanism will be flexural and considers the steepest angle on which compression can occur with the least lateral resistance. The effective height of the outer piers that are firstly exposed to the load is defined by the distance between the lower corner of the opening and the height of the upper storey. Secondly, the outer piers that are not immediately exposed to the load had an effective height equal to the distance between the upper corner of the opening and the lower storey. Lastly the inner piers have a location and height that will depend on the lower corners of the consecutive opening and if such has a position above or below the opening that is firstly exposed to the load.

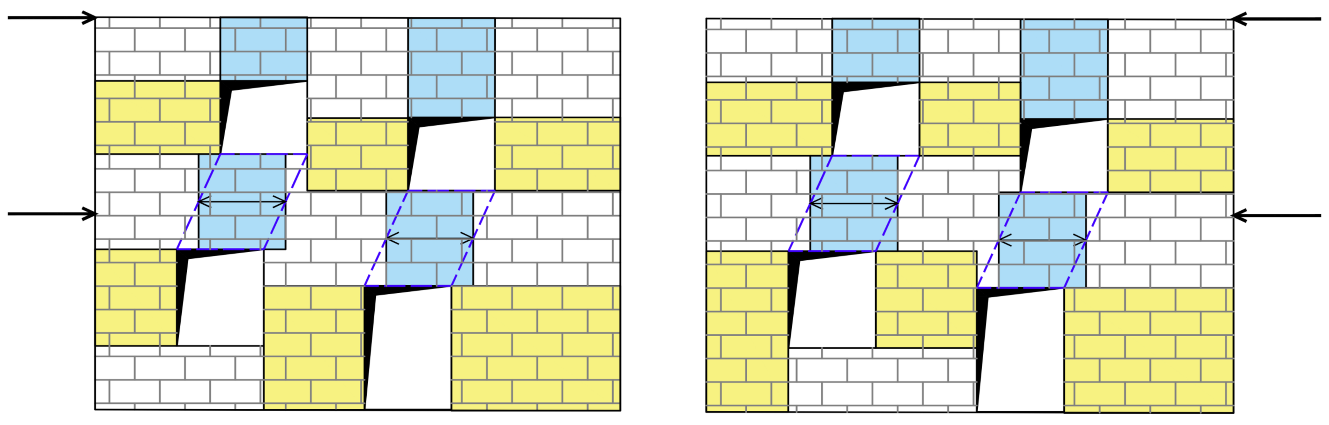

Figure 6. EF definition with the use of Augenti's criteria.
(loads applied in both directions at inter-storey levels in - direction)

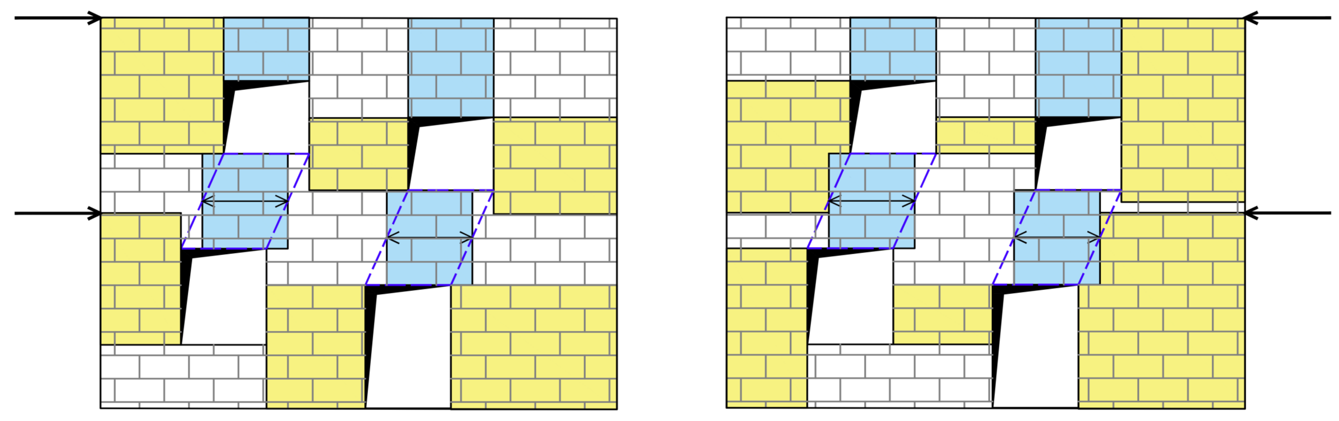

Figure 7. EF definition with the use of Moon's criteria.
(loads applied in both directions at inter-storey levels in - direction)

Comparative of different EF models

Figure 9. Study case D018 and different EF definitions.

