ANNEX 1 – BRICK-WALLS CALCULATIONS

Mortars incorporating alum-sludge as sand replacement: Development and brick-wall calculation

By:

Ismael Esteban Serna Tormo

UPV coordinator:

Dr. Jorge Juan Payá Bernabeu

CONTENT

LIST OF FIGURES

LIST OF TABLES

Annex 1: Brick-Walls Calculation

A1. Introduction

In this section will be calculated the performance of the mortars that have been researched in different typologies of brick-walls. Two different typologies of brick-wall will be calculated:

- Free-standing wall: These walls are mainly used inside residential plots to demarcate the house from others, and to create a visual barrier. They are mainly normally fixed to the floor with a concrete footing (*Figure A.1.1).*
- Residential wall: These walls are attached as an external isolating layer to residential or industrial buildings (Figure A.1.2).

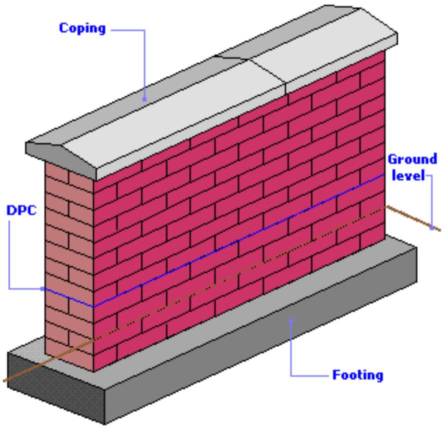

Figure A1.1. *3D view of a free-standing wall.*

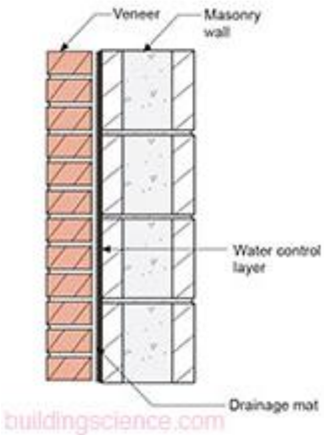

Figure A1.2. *Cross-section of a residential wall.*

It will be developed 5 unreinforced walls with different heights. The walls have 2 bricks thickness:

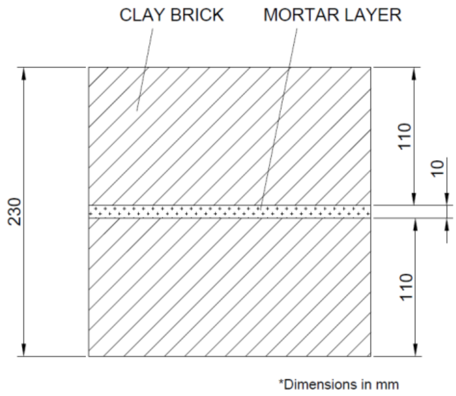

***Figure A1.3**. Perpendicular cross-section of the walls of the model.*

The Walls 1, 2 and 3 are free-standing walls. The Wall 4 is a residential brick-wall supported in the structural members (1-floor buildings, applicable to more floors), and the Wall 5 is a residential brick-wall just anchored to the structural members (2-floor buildings).

***Table A1.1**. Height of each wall with its typology.*

Wall ID	Typology	Height
Wall 1 (2b layer)	Free-standing	3 m
Wall 2 (2b layer)	Free-standing	2 m
Wall 3 (2b layer)	Free-standing	1.5 m
Wall 4 (2b layer)	Residential-wall	3 m
Wall 5 (2b layer)	Residential-wall	6 m

From the *National Construction Code - 2016,* determining an importance level of building 2, the annual probability of exceedance for a non-cyclonic wind is 1:500.

A.2. Forces determination

Wind and earthquake forces will be calculated according to *AS/NZS 11170.2:2011* and *AS/NZS 11170.4:2011.*

A.2.1 Wind force

All the tables and sections mentioned are referenced to *AS/NZS 11170.2:2011*. The procedure for determining the wind actions (*W)* of the model is:

- Determine site wind speeds
- Determine design wind speed
- Determine design wind pressures and distributed forces
- Calculate wind actions

A.2.1.1. Site wind speed

The site wind speeds ($V_{sit,\beta}$) is calculated as follows:

$$V_{sit,\beta} = V_R M_d \left(M_{z,cat} M_s M_t\right) = 45 \cdot 1 \cdot (0.83 \cdot 0.\cdot 1)$$

$$V_{sit,\beta} = 37.35\ m/s$$

where:

- V_R = Regional gust wind speed, for the annual probability of exceedence.

Identifying Adelaide as *Region A1* in *Figure 3.1(A)*, and with an annual probability of exceedance of 500 years, V_R is taken from *Table 3.1* as:

$$V_R = 45\ m/s$$

- M_d= wind directional multipliers for the 8 cardinal points.

