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Engineering methodology to assess the seismic out-of-plane response of two-way spanning unreinforced masonry walls with multiple openings

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Unreinforced masonry buildings show high vulnerability to seismic loading, especially in the out-of-plane direction. Two-way spanning walls are characterized by effective restraints at at least one lateral side of the wall. Their seismic performance under out-of-plane loading has been studied in the literature for walls without openings or with one opening, but it lacks understanding in case of multiple openings. This study presents an engineering approach to calculate the out-of-plane capacity of two-way spanning walls with two openings. Five wall configurations were analysed via non-linear pushover analyses, and crack-pattern evolution tracked. A methodology was proposed which involves dividing the wall into panels whose performance is assessed separately. The division is based on the crack propagation observed in the numerical simulations. Two panels are defined as the wall portions comprised between a side support and an opening which are classified and analysed as three-sided supported walls. Another component corresponds to the wall portion between the two openings and is analysed as a one-way spanning wall. The assessment of the individual panels is based on formulations provided in the Dutch guidelines NPR-9998:2020 which show that the one-way spanning wall panel is the governing one, which is further proved by the analytical calculations.

1. Introduction

The process of gas extraction in the Groningen province, located in the northern part of The Netherlands, has exposed its building stock to induced seismicity. For most buildings in Groningen, the main load-bearing elements are unreinforced masonry walls (URM) spanning in orthogonal directions. Thus, for the safety of these buildings and their occupants, it is necessary that these walls have sufficient in-plane and out-of-plane (OOP) capacity against seismic loading.

Various analysis methods can be used to evaluate the seismic performance of URM walls and buildings such as non-linear time history analysis (NLTH), modal response spectrum (MRS), and non-linear pushover analysis (NLPO). However, the performance of such analysis methods depends highly on user skill, available computational resources, as well as precise knowledge of material properties. Consequently, design rules and analytical methods are still the most widely and commonly utilized methods in engineering practice because of their simplicity and ease of use. In this regard, analytical methods provided in Annex H of NPR 9998:2020 [1], i.e., the Dutch code of practice for seismic assessment of structures, to calculate the OOP capacity of URM walls are the non-linear kinematic analysis (NLKA) and the virtual work method (VWM). The distinction in choice of method is based on its boundary conditions and for two-way spanning walls the VWM is recommended while for one-way spanning walls, NLKA is adopted. The virtual work method for two-way spanning URM walls was first developed by Lawrence and Marshall [2] in 1996 and is also adopted in the Australian masonry code, AS 3700:2011 [3], and added as a note in the New Zealand masonry code, C8 [4]. All these codes, including the NPR 9998:2020 [1], however provide guidelines only for the analysis of two-way spanning walls without any openings or just a single opening. Practicality dictates that the number of openings in a wall may be more than one. To overcome this shortcoming, this paper proposes an engineering methodology to assess the seismic OOP response of two-way spanning URM walls with more than one opening.

2. Calculated crack patterns

To be able to implement the NLKA and VWM for the analytical assessment of URM walls with multiple openings it is required to know the crack pattern, and thus the failure mechanisms, of the wall a-priori. For walls with a single opening the crack patterns for different wall configurations are known through earlier research and are already described in NPR9998:2020 [1] along with corresponding analytical formulations. For the walls with multiple openings any experimental data and literature on the crack patterns is missing and therefore a different approach is necessary to determine the crack patterns. A first method would be to prescribe a certain crack pattern onto a URM wall with multiple openings and then determining the failure load of the wall following that crack pattern. This needs to be done iteratively, after which a governing failure load is found for one of the prescribed crack patterns. However, this does not guarantee that the lowest failure load is found and moreover it is a long and tedious process. Therefore, it is chosen to find the governing crack patterns for a set of wall configurations with two openings through a second method, by numerical simulations. The analyses will result into a crack pattern that can be used for developing the analytical solution, and it will already give an insight in the different failure mechanisms of the wall with multiple openings.

The finite element analysis software DIANA version 10.5[5] is utilized to perform the analyses on the URM wall with multiple openings. The non-linear pushover (NLPO) analysis is used because both NLKA and VWM assume a uniform distribution of OOP loads on the wall, like the NLPO loading scheme.