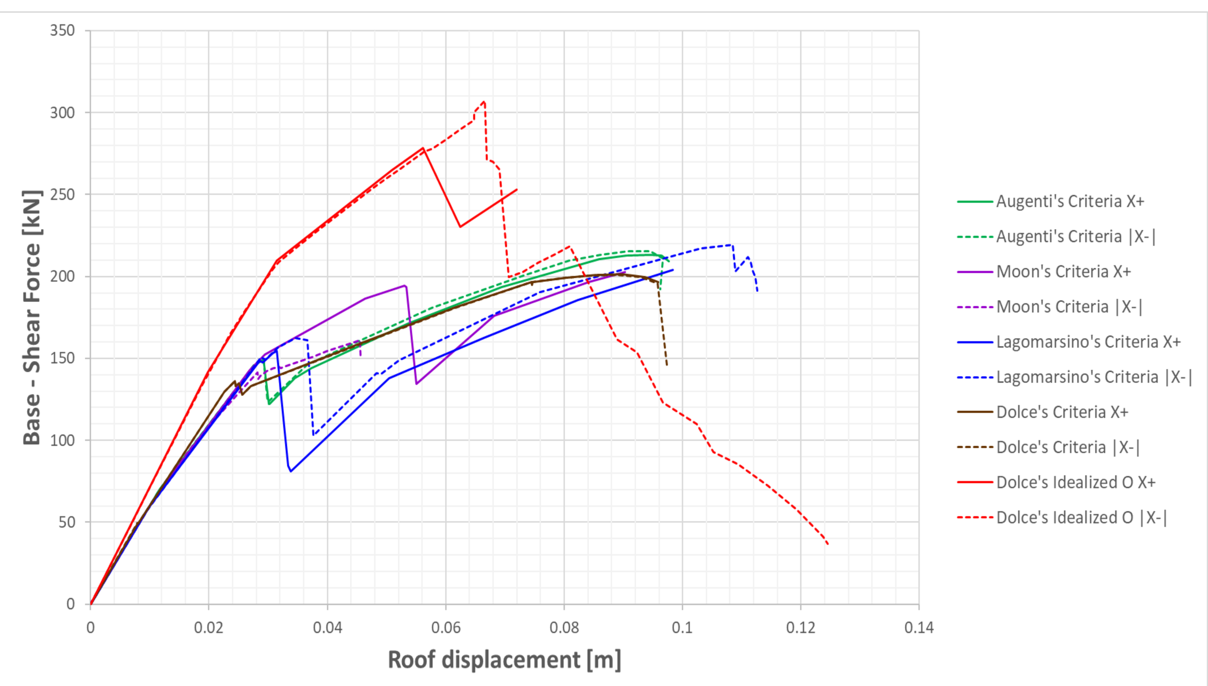

Figure 10. Capacity curves of study case D018.

Calculation of irregularity indexes

To calculate irregularity indexes an ideal regular configuration of the wall must be obtained, this was done following Berti et al. (2017) procedure of averages. Results for Case L005 are as follows:

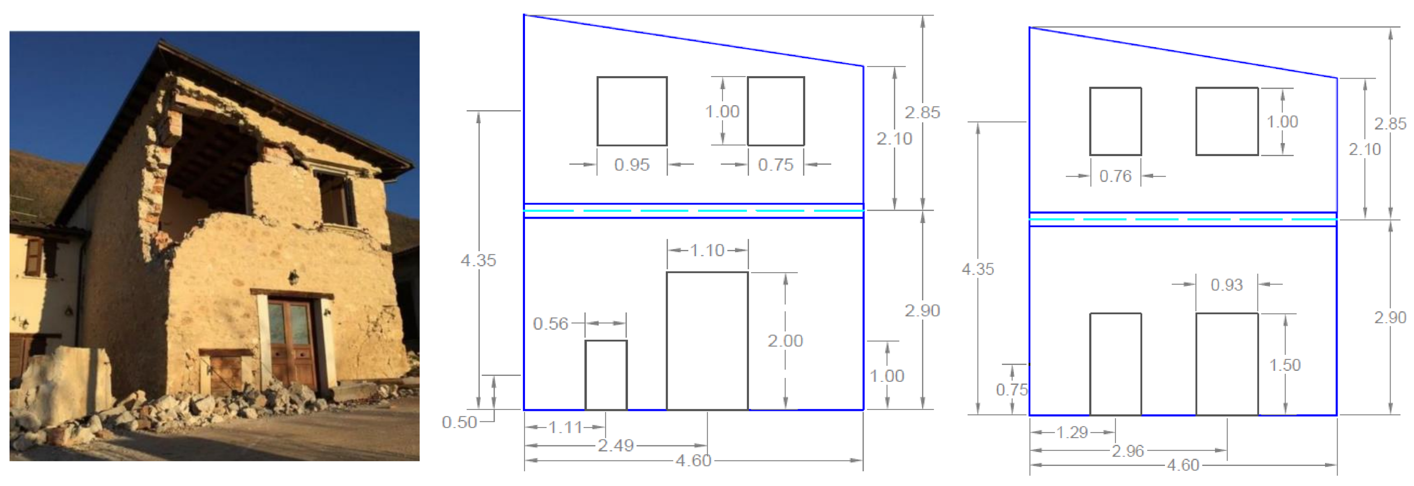

Figure 8. From left to right, original wall case L005, digitized wall and Ideal regular wall.

Irregularity	Horizontal	Vertical	Width	Height
Global index	0.545	0.172	0.237	0.345

Conclusions

- Numerical analyzes were developed that allowed to explore the differences between the criteria for defining the pier elements of Unreinforced Masonry Structures. Comparing the capacity curves derived from the Equivalent Frame Method and Pushover Analysis, no significant differences were observed in terms of displacement and base shear force, but with respect to the number of steps generated for each curve, which represents the quantity and detail of the information obtained.
- The idealized model with regular openings, obtained for the calculation of the irregularity indexes, for all cases presents a better seismic performance, which exemplifies the influence of irregular openings on the decrease of the seismic capacity of the structure.
- Regarding the regularity indexes, further research is needed to find the correlation between these values and how it affects the seismic capacity of masonry structures, otherwise they are only quantitative values that increase according to the different irregularities.

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