M_d is taken from *Table 3.2* as *Any direction* since the wall calculated is a general wall in any residential area of Adelaide.

$$M_d = 1$$

- $M_{z,cat}$ = terrain/height multiplier

Identify any Adelaide residential suburb as *Terrain Category 3 (TC3)*, and having heights not higher than 10 m, the terrain/height multiplier is taken from *Table 4.1.* as:

$$M_{z,cat} = 0.83$$

- M_s = shielding multiplier

For calculating the shielding multiplier it is necessary to calculate first the Shielding parameter (s) as:

$$s = \frac{l_s}{\sqrt{h_s b_s}} = \frac{306}{\sqrt{6 \cdot 10}} = 39.50$$

where:

- l_s= average spacing of shielding buildings =
$$l_s = h\left(\frac{10}{n_s} + 50\right) = 6\left(\frac{10}{10} + 50\right) = 306$$

where:

- n_s = number of upwind shielding within a 45º sector of radius 20h = 10

For approximately calculate this factor a residential suburb of Adelaide is display in *Google Earth* as:

Figure A2.1*. Residential suburb of Adelaide (West Croydon) with a 45º sector of 120 m radius.*

- h_s = average roof height of shielding buildings = 6 m
- b_s = average breadth of shielding buildings = 10 m

Now with *s,* it is possible to take M_s from *Table 4.3* as:

$$M_s = 1$$

- M_t = topographic multiplier

The topographic multiplier is taken as the larger value of the following:

$$M_t = \max(M_h; M_{lee}) = 1$$

- M_h = Hill-shape multiplier. Since most Adelaide suburbs are mostly flat is taken as:

$$M_h = 1$$

- M_{lee} = Lee multiplier. It is just needed for New Zealand so:

$$M_{lee} = 1$$

Table A2.1. *Site wind speed calculation (in m/s).*

Parameter	V_R	M_d	$M_{z,cat}$	M_s	M_t	$\boldsymbol{V_{sit,\beta}}$
Value	45	1	0.83	1	1	**37.35**

A.2.1.2. Design wind speed

The building orthogonal design wind speed ($V_{des,\theta}$) is taken as the maximum cardinal direction site wind speed. As the calculation is going to be developed for any random house in a residential suburb of Adelaide, any orientation is possible. Hence, design wind speed is taken as:

$$\boldsymbol{V_{des,\beta} = 37.35\ m/s}$$

A.2.1.3. Wind pressures and distributed forces

The design wind pressures (*p*) is distributed for the structure as:

$$p = (0.5\rho_{air})\left[V_{des,\beta}\right]^2 C_{fig}\ C_{dyn}$$

where:

- ρ_{air} = density of air = 1.2 kg/m^3
- $V_{des,\beta}$ = design wind speed = 41 m/s
- C_{fig} = aerodynamic shape factor. This factor will vary depending on the direction of the pressure:
  - Pressure normal to surface: $C_{fig1} = C_{p,n} K_a K_l K_p = 1.21 \cdot 1 \cdot 1 \cdot 1 = 1.21$
  - Frictional drag forces: $C_{fig2} = C_f = 0.04$

Going through *Appendix D* it is possible to determine all the factors as:

- $C_{p,n}$= Aerodynamic shape factor for normal net pressure on freestanding walls. From *Table D2 (A)*:

$$\frac{b}{c} = \frac{10}{3} = 3.33$$

$$\frac{c}{h} = \frac{10}{10} = 1$$

*dimensions from *Figure D1*

$$C_{p,n} = 1.3 + 0.5\left(0.3 + \log_{10}\left(\frac{b}{c}\right)\right)\left(0.8 - \frac{c}{h}\right)$$

$$= 1.3 + 0.5\,(0.3 + \log_{10}(3.33))\,(0.8 - 1)$$

$$C_{p,n} = 1.22$$

- K_a= area reduction factor = 1
- K_l = local net pressure factor = 1
- K_p= net porosity factor = 1 – (1 – δ)^2 = 1
  where:
  - δ = is the solidity ratio of the structure (1 for being a brick-wall)
- C_f= Aerodynamic shape factor for frictional drag. From *Table D3* and considering a brick-wall as *Surface with ribs across the wind direction*:

$$C_f = 0.04$$

- $C_{dyn} = 1$ = dynamic response factor. The value is taken as 1.0 for not being a dynamically wind sensitive structure.

Hence, there are two wind pressures:

1. Pressure normal to surface:

$$p_N = (0.5 \cdot 1.2)[37.35]^2 \cdot 1.22 \cdot 1 = 1021.2\ \frac{N}{m^2} = 1.02\ \frac{kN}{m^2}$$

2. Frictional drag force:

$$p_D = (0.5 \cdot 1.2)[37.35]^2 \cdot 0.04 \cdot 1 = 41.9\ \frac{N}{m^2} = 0.04\ \frac{kN}{m^2}$$

Table A2.2. *Pressure normal to surface calculation (in kN/m^2).*

Parameter	ρ_{air}	$V_{des,\beta}$	C_{fig}	C_{dyn}	$\boldsymbol{p_N}$
Value	1.2	37.35	1.21	1	**1.02**

Table A2.3. *Frictional drag force calculation (in kN/m^2).*

Parameter	ρ_{air}	$V_{des,\beta}$	C_{fig}	C_{dyn}	$\boldsymbol{p_N}$
Value	1.2	37.35	0.04	1	**0.04**

A2.3. Earth-quake calculations

For the earth-quake forces will be determined following this process:

- Structure location and importance level: From *AS/NZ 1170.0* the importance level is determined as 1 (the lowest), since the structure is a wall. This means that the structure presents a low degree of hazard to life and other property.
- Soil Class: Most of the Adelaide soil is classified as *Clay*.
- EDC category: The wall is in EDC 1.

