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Development of Macro-Block Models for Masonry Walls Subject to Lateral Loading

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ABSTRACT: Limit analysis with rigid block models has been successfully used for the assessment of ancient masonry buildings. Nevertheless, analysis results strongly depend on the model geometry. This paper presents a proposal for the construction of macro-block models of masonry walls with openings subject to lateral loading in such a way that the results are comparable with those of micro-models.

1 INTRODUCTION

The possibilities of limit analysis with rigid block models for the structural assessment of ancient masonry constructions, within sound computational frameworks, have been explored in recent years. The pioneer in this field is Livesley (1978, 1992). Other works include those of Gilbert and Melbourne (1994); Baggio and Trovalusci (1998); Ferris and TinLoi (2001) and Orduña and Lourenço (2005a, b).

Limit analysis with rigid block models has proven to be a valuable tool in the field of ancient masonry structures. Nevertheless, micro-models, where each masonry piece and joint is modelled separately, are constrained to research tasks or small structures. Real size, practical constructions have to be tackled by a macro-model strategy. In a macro-model, each block in the model represents a large portion of undamaged, or little damaged, masonry, and each joint represents a (potential) macro-crack. The problem with this approach is that the results strongly depend on model geometry (Orduña and Lourenço 2001). Giuffrè (1991) used a mechanism based approach for the seismic assessment of ancient buildings in Italy. After this work, Orduña (2003) developed guidelines for the construction of macro-block models for shear walls. Nevertheless, the modelling of lintels continues to be an unsolved problem.

The aim of this work is to develop macro-modelling strategies for masonry walls with openings in such a way that the results obtained are reliable while maintaining competitive computer running times. The limit analyses reported here were performed on the software Block2D (Orduña 2004) based on the formulation presented in Orduña and Lourenço (2001). The next section of the document presents two series of shear wall micro-models. The first series serves to study the effect of the opening position on the lateral load strength of the wall. The second series studies the effect of the opening width on the lateral strength. The second part of the document compares two proposals to construct macro-models and validates them against the micro-model results. Finally, the main conclusions arising from this work are presented.

2 MICRO MODELS

The basic model is a two stories wall with two centred openings, one at each level; see Fig. 1. The overall dimensions of the wall are: thickness 0.4 m, height 6.0 m and width $W = 5.2$ m. The blocks are 0.4×0.2×0.4 m (width × height × thickness). The two openings have the same dimensions, the width is w (1.2 m for the basic model), the height is 2.0 m and the arch rise is a (0.2 m for the basic model). The width to rise ratio is constant for all models $w/a = 6.0$. The horizontal position of the centre of the openings respect to the left edge is x (2.6 m or centred, for the basic model). The permanent loads are the self-weights of the blocks. The variable loads are numerically equal to the self-weights, but horizontally applied from left to right, simulating an equivalent seismic action. The effective compressive stress is infinity and the friction coefficient is 0.7.

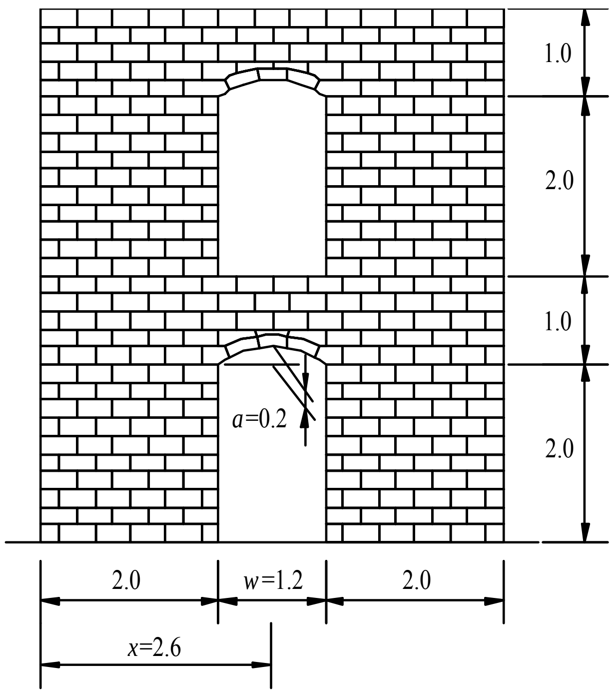


Figure 1 : Basic geometry of the micro-models.