For the numerical model of the URM wall with two openings certain parameters are kept constant for consistency in the process and results, such as the material properties of the masonry and the dimensions of the wall. The wall is modelled via shell elements with 7 integration points over the thickness and it is discretized by means of linear quadrilateral elements with the full integration scheme over element area. For the analysis in DIANA the regular Newton-Raphson iteration scheme is adopted along with a force and displacement convergence norm that both need to be satisfied. Lintels are considered due to their presence in most URM walls found in the Netherlands and are modelled via linear elastic beam elements.

2.1. Calibration numerical model

To calibrate the numerical model, the work of Vaculik [6] is used as a benchmark to check the crack patterns. Vaculik [6] conducted tests on small masonry specimens in accordance with the guidelines of the Australian masonry code AS 3700:2011 [4]. Since the interest of this research is focused on walls with openings, a test specimen that has one opening is chosen to be replicated in DIANA [5] after which the analysis result for the crack pattern can be compared to the experimental result. The set-up additionally consists of two return walls to stabilise the wall against overturning and implement rotational fixity at the vertical edges. All other wall edges are simply supported in the out-of-plane direction of the main wall and the bottom edges are translationally supported in vertical direction. No overburden load on the specimen is considered, consistent with the performed experiment. Figure 1 shows the geometry of the masonry specimen including the return walls. The thickness of the walls is equal to 110 mm. The material model used is the total strain-based rotating crack (TSRC) model [5]. Chang et al [7] proposes the material properties for the TSRC constitutive model based on experimental records from the work of Vaculik [6] and calibrations according to recommendations in the literature. The TSRC model can accommodate a more realistic and sharper crack localization behavior as opposed to other masonry material models. This has been presented in a validation report for the modeling of masonry by DIANA FEA and the TU Delft [8]. Table 1 shows the material properties of masonry and Figure 2 shows the masonry constitutive model.

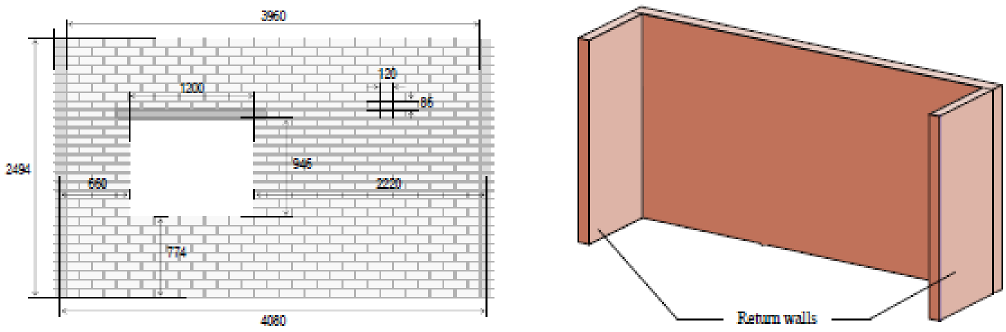

Figure 1. Geometry masonry specimen with one opening, all dimensions in mm (reproduced from **[6]**).

Table 1. Material properties masonry.

Young's modulus (N/mm^2)	7080
Poisson's ratio	0.16
Tensile strength (N/mm^2)	0.205
Mode-I fracture energy (N/mm)	0.0328
Compressive strength (N/mm^2)	16
Compressive fracture energy (N/mm)	31.5

(a) (b)

Figure 2. Masonry constitutive model, (a) represents the tensile and (b) the compressive behaviour

Although the experiment had a slightly different loading scheme, the results are still comparable. The first stage of the experiment involved an ultimate strength test, subjecting the uncracked wall to a monotonic load until it reached its ultimate load capacity. Hereafter a cyclic loading was applied on the cracked wall. With the NLPO analysis in DIANA the initial part of the analyses is similar since the wall is subjected to a monotonic load. However, for the NLPO the monotonic load is continued after reaching the ultimate load capacity. A uniform loading pattern is applied to the wall surface.