With all these data, and knowing that the Hazard Design Factor (z) for Adelaide is 0.10 according to *Table 3.2*, it is possible to realize that earthquake forces will not be really high. Since, as pointed in this standard, earthquake forces shall not be considered when wind forces are higher, the earthquake forces calculations will not be necessary, having the wind forces as the most critical force acting on the wall.

A3. Modelling

A structural model is developed using the software *SAP2000* to calculate the stresses acting in the wall. To develop the wall it will be selected an average strength clay brick from the code.

The 5 different walls were model for 1 m width, and with its corresponding height. A mesh transition to a denser mesh in the fixed support of the free-standing walls was developed to have more accurate results in the most critical sections. The walls for isolation layers in residential buildings have been developed with pinned supports. For Wall 4 the vertical displacement is restricted (wall vertically supported in the structural frames) and for Wall 5 the vertical displacement is free, the wall is only secured to the vertical frames to avoid out-of-plane displacements.

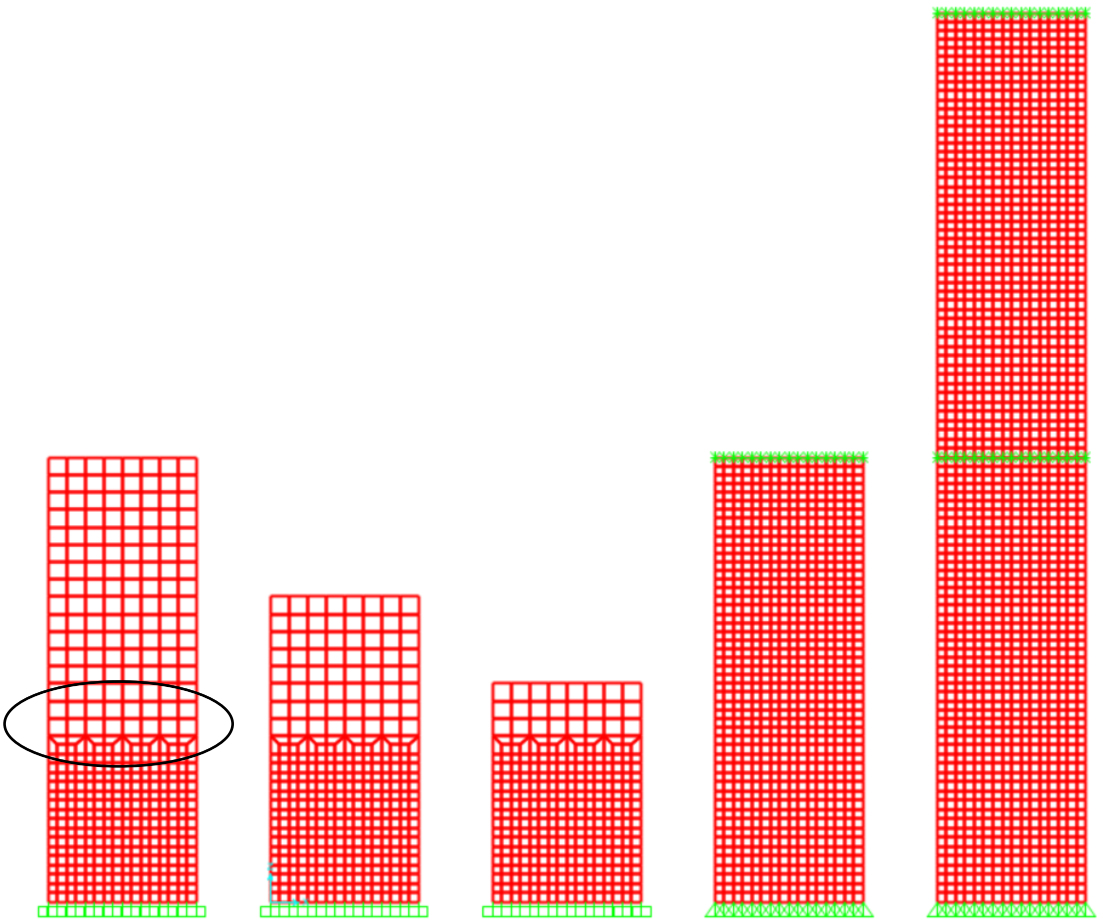

Figure A3.1. *Display of the 5 walls with their respective boundaries and mesh. Walls 1-5 from left to right.*