In the first series of analyses, the position of the openings varies and the controlling parameter is the ratio opening position to total wall width, x/W. Fig. 2 shows the graph x/W vs. limit load factor. The limit load factor is the ratio between the horizontal load producing collapse and the total wall weight; therefore, it is comparable to a seismic coefficient. Note that, for seismic, reversal loading, only the graph with $x/W \geq 0.5$ makes sense; nevertheless, it is also interesting to study the behaviour of long walls. Fig. 2 illustrates that as x/W increases the limit load factor decreases. Fig. 3 presents three failure mechanisms for $x/W = 0.2$, 0.5 and 0.8, respectively. Fig. 3a illustrates that the long right wall provides a large strength to the system. In Fig. 3b, both equal piers provide a medium strength and, in Fig. 3c, the slender right pier fails locally, producing a reduced lateral strength. Observe that in the three cases the lintels have an intervention in the failure mechanism.

The second series of analyses use the width of the openings as variable parameter, normalized with the total wall width. Fig. 4 shows the w/W vs. limit load factor graph. This figure illustrates that the limit load factor decreases as the width of the openings increase. Fig. 5 presents the failure mechanisms for $w/W = 0.38$ and 0.53. See also Fig. 3b for $w/W = 0.23$. Observe that for narrow openings (Fig. 3b) both left and right piers participate in the failure mechanism and for wide openings (Fig. 5) only the right pier fails. Also, it is important to see that always the lintels take a role in the failure mechanism.

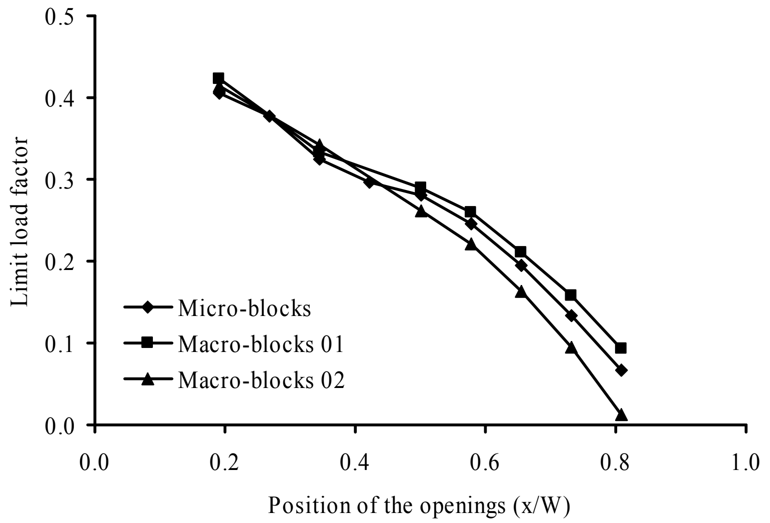


Figure 2 : Position of the openings vs. limit load factor graph.

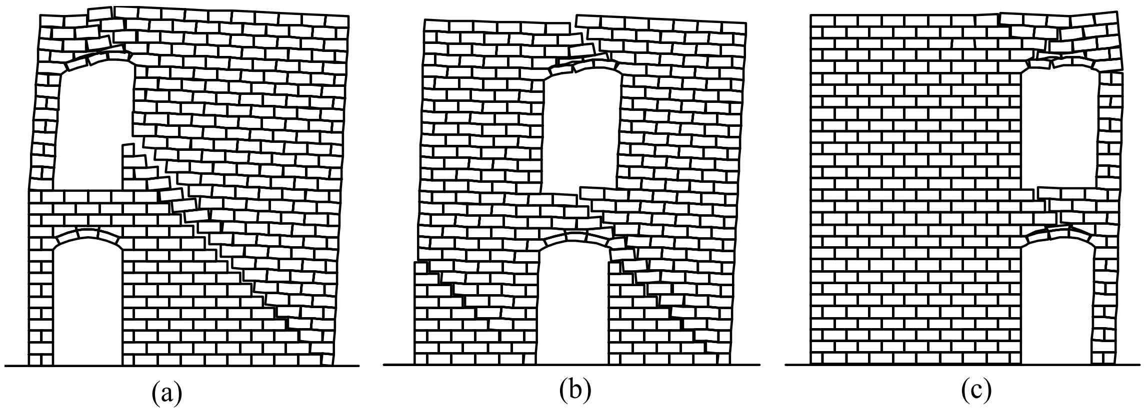


Figure 3 : Failure mechanisms for micro-blocks with (a) $x/W = 0.2$; (b) $x/W = 0.5$ and (c) $x/W = 0.8$.

