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Parametric Study of Concrete Load Bearing Wall with Opening Based on Stress Criterion

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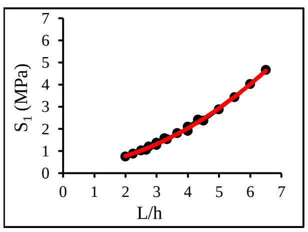
Graphical abstract



Relationship between the maximum principal Stress and *L/h* ratio in rectangular opening

Abstract

In load bearing wall, reinforcement is only provided to control cracking, not for strength. In this paper A 3D linear finite element stress analysis of concrete load bearing wall reinforced with a single layer of wire mesh for use in double storey houses is performed. Opening in the wall for doors and windows inclusion is included in the model. Haunches are also considered at the opening corners to strengthen the wall section above the opening. Critical stress in the wall based on an appropriate stress criterion is compared with allowable tensile and compressive stress of the concrete in accordance with Eurocode 2. Parametric studies are carried out on dimensions of rectangular opening and also on sizes of haunches in the load bearing wall with openings. This research states that the reduction in the height and length of the rectangular opening together has more effect in decreasing the critical maximum principal stress of the load bearing concrete walls. Also, adding haunches to the corners of rectangular opening causes to decrease the maximum principal stresses significantly, especially for bigger dimension of haunches.

Keywords: Load bearing wall; stress criterion; rectangular opening; maximum principal stress

1.0 INTRODUCTION

For a typical double storey house, the use of ordinary reinforced concrete wall is excessive in terms of strength in regions with low wind load speed such as Malaysia. This is due to the fact that the loading for the wall of double storey houses is not too big. For cost saving and quick and easy utilization, constructing load-bearing (plain) concrete wall with minimum reinforcement may be sufficient to take the load instead of ordinary reinforced concrete walls. Openings are generally present in load bearing walls for the provision of services, doors and windows. On the other hands, the sizes of openings affect the failure characteristics of load bearing walls.

There are some benefits for this type of wall system can be summarized in the following items:

- Elimination of some structural components such as beam and column and reduction on building foundation and footings
- Reduce the time of construction by reduction in structural requirements and usage of labor
- Fast track construction and easy to design
- Cost savings due to the above factors

Concrete load bearing walls have been increasingly used in industrialized building systems. Investigations on the strength and behavior of this type of walls have been comparatively few. Saheb and Desayi[1] were the first to set up an adequate amount of test data on walls with openings. A method for predicting the strength of plain concrete walls was suggested by Yokel.[2] Research results of Pillai and Parthasarathy[3-4] showed that the steel ratio had little effect on the ultimate strength of load bearing walls.

Openings are generally present in load bearing walls to provide services, doors and windows. Thus it is important that the behavior of walls with openings is widely understood. This requires an understanding of the effect of opening parameters such as size, location and type of the failure characteristics of load bearing walls. A number of studies and laboratory testing were accomplished on concrete walls with various openings.[5-9]

Mostly, in the analysis of concrete walls tensile strength is assumed to be zero and a relatively simple stress–strain relationship in compression is used.[2, 10-11] Chen and Atsuta[12] found that the small tensile strength and ductility of plain concrete or masonry have a significant effect on the strength of walls and should not be neglected in analysis.

This paper reports the result of 3D finite element analysis performed on a moderate strength concrete wall used as load bearing wall for construction of double storey houses. The analysis was carried out using LUSAS software. The wall was assumed to be homogenous and linear elastic stress analysis was performed to study the critical stress due to load that comes from the roof and the first floor walls and slabs. The opening for windows and doors is also considered and the haunches are provided at the upper corners of the opening to strengthen the concrete wall above the opening. Based on the maximum principal stress criterion and allowable tensile and compression stress in accordance with a concrete standard, parametric studies are carried out on the load bearing wall with rectangular opening and the wall with haunches in the corners of the opening. It demonstrates that acceptable tensile and compression stresses can be achieved by adding haunches to the corners of rectangular openings.

2.0 FINITE ELEMENT MODELLING

Figure 1 illustrates the elevation of a typical double storey low cost house in Malaysia. In this study the FE analysis is carried out on the first floor of such a wall with opening that carries loads from upper floor wall and slab using LUSAS software which is a computer software for structural analysis based on the finite element method. The modeling and analysis was conducted with the following considerations:

- Linear elastic analysis where concrete and reinforcement behave as linear material.
- Concrete was considered as homogenous material and the critical stress was analyzed in the concrete.
- Vertical loads which were applied as uniform loads on top of the wall under studied.
- Perfect bond exists between concrete and reinforcement.
- Vertical displacement in the structure due to settlement is neglected.