It is evident that quite similar crack patterns are found for the numerical model and the experiment as seen in Figure 3. The experimental result is not exactly the same in terms of the crack pattern, but this could be caused due to the inhomogeneous material in the specimen, whereas the numerical model assumes a completely homogeneous material. This inhomogeneity might lead to formation of cracks in different locations. A second comparison is made for the ultimate load capacity of the wall. The ultimate load that follows from the numerical analysis is equal to 2.95 kPa, whereas the experiment results in a load of 3.59 kPa. The computed difference (-18%) is sufficiently small, and it shows that the numerical model is more on the conservative side compared to the experiment. The higher value measured experimentally may also be attributed to the extra vertical cracks that formed experimentally but not numerically, which may suggest the presence of slight different boundary conditions at the top and bottom of the wall.

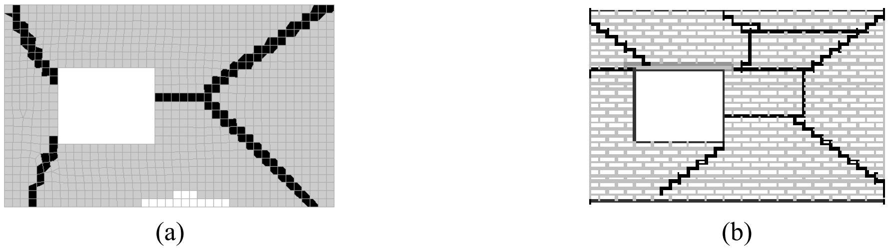

Figure 3. Crack patterns for masonry specimen (a) from numerical calculation and (b) from experiments (reproduced from [6]).

It is concluded that the numerical model, including its geometry and constitutive models, is performing to expectation and produces conservative but sufficiently accurate results. Therefore, the model is assumed to be calibrated and can be utilized to calculate crack patterns for walls with two openings.

2.2. Numerical Calculation: Wall with two openings

Investigation into the development of the failure mechanism for two-way spanning walls with two openings is conducted for two distinct wall set-ups. The first set-up consists of two windows and will be discussed in section 2.2.1 and the second set-up consists of a window and door and is described in section 2.2.2. For both set-ups the dimensions of the wall are chosen to be 5 x 3 m^2 with a thickness of 100 mm. The material properties for the masonry are described in Table 1. The configuration of the openings are standardized to a general URM house in the Netherlands.

The different numerical analyses will show crack patterns at two different locations along the loading path, giving insight in the development of the failure mechanism in the wall.

2.2.1. Set-up 1: wall with two windows

For the wall set-up with two windows, three different wall configurations are chosen. Table 2 gives an overview of the dimensions of the three different configurations referring to the naming convention of dimensions in Figure 9. It should be noted that for all configurations $H_{d1} = H_{d2} = H_{d3} = H_{d4}$ and $L_{d1} = L_{d2}$.

Table 2. Dimensions wall configurations with two windows (in m).

	L_1	H_1	L_2	H_2	H_{d1}	L_{d1}	L_{int}
Configuration 1	1.50	1.50	1.50	1.50	0.75	0.70	0.60
Configuration 2	1.00	1.50	1.00	1.50	0.75	1.00	1.00
Configuration 3	1.50	1.50	1.00	1.50	0.75	0.90	0.70

In Figure 4 to Figure 6 the crack patterns for the three wall configurations with two windows are shown along with the pushover curves of the walls. The markers on the curves denote the points at which the crack patterns are given. The green marker is located at the ultimate load capacity and therefore shows the crack pattern belonging to the initialization of the failure mechanism. The red marker is located at a maximum out-of-plane displacement of 80 mm. This point is chosen because it is considered as the maximum displacement that still provide numerically reliable results for walls with a thickness of 100 mm and it will therefore show the full failure mechanism of the wall.

From the crack patterns of all configurations at the ultimate load capacity it becomes evident that the middle pier, the one-way spanning panel, of the wall is governing for the initialization of the failure mechanism. It should be noted that this will not cause failure of the whole wall, since it becomes clear from the pushover curves that there is still residual capacity in the wall. The crack patterns at a displacement of 80 mm are comparable and show similarity with the crack patterns from NPR9998:2020 [1] if the wall would be divided in separate panels assuming different boundary conditions.