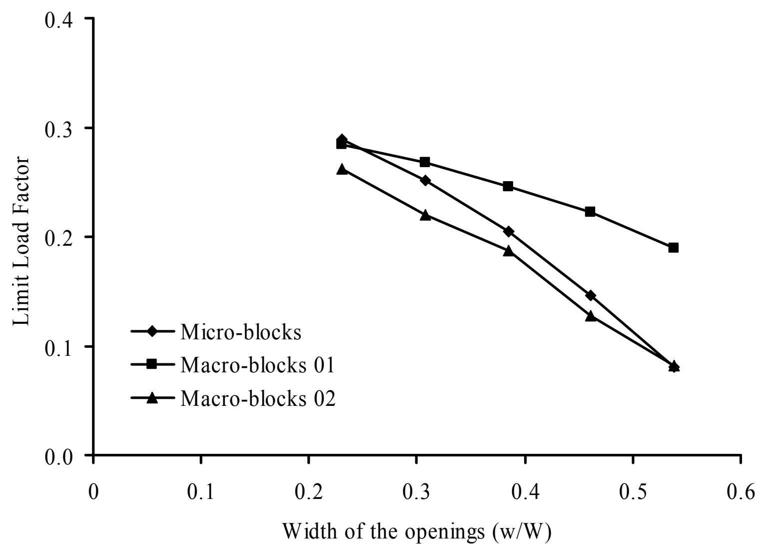
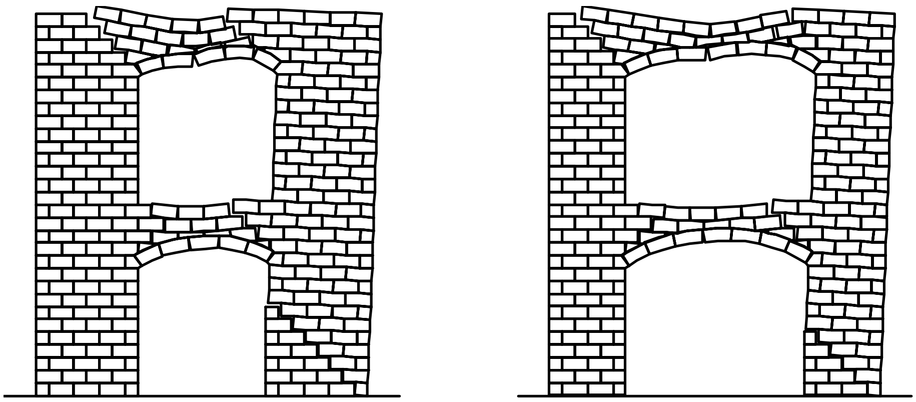


Figure 4 : Width of the openings vs. limit load factor graph.



(a) (b)

Figure 5 : Failure mechanisms for micro-blocks with (a) *w/W* = 0.38 and (b) *w/W* = 0.53.

3 MACRO MODELS

In this section two macro-modelling strategies are analyzed. The first one was proposed in Orduña (2003) and here is named as Macro-blocks 01. The second modelling strategy is a modification to the first one and here named as Macro-blocks 02.

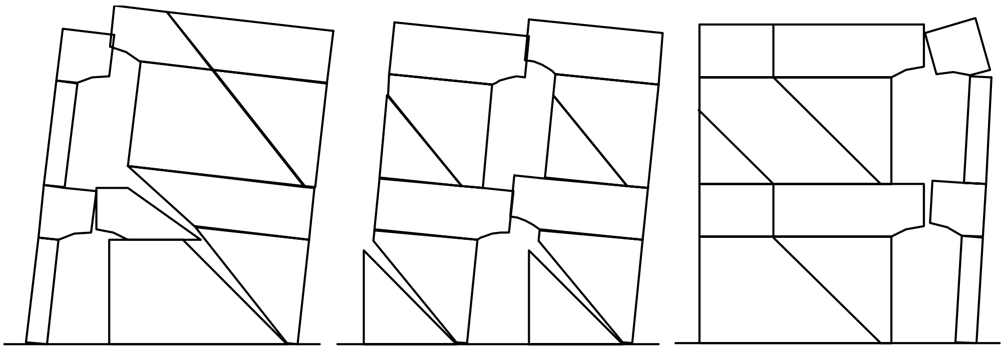
In both modelling strategies the individual shear walls are constructed about the same way: there is a inclined interface from bottom right to upper left parts of the wall, and at the base of the upper block there is a horizontal interface that carries the self-weight. In Orduña (2003) there are guidelines for the length of the horizontal interface and for the inclination of the diagonal one. In this work, and for consistency between the models, the horizontal interface length is taken a half-block width, i.e. 0.2 m, and the angle between the horizontal direction and the inclined interface is 45º. Fig. 6b is a good example of this strategy. For slender walls, height to width ratio larger than four, the inclined crack disappears and the model is a single rectangular block. See the left piers in Fig. 6a.