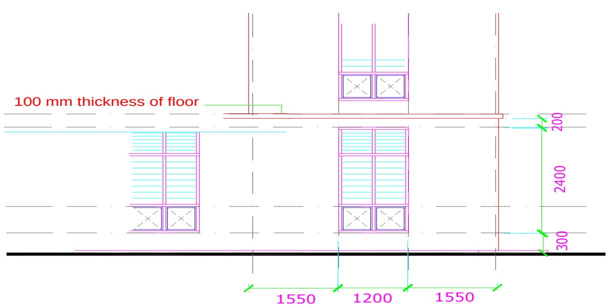


Figure 1 Geometry of selected wall

2.1 Modelling of the Wall with Opening

The concrete was modeled with hexahedral solid element (HX20) and the wire mesh was modeled with 3D bar element. The bar nodes were coincided with the concrete mesh, hence complete interaction was assured between the two materials (in model B). Figure 2 shows the mesh for the wall model A (without reinforcement) with mesh sizes of 0.025 and 0.050 for concrete which is drawn with the dimensions stated in Figure 1.

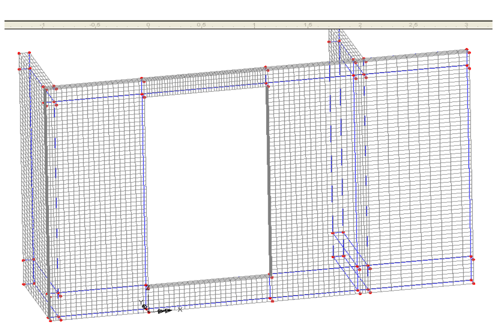


Figure 2 Model A with HX20 solid mesh

For selected wall, linear elastic materials were assigned to all of the elements and concrete with grade 30 (C30) was selected. The value of Young modulus and Poison's ratio were 26 GPa and 0.2, respectively.

To define the model supports, surfaces at the bottom of the model were prevented from translations along the X, Y and Z axis but allowing rotation about X, Y and Z axis. Load was assumed uniform along the wall and calculated assuming that the roof and floor are transmitting the load to the wall in a simply supported manner.

Eurocode 2[13] does not give any specific values for reinforcement in plain walls so the comments given within the BS 8110[14] design section with respect to the matter of reinforcement to control cracking can be applied to a design to Eurocode 2.

The minimum quantity of reinforcement in each direction of load bearing concrete walls is recommended by BS 8110-1[14] as shown in Table 1. The amount is based on the grade of steel reinforcement. Wire mesh size A9 with cross section area of (318 mm^2/mm) was provided (model B).

Table 1 Minimum percentage of reinforcement in load bearing concrete walls (BS 8110-1[14])

Reinforcement Type	Specified Characteristic Strength, f_y(N/mm^2)	Definition of Percentage	Minimum Percentage in each Direction
Hot Rolled Mild Steel	250	$100A_S/A_C$	0.30
High Yield Steel	500	$100A_S/A_C$	0.25

To reduce the stress in the upper part of the wall, openings with haunches were suggested. Different sizes of openings with different dimensions of haunches were modeled which is presented in Figure 3 and Table 2.

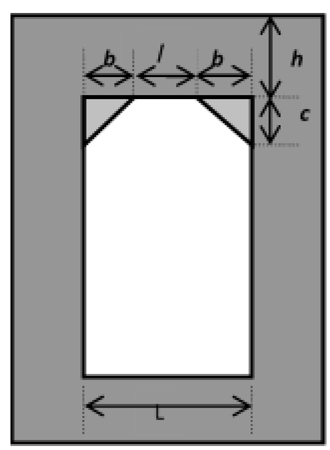


Figure 3 Wall with haunches in the opening

Table 2 Geometry of opening with haunches and models name in LUSA (Refer Figure 3)

b × 10^2 (mm)	h=2×10^{2}mm c×10^2 (mm)				h=3×10^{2}mm c×10^2 (mm)				h=4×10^{2}mm c×10^2 (mm)			
	1	2	3	4	1	2	3	4	1	2	3	4
1	C_2	D_2	E_2	F_2	C_3	D_3	E_3	F_3	C_4	D_4	E_4	F_4
2	G_2	H_2	I_2	J_2	G_3	H_3	I_3	J_3	G_4	H_4	I_4	J_4
3	K_2	L_2	M_2	N_2	K_3	L_3	M_3	N_3	K_4	L_4	M_4	N_4
4	O_2	P_2	Q_2	R_2	O_3	P_3	Q_3	R_3	O_4	P_4	Q_4	R_4

■3.0 ANALYSIS OF LOAD BEARING WALL MODELLS

In this section, the results of analysis of several wall models are presented. The effects of the geometric parameters such as L, h, b, a, and applied load on the maximum principal stress of the model were investigated. At the first step, openings were considered to be rectangle so a parametric study was carried out on the length of the opening (L), the height of the wall above the openings (h) and L/h ratio. In the second step, parametric study was performed on the dimensions of haunches (b and c) in the corners of rectangular opening.