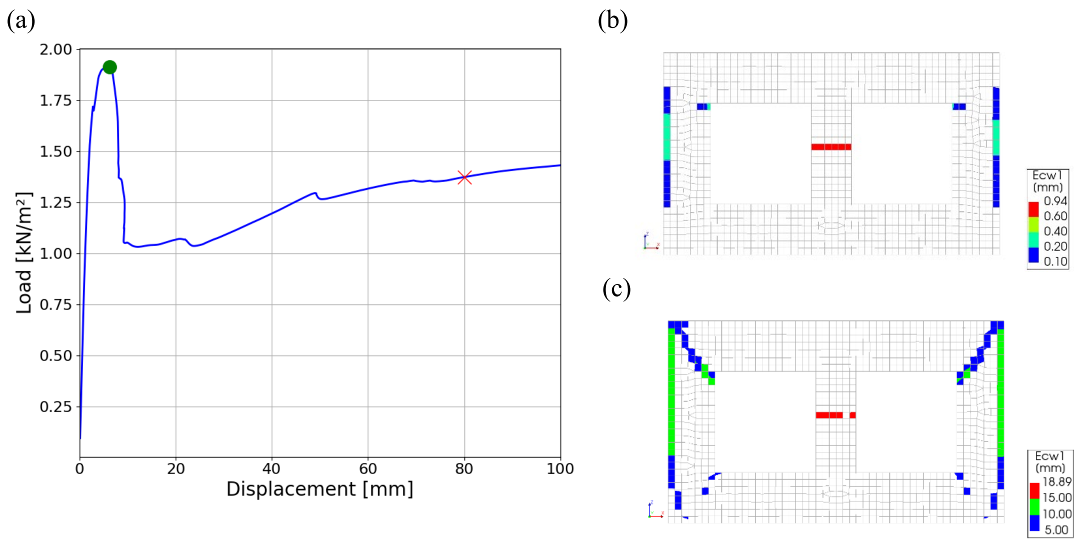

Figure 4. Crack patterns configuration 1: wall with two windows of 1.5 x 1.5 m^2 at (b) ultimate load capacity ((a) green marker) and at (c) a maximum out-of-plane wall displacement of 80 mm ((a) red marker).

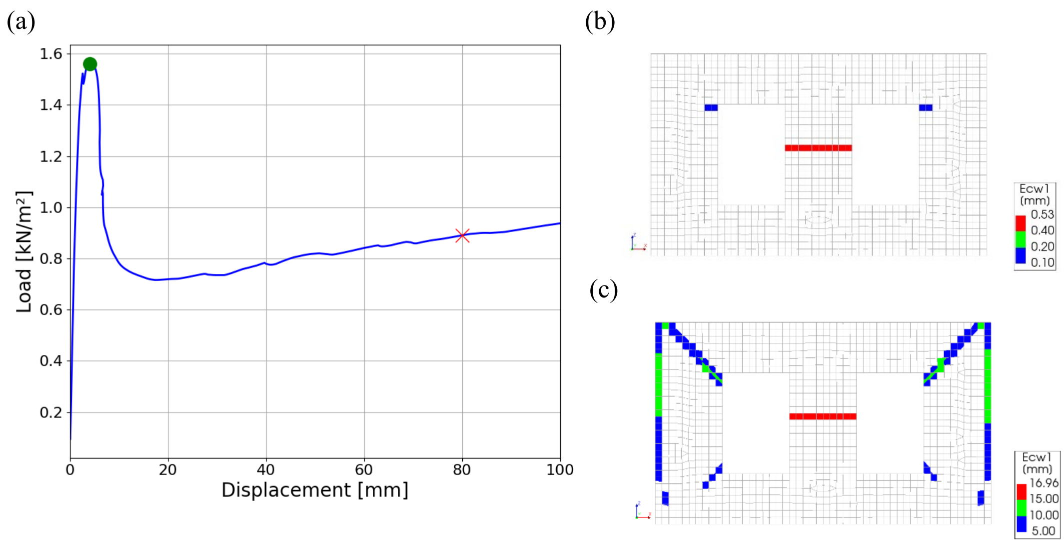

Figure 5. Crack patterns configuration 2: wall with two windows of 1.0 x 1.5 m^2 at (b) ultimate load capacity ((a) green marker) and at (c) a maximum out-of-plane wall displacement of 80 mm ((a) red marker).