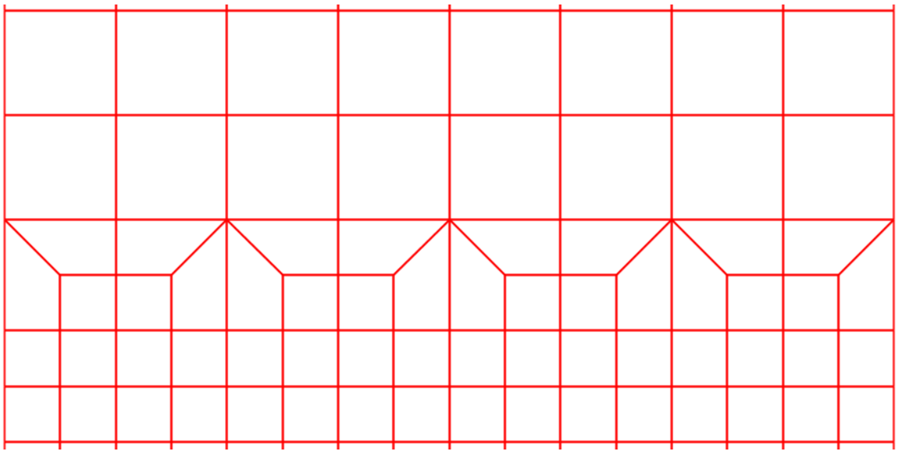

Figure A3.2. *Detail of the mesh transition to a denser mesh.*

For the acting forces, the wind was applied as an area force with the positive direction of axis Y and X with the values (0.04; 1.02; 0) as follows:

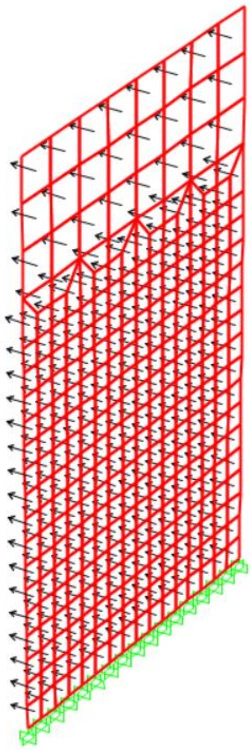

Figure A3.3. *Display of forces applied on the wall.*

After running the model, it is possible to display the diagram for the resultant forces as:

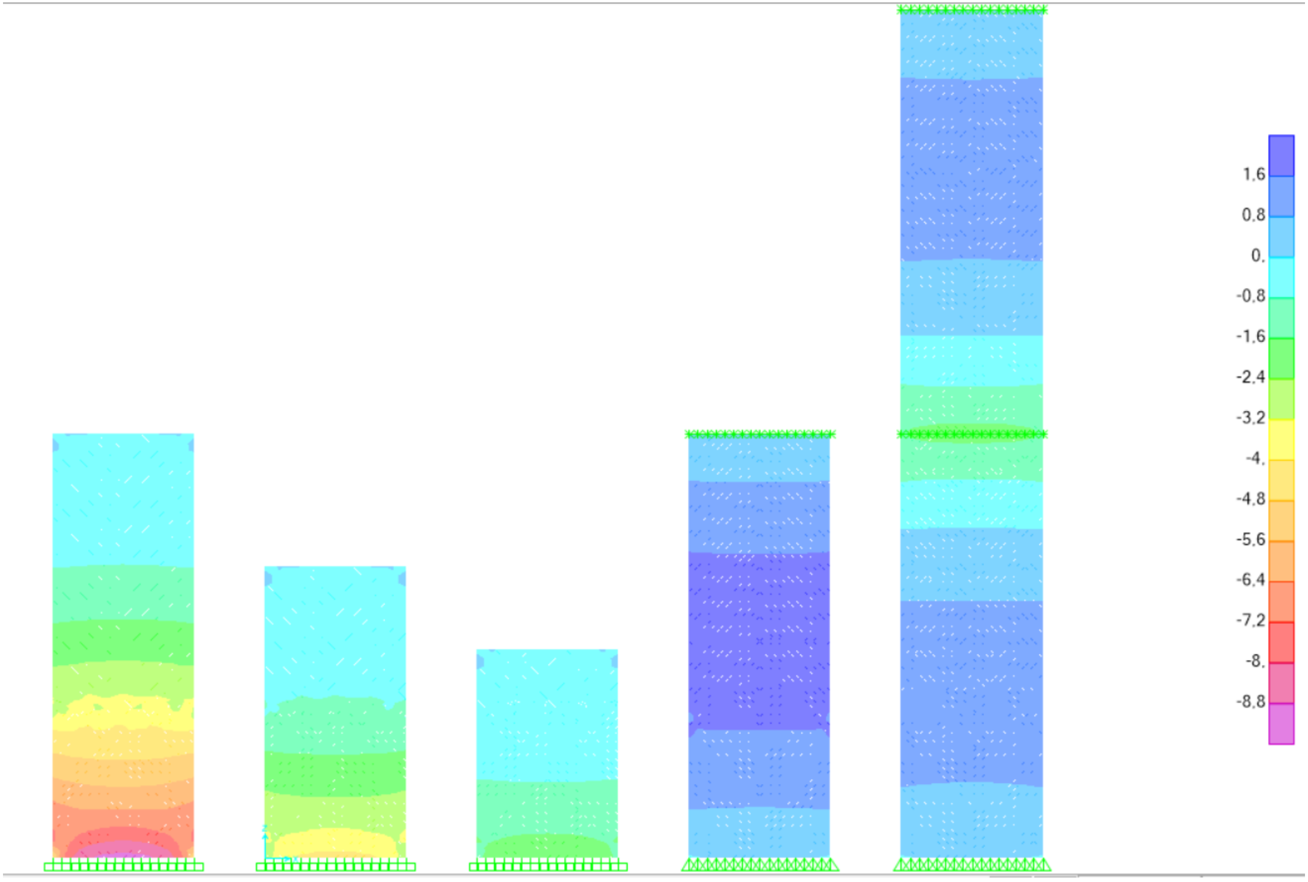

Figure A3.4.*Bending vertical moment diagram for each wall. Values in kN · m.*

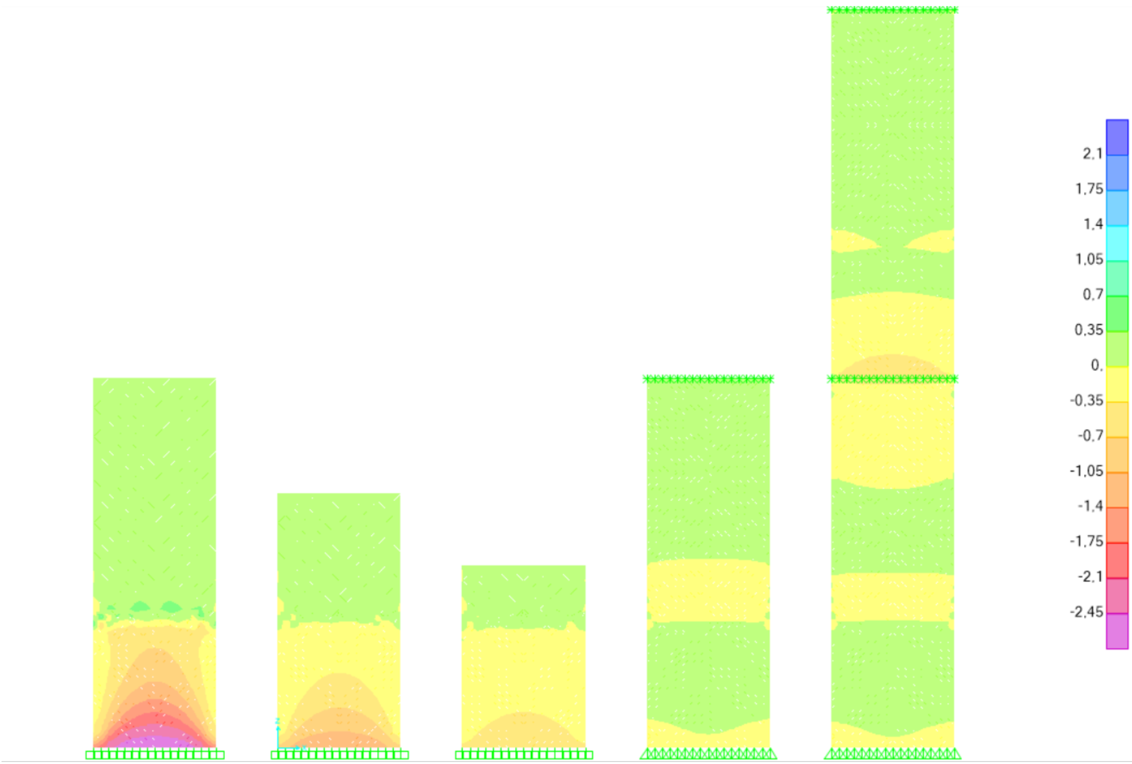

Figure A3.5. *Bending horizontal moment diagram for each wall. Values in kN · m.*