3.1 Critical Principal Stress

Figure 4 shows the contour of maximum principle stress of model A. It is clearly shown that the mid-span of wall above the opening was the most critical area and the maximum and minimum principal stresses of this part were compared with the allowable stress according to Eurocode 2.[13]

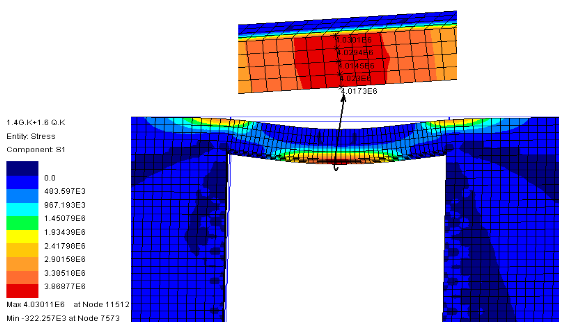


Figure 4 Maximum principal stress (S_1) contour of model A

Maximum principal stress, S_1, intermediate principal stress, S_3, and minimum principal stress, S_3, values shown in Table 3 should satisfy the maximum normal stress criterion.[15-16] According to the maximum stress criterion, failure occurs when the maximum (normal) principal stress reaches either σt or σc:

$$-\sigma_c < \{ S_1 , S_2 , S_3 \} < \sigma_t \quad (1)$$

σ_t and σ_c are the uniaxial tension strength and the uniaxial compression strength, respectively.

To design the walls,[13] allowable compression stress for f_{ck}=30 MPa, a_{cc}=0.85 (recommended by Eurocode 2) and γ_c=1.5 is:

$f_{cd} = a_{cc} \cdot f_{ck} / \gamma_c = 17\times103$ MPa

Allowable tensile stress for $a_{ct} = 0.8$ (recommended by Eurocode 2) and $f_{ctk,0.05} = 0.21 f_{ck}^{2/3}$ is:

$f_{ctd} = a_{ct} \cdot f_{ctk,0.05} / \gamma_c = 1.08$ MPa

Therefore, results given in Table 3, should satisfy the following limitations:

$$-17\times103 \text{ MPa} < \{ S_1 , S_2 , S_3 \} < 1.08 \text{ MPa}$$

NOTE: S_1, S_2 and S_3 are the maximum, intermediate and minimum principal stress values obtained from the analysis of model by LUSAS software.

Table 3 Principal stresses results of analysis model A for Load=0.353 N/mm²

S_1 (MPa)	Satisfactory	S_2 (MPa)	satisfactory	S_3 (MPa)	Satisfactory
4.03	No	0.158	Yes	-6.49	Yes

Results in Table 3 reveal that the most critical principal stress is maximum principal stress, S_1, and should be decreased to be accepted according to the maximum normal stress criterion.

3.2 Effect of Reinforcement in Load Bearing Concrete Wall

To investigate the effect of steel reinforcement mesh in the maximum principal stresses of load bearing concrete wall, model A and B were analyzed. Model A and B represent a load bearing wall without reinforcement and with a layer of steel wire mesh (A9) in the middle of the concrete wall, respectively. Figure 5 shows the maximum principal stress contour in model A and B.

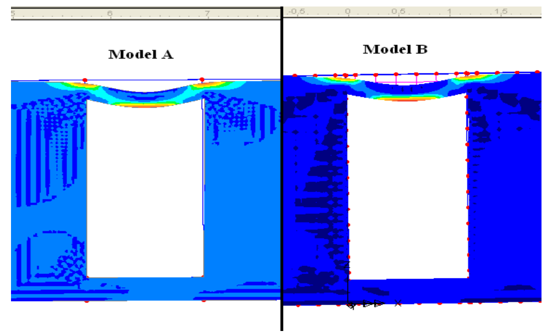


Figure 5 Maximum principal stress contours of models A and B

A comparison between model A and model B analysis results proves that the maximum principal stresses increases by 0.05% in the presence of wire mesh. This fact confirms that the steel reinforcement in load bearing walls does not contribute to the strength of the walls hence the stress in the reinforcement was ignored.