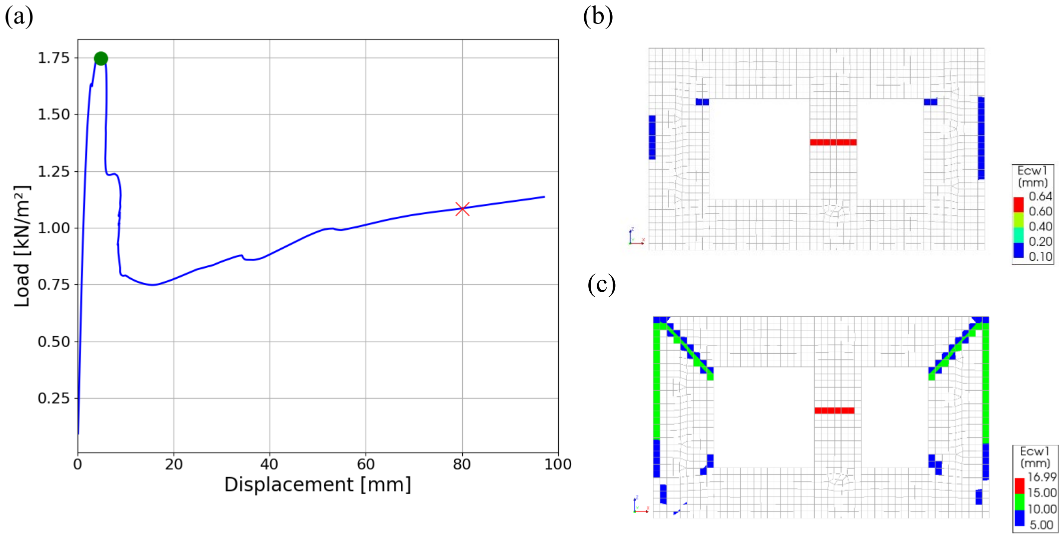

Figure 6. Crack patterns configuration 3: wall with a window of 1.5 x 1.5 m^2 and a window of 1.0 x 1.5 m^2 at (b) ultimate load capacity ((a) green marker) and at (c) a maximum out-of-plane wall displacement of 80 mm ((a) red marker).

2.2.2. Set-up 2: wall with a window and door

The second wall set-up consists of a window and door. Two different configurations are chosen for this set-up to be examined. Table 3 gives an overview of the dimensions of the two different configurations where the naming convention of the dimensions is found in Figure 9. It should be noted that for both configurations $H_{d3} = H_{d4}$ and $L_{d1} = L_{d2}$.

Table 3. Dimensions wall configurations with one window and one door (in m).

	L_1	H_1	L_2	H_2	H_{d1}	H_{d2}	H_{d3}	L_{d1}	L_{int}
Configuration 1	1.50	1.50	1.00	2.20	0.70	0.00	0.80	0.80	0.90
Configuration 2	1.00	1.50	1.00	2.20	0.70	0.00	0.80	1.00	1.00

In Figure 7 and Figure 8 the crack patterns for the two wall configurations with a door and a window are shown along with the pushover curves of the walls. The markers on the curves are at the same locations as described in section 2.2.

From the crack patterns of the two configurations at the ultimate load capacity it is evident that, like the wall with two windows, the middle pier of the wall is governing for the initialization of the failure mechanism. As for the wall with two windows there is still residual capacity in the wall after the ultimate load capacity is reached. The crack patterns at a displacement of 80 mm are comparable apart from the panel right of the door. However, in general the crack patterns of individual panels in the wall can be compared to the ones mentioned in NPR9998:2020 [1].