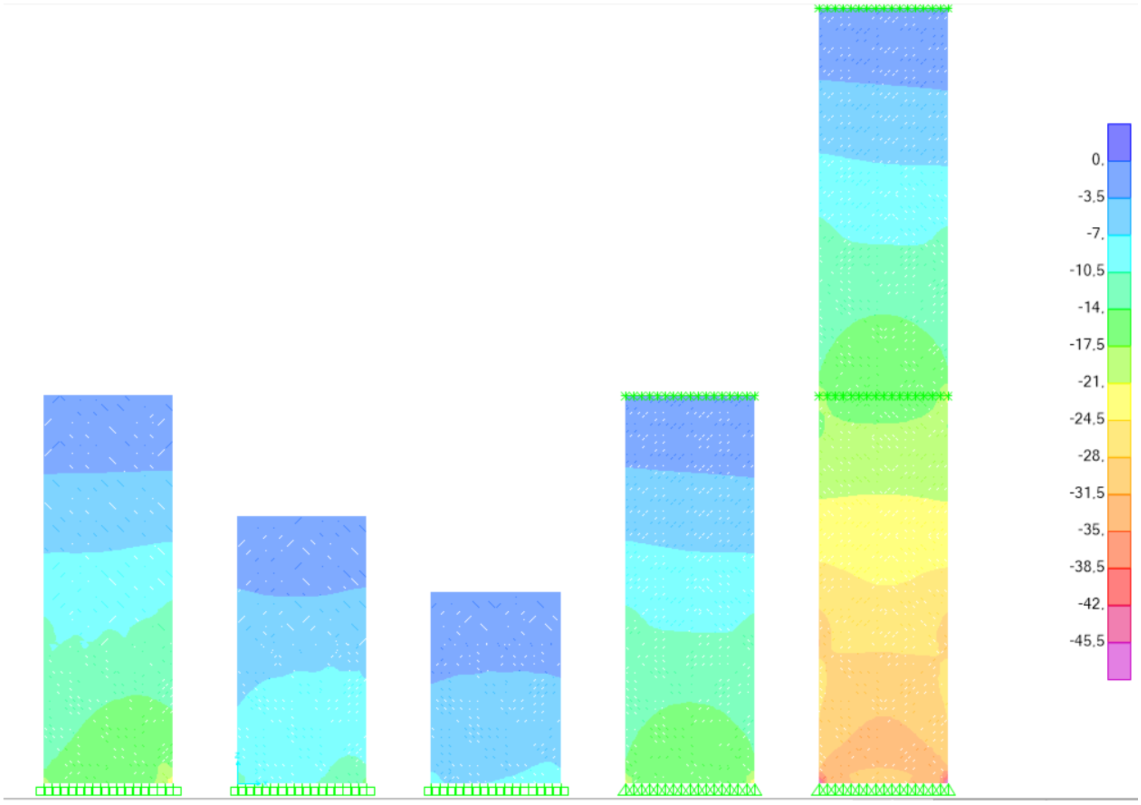

***Figure A3.6**. Vertical force diagram for each wall. Values in kN.*

Hence, the maximum resultant forces and moments are:

***Table A3.1.** Values of the resultant forces and moments of each wall.*

	Wall 1	Wall 2	Wall 3	Wall 4	Wall 5
Maximum Vertical Moment (kN m)	-	-	-	1.9	1.1
Minimum Vertical Moment (kN m)	-9.1	-4.2	-2.1	-	-1.8
Minimum Horizontal Moment (kN m)	-2.8	-1.3	-0.6	-	-
Maximum Horizontal Moment (kN m)	-	-	-	-	-
Axial Force (kN)	-26.6	-16.9	-11.1	-24.4	-48.9

A4. Brick-walls capacity

Following the section *3.3.2 Compressive strength* the characteristic compressive strength of masonry will be:

$$f'_m = k_h f'_{mb}$$

The factors k_h and f'_{mb} are taken from *Table 3.1* of the standard for an average strength Masonry unit of Adelaide surroundings (f'_{uc} = 10MPa) and a type of mortar M4 as:

$$k_h = 2.0$$

$$f'_{mb} = 6.3\ MPa$$

Hence:

$$f'_m = 2.0 \cdot 6.3 = 12.6\ MPa$$

Following *Table 3.4* of the standard, the formula to calculate the elasticity modulus is:

$$E_{short-term} = 700 f'_m$$

In *Table A4.1* it is shown the properties of the material used in the model. Flexural strength will depend on the mixture, and since the failure mechanism under wind and earthquake actions is more critical for bond strength (see *Figure A4.1)*, it will be chosen from these test results (see *Table 5)*.

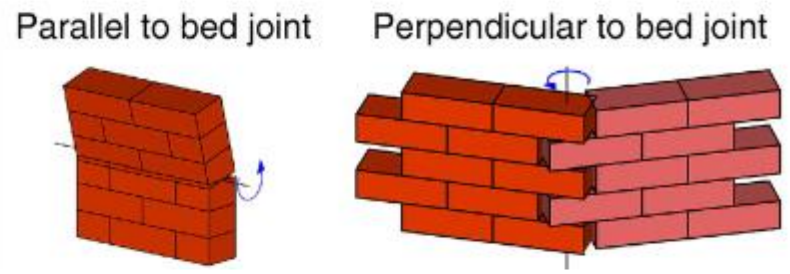

Figure A4.1*. Critical bending failure for brick-walls.*

Table A4.1. *Properties of the material used for the brick-wall design.*

Weight per unit volume	Area of cross-section	Compressive Strength (f'_m)	Flexural Strength (f'_{mt})	$\mathbf{E_{short-term}}$
20 kN/m^3	0.0025 m^2	12.6 MPa	Depending on mixture	8,820 MPa

A4.1 Compressive capacity

With this data, following *SECTION 7: Structural Design of Unreinforced Masonry*, it is possible to determine the basic compressive capacity of a masonry wall as:

$$F_o = \Phi\, f'_m A_b$$

where:

- Φ = capacity reduction factor (from *Clause 4.4*), for unreinforced hollow masonry in compression = 0.5
- f'_m = 12.6 MPa = 12,600 kN/m^2
- A_b= bedded area of the masonry member cross-section (2 bricks) = 0.052 m^2

Hence:

$$F_o = 0.5 \cdot 12{,}600 \cdot 0.052 = 327.6\ kN$$

Table A4.2. *Compressive capacity calculation (in kN).*

Parameter	Φ	f'_m	A_b	F_o
Value	0.5	12,600	0.052	**327.6**

A4.2 Vertical Bending Capacity

The wall capacity for vertical bending following *Section 7.4.2* ("from actions of a short-term transient nature, which include out-of-plane wind loads and earthquake loads"):

$$M_{dv} \le M_{cv}$$

where:

- M_{dv} = the design vertical bending moment resulting from transient out-of-plan forces acting on the member in vertical-spanning action
- M_{cv} = the vertical bending moment capacity of the member. It will be taken the least of:

Where:

$f'_{mt} > 0$;

M_{cv} will be the lesser of:

$$M_{cv} = \Phi\ f'_{mt} Z_d + f_d Z_d$$

$$M_{cv} = 3.0\ \Phi\ f'_{mt} Z_d$$

where:

- Z_d = the section modulus of the bedded area:

$$Z_d = \frac{\frac{1}{12} b\, h^3}{\frac{h}{2}} = \frac{\frac{1}{12} \cdot 0.225 \cdot 0.23^3}{\frac{0.23}{2}} = 0.00198\ m^3$$

- Φ = capacity reduction factor (from *Clause 4.4*), for unreinforced hollow masonry in bending = 0.6
- f_d = minimum design compressive stress on the bed joints, taken as the compressive stress at the bed joint under consideration, resulting from the minimum design compressive force.*

*For the different walls, the compressive strength force from the self-weight varies approximately from 7 kN to 30 kN in the most critical bending section, so f_d would vary from 147 kPa to 631 kPa. For each case, the most pessimistic formula will be used.

$$M_{cv} = 0.6 \cdot (bond\ strength) \cdot 0.001815 + (f_{d\,i} \cdot 0.00198)$$

$$M_{cv} = 3.0\ \Phi\ f'_{mt} Z_d = 3.0 \cdot 0.6 \cdot (bond\ strength) \cdot 0.00198$$

The final bending capacities are reflected in *Table A4.2*:

***Table A4.3**. Bending vertical capacity in kN · m for each wall/mixture combination.*

	Wall 1 (2b layer)	**Wall 2 (2b layer)**	**Wall 3 (2b layer)**	**Wall 4 (2b layer)**	**Wall 5 (2b layer)**
M0	1.49	1.28	1.16	1.49	2.08
M5-US	1.71	1.51	1.38	1.71	2.31
M10-US	1.28	1.08	0.95	1.28	1.88
M5-TS	1.81	1.61	1.48	1.81	2.41
M10-TS	1.68	1.48	1.35	1.68	2.28

Since the capacity of the free-standing walls (Walls 1-3) seem a priori much smaller than the resultant forces, it will be calculated the capacity of the same wall typology with a layer of 4 bricks to increase the capacity. The new properties are:

$$h = 0.46\ m$$

$$A_b = 0.104\ m^2$$

$$Z_d = 0.0079\ m^3$$

And the vertical bending capacity for a 4 brick thickness wall:

***Table A4.4**. Bending vertical capacity in kN · m for each new 4 brick-thickness wall.*

	Wall 1 (4b layer)	**Wall 2 (4b layer)**	**Wall 3 (4b layer)**
M0	4.71	4.26	4.12
M5-NT	5.59	5.15	5.00
M10-NT	3.88	3.43	3.29
M5-T	6.01	5.56	5.42
M10-T	5.48	5.03	4.89

A4.3 Horizontal Bending Capacity

The wall capacity for horizontal bending following *Section 7.4.3* is:

$$M_{dh} \leq M_{ch}$$

where:

- M_{dh} = the design horizontal bending moment resulting from transient out-of-plan forces acting on the member in horizontal-spanning action
- M_{ch} = the horizontal bending moment capacity of the member. It will be taken the least of:

$$M_{cv} = 2.0\ \Phi\ k_p \sqrt{f'_{mt}} \left(1 + \frac{f_d}{f'_{mt}}\right) Z_d$$

$$M_{cv} = 4.0\ \Phi\ k_p \sqrt{f'_{mt}}\ Z_d$$

$$M_{cv} = \Phi\left(\ 0.44\ \ f'_{ut} Z_u + 0.56\ \ f'_{mt} Z_p\right)$$

where:

- k_p= perpendicular spacing factor assessed in accordance with *Clause 7.4.3.3*. Following this clause is taken k_p= 1 for these calculations.

For each case, the most pessimistic formula has been used showing the results in *Table A4.5:*

Table A4.5. *Bending horizontal capacity in kN · m for each wall/mixture combination.*

	Wall 1 (4b layer)	**Wall 2 (4b layer)**	**Wall 3 (4b layer)**	**Wall 4 (2b layer)**	**Wall 5 (2b layer)**
M0	11,56	10,43	9,72	2.89	3.72
M5-NT	12,18	11,17	10,54	3.04	3.79
M10-NT	11,01	9,72	8,92	2.75	3.59
M5-T	12,47	11,50	10,90	3.12	3.83
M10-T	12,10	11,07	10,43	3.02	3.78

A5. Results

With the capacity values and the acting forces on the wall, it is possible to determine the suitability of each mixture for every wall. The acceptable mixture-wall combinations are displayed in bold.

Table A5.1. *Acting forces and resisting capacities for each brick-wall/mixture combination with their suitability.*