In the Macro-blocks 01 strategy models there is a horizontal interface at the springer of the arches. For long walls, the inclined cracks turn to a vertical direction at the intersection with the horizontal interface; see the left piers at Fig. 6c. In this modelling strategy, the model for the lintels failure is a horizontal interface at the middle of the opening. The reason for this strategy is that lintels transmit small normal forces and a shear failure is expected (Orduña 2003).

Fig. 2 shows the *x/W* vs. limit load factor graph for the Macro-blocks 01 modelling strategy, compared with the micro-blocks one. Observe that they are very similar. Fig. 4 presents the w/W vs. limit load factor curve for this macro-modelling strategy, compared with the micro-blocks one. In this case, the macro-modelling strategy overestimates the limit load factor for wide openings (large values of *w/W*). Fig. 6 shows the failure mechanisms for *x/W* = 0.2, 0.5 and 0.8 for the Macro-blocks 01 modelling strategy. These are comparable to the failure mechanisms for micro-block models in Fig. 3. Fig. 7 presents the failure mechanisms for *w/W* = 0.38 and 0.53 for the first macro-modelling strategy; compare with Fig. 5.

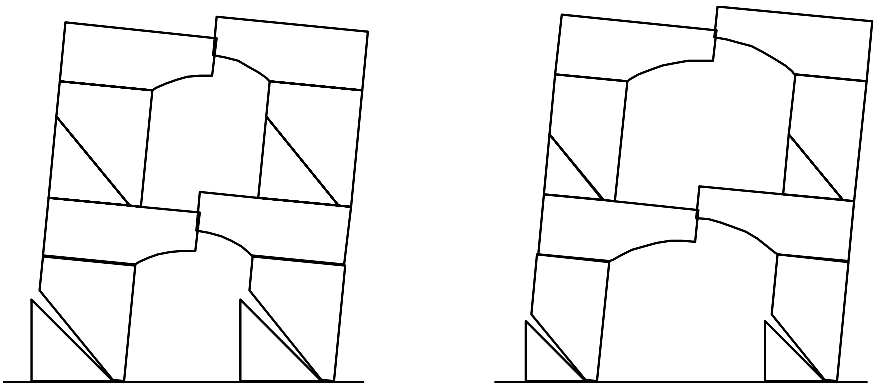
The comparison of the failure mechanisms indicates that the shear wall modelling strategy is good, in general terms. Although, the horizontal interfaces at the level of the sprigers of the arches seems to be not necessary. Also, the failures at the lintels are very different in the corresponding micro- and macro models. The differences between both modelling strategies motivated the proposal of a modification to the macro-blocks one.

The Macro-block 02 strategy eliminates the horizontal interface at the springers of the arches and modifies the lintel modelling. The vertical interface at the middle of the opening is maintained and two additional potential cracks at each lintel are included. These last cracks are two interfaces: the first one starts at the opening upper corner and follows the direction and length of the beginning of the arch interface, the second one starts from here and goes to the upper part of the lintel. In the case of intermediate levels, this second interface ends in the lower corner of the upper opening. In the case of the top level, the second interface is vertical; see Fig. 8b. For slender piers, the two interfaces strategy is not possible and is substituted for a horizontal interface; see Fig. 8a, c.



(a) (b) (c)

Figure 6 : Failure mechanisms for Macro-blocks 01 with (a) $x/W = 0.2$; (b) $x/W = 0.5$ and (c) $x/W = 0.8$



(a) (b)