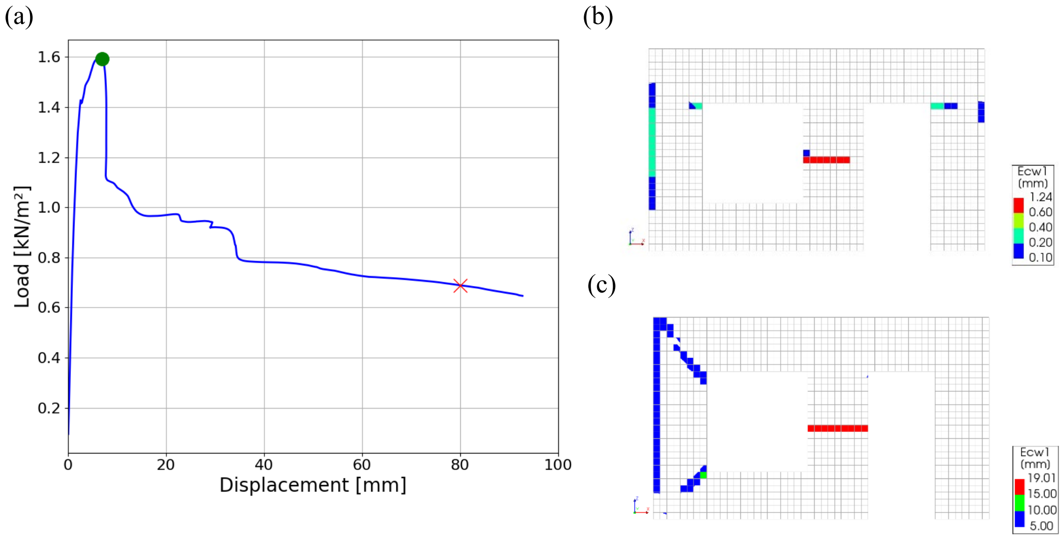

Figure 7. Crack patterns configuration 1: wall with a door of 1.0 x 2.2 m and a window of 1.5 x 1.5 m at (b) ultimate load capacity ((a) green marker) and at (c) a maximum out-of-plane wall displacement of 80 mm ((a) red marker).

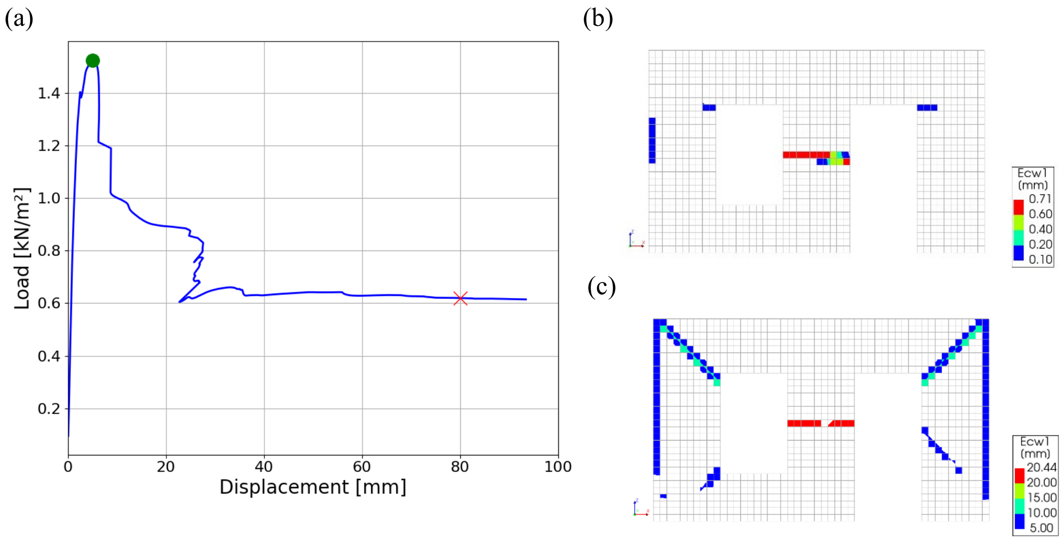

Figure 8. Crack patterns configuration 2: wall with a door of 1.0 x 2.2 m and a window of 1.0 x 1.5 m at (b) ultimate load capacity ((a) green marker) and at (c) a maximum out-of-plane wall displacement of 80 mm ((a) red marker).

3. Proposed engineering methodology: panel approach

Based on the results observed in section 2, a proposal to assess four-sided supported walls with multiple openings is proposed. The approach is to divide the wall into different panels and assess each of the panels separately using the theories and formulas (i.e. NLKA and VWM) mentioned in NPR9998-2020 [1]. The approach also ensures the same seismic demand when analysing the panels, which is dependent on the natural period of the original wall with multiple openings.