ID	Mdv (kN ·m)	Mcv (kN ·m)	Condition	Mdh (kN ·m)	Mch (kN ·m)	Condition	N (kN)	Fo (kN)	Condition
M0-Wall 1 (4b layer)	9.1	4.71	NON-SUITABLE	2.8	11.6	SUITABLE	42.8	652	SUITABLE
M5US-Wall 1 (4b layer)	9.1	5.59	NON-SUITABLE	2.8	12.2	SUITABLE	42.8	652	SUITABLE
M10US-Wall 1 (4b layer)	9.1	3.88	NON-SUITABLE	2.8	11.0	NON-SUITABLE	42.8	652	SUITABLE
M5TS-Wall 1 (4b layer)	9.1	6.01	NON-SUITABLE	2.8	12.5	SUITABLE	42.8	652	SUITABLE
M10TS-Wall 1 (4b layer)	9.1	5.48	NON-SUITABLE	2.8	12.1	SUITABLE	42.8	652	SUITABLE
M0-Wall 2 (4b layer)	4.2	4.26	SUITABLE	1.3	10.4	SUITABLE	28.4	652	SUITABLE
M5US-Wall 2 (4b layer)	4.2	5.15	SUITABLE	1.3	11.2	SUITABLE	28.4	652	SUITABLE
M10US-Wall 2 (4b layer)	4.2	3.43	NON-SUITABLE	1.3	9.7	SUITABLE	28.4	652	SUITABLE
M5TS-Wall 2 (4b layer)	4.2	5.56	SUITABLE	1.3	11.5	SUITABLE	28.4	652	SUITABLE
M10TS-Wall 2 (4b layer)	4.2	5.03	SUITABLE	1.3	11.1	SUITABLE	28.4	652	SUITABLE
M0-Wall 3 (4b layer)	2.1	4.12	SUITABLE	0.6	9.7	SUITABLE	19.7	652	SUITABLE
M5US-Wall 3 (4b layer)	2.1	5.00	SUITABLE	0.6	10.5	SUITABLE	19.7	652	SUITABLE
M10US-Wall 3 (4b layer)	2.1	3.29	SUITABLE	0.6	8.9	SUITABLE	19.7	652	SUITABLE
M5TS-Wall 3 (4b layer)	2.1	5.42	SUITABLE	0.6	10.9	SUITABLE	19.7	652	SUITABLE
M10TS-Wall 3 (4b layer)	2.1	4.89	SUITABLE	0.6	10.4	SUITABLE	19.7	652	SUITABLE
M0-Wall 4	1.9	1.49	NON-SUITABLE	0	-	-	24.4	327	SUITABLE
M5US-Wall 4 (2b layer)	1.9	1.71	NON-SUITABLE	0	-	-	24.4	327	SUITABLE
M10US-Wall 4 (2b layer)	1.9	1.28	NON-SUITABLE	0	-	-	24.4	327	SUITABLE
M5TS-Wall 4 (2b layer)	1.9	1.81	NON-SUITABLE	0	-	-	24.4	327	SUITABLE
M10TS-Wall 4 (2b layer)	1.9	1.68	NON-SUITABLE	0	-	-	24.4	327	SUITABLE
M0-Wall 5 (2b layer)	1.8	2.08	SUITABLE	0	-	-	48.9	327	SUITABLE
M5US-Wall 5 (2b layer)	1.8	2.31	SUITABLE	0	-	-	48.9	327	SUITABLE
M10US-Wall 5 (2b layer)	1.8	1.88	SUITABLE	0	-	-	48.9	327	SUITABLE

M5TS-Wall 5 (2b layer)	1.8	2.41	SUITABLE	0	-	-	48.9	327	SUITABLE
M10TS-Wall 5 (2b layer)	1.8	2.28	SUITABLE	0	-	-	48.9	327	SUITABLE

Since Wall 4 (2b layer) is very close to meet the condition for vertical bending, actions are re-calculated for slightly smaller height (h_{WALL}=2.75 m) showing the following performance:

Table A5.2*. Acting forces and resisting capacities for the new 2.75 m height Wall 4 (2b layer) with their capacities.*

ID	Mdv (kN ·m)	Mcv (kN ·m)	Condition	Mdh (kN ·m)	Mch (kN ·m)	Condition	N (kN)	Fo (kN)	Condition
M0-Wall 4 (2b layer)'	1.63	1.49	NON-SUITABLE	0	-	-	22.0	327	SUITABLE
M5US-Wall 4 (2b layer)'	1.63	1.71	SUITABLE	0	-	-	22.0	327	SUITABLE
M10US-Wall 4 (2b layer)'	1.63	1.28	NON-SUITABLE	0	-	-	22.0	327	SUITABLE
M5TS-Wall 4 (2b layer)'	1.63	1.81	SUITABLE	0	-	-	22.0	327	SUITABLE
M10TS-Wall 4 (2b layer)'	1.63	1.68	SUITABLE	0	-	-	22.0	327	SUITABLE

The reference mortar seems a suitable solution for free-standing walls up to 2 m height, with a 4 bricks layer, since it did not meet the requirements with a height of 3 m. Except for the mortar M10-UT, the rest of the mortars with sludge content showed an even better performance in its use as mortar for unreinforced masonry walls, being M5-TS the mortar with the best capacity. However, 4 bricks thickness in residential delimiting brick-walls seems a bit excessive. The calculations were done also for 3 bricks thickness, showing feasible results for 1.5 m heights, which may be the most efficient option.

In residential buildings with the defined conditions, the reference mortar has not enough capacity in walls supported in the structural beams. Nevertheless, mortars M5-US, M5-TS, and M10-TS showed a good performance for a maximum height of 2.75 m, and they are a better option than M0. The wall just anchored to the structural members has a really good performance up to 6 m height (2 floors buildings) with all the mortars. Even though these mortars are suitable, 2 bricks thickness for an isolating layer seems to be a bit excessive, and probably pre-fabricated brick-wall modules, higher performance clay bricks and mortars or a wall better anchored may be a more efficient option.