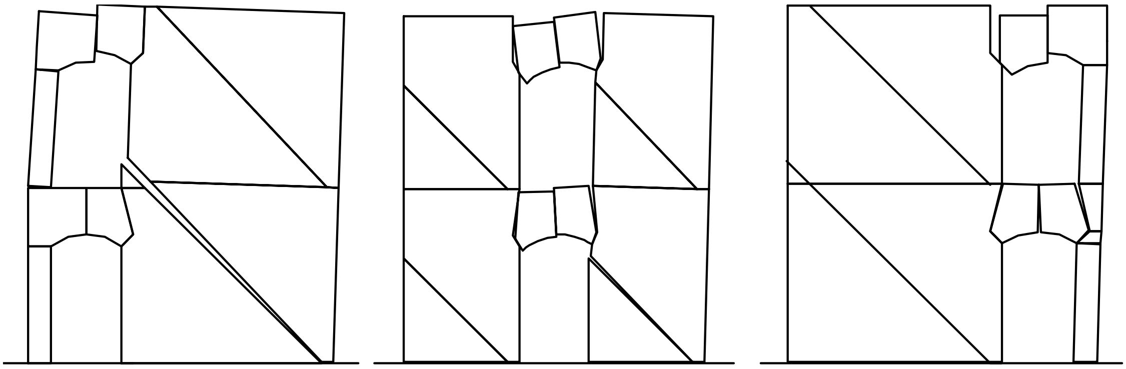
Figure 7 : Failure mechanisms for Macro-blocks 01 with (a) $w/W = 0.38$ and (b) $w/W = 0.53$

Fig. 2 compares the x/W vs. limit load factor curves for the three modelling strategies. This figure shows that for small values of x/W, both macro-block strategies are close to the micro-block results. For large values of x/W the Macro-blocks 02 strategy underestimates the limit load factor, and the difference can be large in terms of relative values. Fig. 4 presents the w/W vs. limit load factor for the three modelling strategies. In this case, the Macro-blocks 02 strategy always underestimates the limit load factor, but the behaviour is better than the shown by the Macro-blocks 01 strategy. In terms of failure mechanisms, Figs. 8 and 9 present the results obtained with the second macro-modelling strategy for various x/W and w/W values, respectively. Fig. 8 is comparable with Figs. 3 and 6; and Fig. 9 is comparable with Figs. 5 and 7. A slightly better agreement is observed for the failure mechanisms for the second macro-block strategy than for the first one, compared with the micro-blocks results. Nevertheless, the agreement is not as good as would be desirable. An explanation for this fact is that the failure mechanism in the micro-models is a complex interaction between several blocks, and the substitution of this behaviour with a reduced number of blocks is in fact a difficult task.

4 CONCLUSIONS

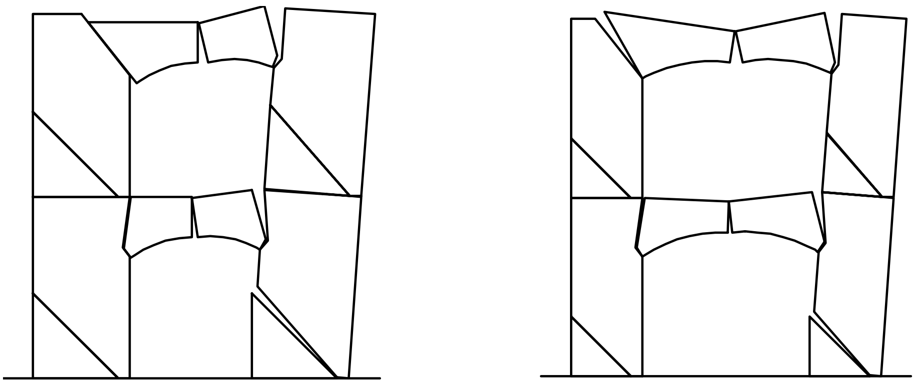
The behaviour of a two stories shear wall with two openings has been studied in relation to the position of the openings and to the width of them. The results indicate that the limit load factor decreases as the openings approach the right side of the wall for lateral load from left to right.

For reversal loading, the best position of the door is centred. Also, the limit load factor decreases as the openings are wider.



(a) (b) (c)

Figure 8 : Failure mechanisms for Macro-blocks 02 with (a) $x/W = 0.2$; (b) $x/W = 0.5$ and (c) $x/W = 0.8$.



(a) (b)

Figure 9 : Failure mechanisms for Macro-blocks 02 with (a) $w/W = 0.38$ and (b) $w/W = 0.53$

Two macro-block modelling strategies were proposed. The Macro-blocks 02 strategy provides slightly better results than the first one. Nevertheless, more research is needed in order to develop reliable strategies for macro-block modelling that are competitive in time considering the model construction, solution and visualization of results. This research can include the proposal of more refined macro-block strategies and the modification of the interfaces behaviour, in order to take into account the scale of the model.

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