For a four-sided simply supported wall with two openings and lintels as shown in Figure 9, the panel division would result in the following:

- Two-way spanning three-sided supported wall with a vertical free edge, with a design length of L_{d1} and design height of H (leftmost side of the wall), shown in red colour in Figure 9;
- One-way spanning wall in between the two openings, with a design height of H, shown in cyan colours in Figure 9;
- Two-way spanning three-sided supported wall with a vertical free edge, with a design length of L_{d2} and design height of H (rightmost side of the wall), shown in green colour in Figure 9;

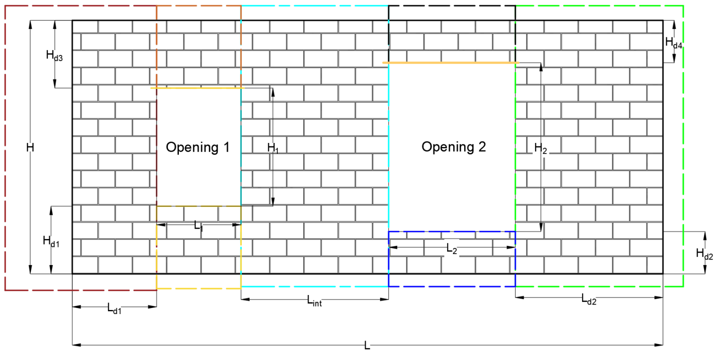

Figure 9. Wall panel division for a four-sided supported wall with two openings.

The division for the panel above and below the opening can be done either into a three-sided supported wall or a four-sided supported wall, which is dependent on the sequence of crack progression. From the numerical calculations, it was seen that if the location of the opening is comparatively centred, the bottom part of the opening can be classified as three-sided supported wall with free top edge and the top part of the opening can be classified as a four-sided supported wall, because of the presence of lintel. However, these panels will not be governing because of short length and height.

4. Analytical calculation

The seismic out-of-plane resistance a_R of walls with two window openings and window and door opening has been calculated following the virtual work approach as described in [6]:

$$a_R = \frac{\sum_N m_i l_i \theta_i}{\rho g t V_{tot}} \tag{1}$$

where m_i, l_i and θ_i are the bending moment, length, and virtual rotation respectively of crack i, N the number of cracks, ρ the mass density of masonry (1950 kg/m^3), t its thickness, g the gravity acceleration (9.8 m/s^2) and V_{tot} the total displaced volume. The numerator of the latter equation will be referred to as the total internal virtual work. Diagonal bending has been defined according to NPR9998:2020 [1] assuming bricks of 0.21x0.10x0.05 m^3, mortar joint thickness of 0.01 m, and average bending strength of masonry equal to 0.15 MPa. Furthermore, the side and middle panels have also been calculated as two-way spanning (virtual work method) and one-way spanning walls (non-linear kinematic analysis) respectively according to NPR9998:2020 [1]. Medium stiff supports ($R_{f1} = R_{f2} = 0.5$) has been assumed for two-way spanning cases, and results for both centric (flexible) and eccentric (rigid) bottom supports for the one-way spanning case are presented.

4.1. Analytical Calculation: Wall with two openings

Analytical calculations were performed on the wall configurations mentioned in section 2.2 For the analysis, the number for virtual work and displaced volume are based on a maximum virtual out-of-plane displacement of 0.1 m.

4.1.1 Wall with two window openings

The crack patterns as identified in section 2.2.1 led to the assumed failure modes shown in Figure 10. Cracks intersect the outer corners of the windows in all three configurations. Based on those schematic crack patterns the seismic out-of-plane resistances have been obtained as listed in Table 4. The side panel seismic resistance has been determined both for a length of L_{d1} and $L_{d1}+L_1$ (refer to Figure 9 for notations). The latter means that the opening is considered as solid masonry.

Table 4. Analytical calculation results for out-of-plane seismic resistance of masonry wall configurations mentioned in Table 2.