3.3 Mesh Convergence Studies

A mesh convergence study was conducted in order to reach the best mesh sizes of the load bearing wall model in view of running time. Since the critical maximum stress located at the middle of the wall above the opening, the mesh sizes of this part was varied from 0.1 m to 0.01 m. From Table 4, it is shown that the most economical mesh size is 0.025 employing 3072 hexahedral concrete elements in the wall above the opening.

Table 4 Results of mesh convergence study

Mesh Size (m^3)	Number of Elements in the Wall above the Opening	S_1 at the Mid-span of the Wall above the Opening (MPa)
0.1000×0.1000×0.1000	48	3.944
0.0500×0.0500×0.0500	384	4.027
0.0250×0.0250×0.0250	3072	4.030
0.0125×0.0125×0.0125	24576	4.031
0.0010×0.0010×0.0010	48000	4.031

3.4 Parametric Study of Load Bearing Wall with Rectangular Opening

In order to better understanding the behavior of load bearing concrete walls, a parametric study carried out using LUSAS software on the wall models of different geometry of rectangular opening. The parameters are the length of the opening (L), height of the wall above the opening (h). A total of 13 models for L and h variation were analyzed. The height of the wall above the opening was varied from 200 mm to 400 mm and the length of the opening was differed from 800 mm to 1300 mm.

3.4.1 Variation of the Opening Length (L)

For parametric study the length of the opening varied from 800mm to 1300 mm for three different h values. The maximum principal stress (S_1) results of analysis the wall models are demonstrated in Figure 6.

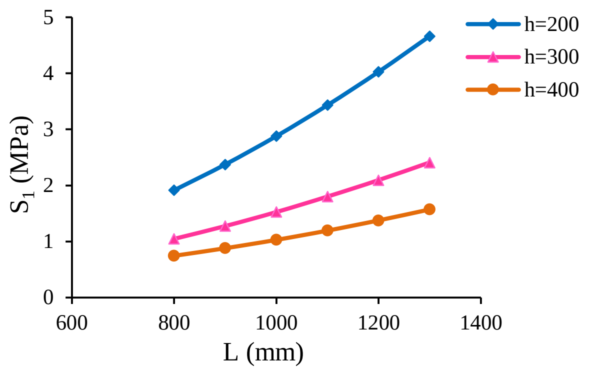


Figure 6 Maximum principal stress (S_1) versus L

The results indicate that, when the length of the opening decreases from 1300mm to 800mm, the maximum principal stress value decreases by approximately 59% for h=200mm, and 53% for h=400mm. As can be seen for smaller h value, reduction in the maximum principal stress value due to the decreasing in the length of the opening is more than for bigger h value.

3.4.2 Variation of the Wall Height Above the Opening (h)

In this section, the variation of h investigated by modeling the wall with different opening height. Results shown in the Figure 7 confirms that the maximum principal stress decreases by increasing in the h value as expected. By increasing the h value from 200mm to 400 mm, reduction in the maximum principal stress is around 61% for L=800 mm and 66% for L=1300 mm.

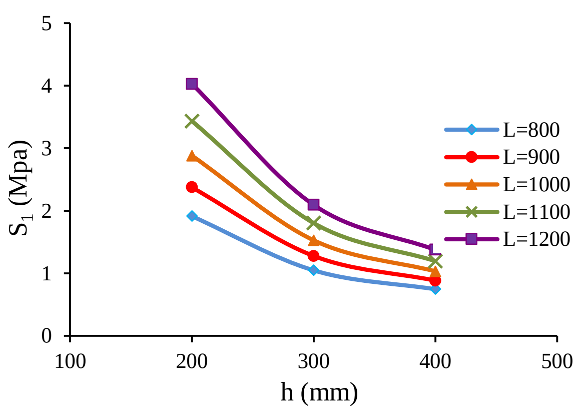


Figure 7 Maximum principal stress (S1) versus h

3.4.3 Variation of L/h Ratio

To ensure a safe design, the combined effects of increasing the opening length (L) together with the height of the wall above opening (h) should be incorporated into the dimensionless opening parameter. Maximum principal stress results for a load of 0.353 N/mm^2 with different L/h ratio are presented in Table 5.