Configuration	Unit	1	2	3
Total internal virtual work	J	117	136	122
Total displaced volume	m^3	0.290	0.350	0.311
Seismic resistance	kN/m^2	0.40	0.39	0.39
	g	0.21	0.20	0.20
Side panel seismic resistance				
Size L_{d1}	g	1.44	0.78	0.93
Size $L_{d1}+L_1$	g	0.23	0.26	0.20
Middle panel seismic resistance				
Centric bottom support	g	0.09	0.09	0.09
Eccentric bottom support	g	0.19	0.19	0.19

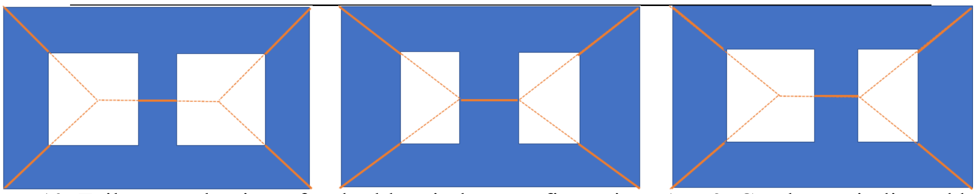

Figure 10. Failure mechanisms for double window configurations 1 to 3. Cracks are indicated by the solid orange lines.

4.1.2 Wall with a window and door opening

The crack patterns as identified in section 2.2.2 led to the assumed failure modes shown in Figure 11. Cracks intersect the outer corners of the window and door in both configurations. In the first configuration two cracks in the right panel are assumed to intersect at a vertical distance of 0.7 m from the bottom of the wall. In the second configuration this vertical distance is assumed to be 0.4 m. Based on those crack patterns the seismic out-of-plane resistances have been obtained as listed in Table 5.

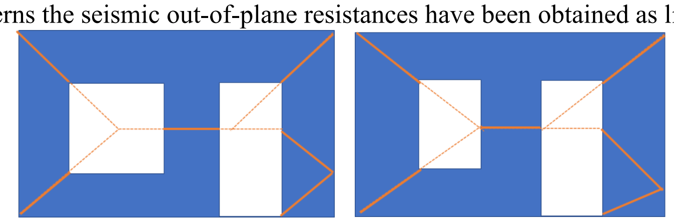

Figure 11. Failure mechanism for window-door configurations 1 and 2. Cracks are indicated by the solid orange lines.

Table 5. Analytical calculation results for out-of-plane seismic resistance of masonry wall configurations mentioned in Table 3

Configuration	Unit	1	2
Total internal virtual work	J	132	161
Total displaced volume	m^3	0.302	0.323
Seismic resistance	kN/m^2	0.44	0.50
	g	0.23	0.26
Side panel seismic resistance			
Size L_{d1}	g	1.14	0.78
Size $L_{d1}+L_1$	g	0.22	0.26
Middle panel seismic resistance			

Centric bottom support	g	0.09	0.09
Eccentric bottom support	g	0.19	0.19

After comparison of the pressures mentioned in Table 4 and Table 5 under seismic resistance, to the loads at 80 mm of displacement in the corresponding pushover curves, it appears that the analytical capacities are more conservative, as expected

5. Conclusions

From the study, the following conclusions are drawn:

- Non-Linear Pushover (NLPO) analysis was performed on five different wall configurations with two openings and the calibrated material properties from Vaculik's thesis [6]. The crack patterns from all calculations show that the middle panel between the opening's cracks before the attainment of the ultimate load capacity. Cracks further propagates in the side panels, effectively behaving like the configuration identified in NPR9998:2020 [1] as a three sided-supported wall with a free vertical edge. Furthermore, each of the cracks in an individual component develop at a different instant in the analysis.
- Based on the results of the numerical calculations, an engineering analytical methodology is proposed to analyse four-sided simply supported walls with two openings, by dividing the walls into different panels. The panel in between the two openings should be analysed as a one-way spanning wall. The panels between a vertical support and an opening should be analysed as a three-sided supported wall with a free vertical edge. If the location of the opening is comparatively centred to the wall, the panel below the opening can be divided into a three-sided supported wall panel with free top edge and the panel above the opening can be divided into a four-sided supported wall, being supported by the lintel at the bottom. In this approach, the acceleration demand for each individual panel should be the same and should be calculated based on the natural frequency of the whole wall with two openings.
- The analytical calculation of two-way spanning walls with multiple openings shows that the one-way spanning panel between the openings is governing, having the least force resistance, which is also confirmed by the crack progression in the numerical calculations. However, additional capacity, after the crack of the one-way spanning panel, is present, and hence the presented methodology provides a conservative prediction of the wall capacity.

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