Table 5 Maximum principal stress results of analysis wall models for load= 0.353 N/mm^2 and different L/h ratio

	h×10^2 (mm)	L×10^2 (mm) 8	9	10	11	12	13
L/h	2	4	4.5	5	5.5	6	6.5
S_1 (MPa)		1.195	2.375	2.880	3.433	4.028	4.665
L/h	3	2.667	3	3.333	3.667	4	4.333
S_1 (MPa)		1.049	1.277	1.527	1.803	2.096	2.411

It is to be expected that as L/h ratio increased, the maximum principal stress (S_1) is raised. A quadratic graph can be drawn through the most of the points as presented in Figure 8. An equation connecting the maximum principal stress (S_1) and L/h ratio points of different wall models can be proposed as follows:

$$S_1=0.0969(L/h)^2+0.0315(L/h)+0.345 \qquad (2)$$

S_1: Maximum principal stress at the mid-span of the wall above the rectangular opening under specific load value (0.353 N/mm^2) in MPa

$$S_1 = 0.0969(\frac{L}{h})^2 + 0.0315(\frac{L}{h}) + 0.345$$

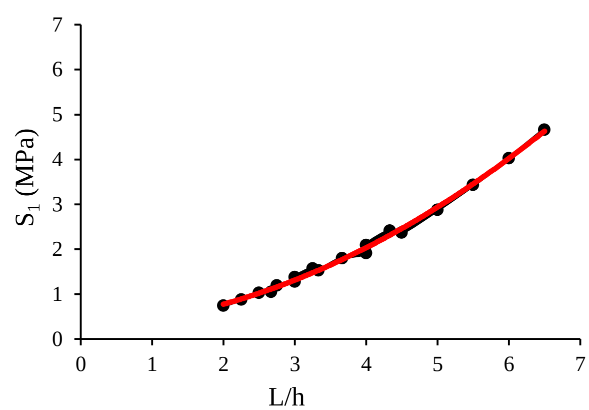


Figure 8 Relationship between the maximum principal stress and L/h ratio and L/h in rectangular opening

This equation is for specific value of load (0.353 N/mm²) of the wall model with rectangular opening. More general equation would be:

$$S^*_1=\omega[0.0969(L/h)^2+0.0315(L/h)+0.345]/0.353$$
$$S^*_1=\omega[0.275(L/h)^2+0.0892(L/h)+0.977] \qquad (3)$$

S^*_1: Maximum normal stress at the mid-span of the wall above the rectangular opening (MPa)
ω : Load applied on the wall in N/mm²

To determine the accuracy of equation 3, different sizes of rectangular opening with different value of loads were analyzed.

The results are presented in Table 6 and shows that the equation 3 can be used to determine the maximum principal stress at the mid-span of the rectangular opening in load bearing concrete wall with a high accuracy.

Table 6 Percent error of equation 3 compare to LUSAS analysis

ω (N/mm²)	L/h	$S^*_1\times10^6$, LUSAS (N/m²)	$S^*_1\times106$, Eq.3 (N/m²)	Percent Error
0.310	4	1.696	1.777	4.8 %
0.388	3	1.394	1.443	3.5 %
0.263	3	0.941	0.978	3.9 %
0.266	2.75	0.885	0.878	0.8 %
0.193	2.75	0.630	0.637	1.1 %

3.5 Parametric Study of Load Bearing Wall with Haunches

By adding haunches to the opening of load bearing concrete walls, maximum principal stress values in the critical areas of the rectangular openings decreases. In order to find out the effect of dimensions of haunches on the maximum principal stress values, several walls with haunches were modeled. In each model, was tried to vary the b and c from 100mm to 400mm for different h values (h=200, 300 and, 400mm). Analysis results are presented in Table 7. Bold numbers are within acceptable limits according to BS 8110-1 and the maximum principal stress criterion.

Table 7 Maximum principal stress values at the mid-span of the openingwith haunches
I.

Model name	**C_2**	**D_2**	**E_2**	**F_2**	**G_2**	**H_2**	**I_2**	**J_2**
S_1, LUSAS (MPa)	3.197	3.013	2.949	2.917	2.776	2.316	2.125	2.031
Reduction in S_1 (%)	20	25	27	27	31	42	47	49
Model name	**K_2**	**L_2**	**M_2**	**N_2**	**O_2**	**P_2**	**Q_2**	**R_2**
S_1, LUSAS (MPa)	2.555	1.867	1.534	1.356	2.473	1.629	1.166	**0.901**
Reduction in S_1 , (%)	36	53	62	66	38	59	71	77
Model name	**C_3**	**D_3**	**E_3**	**F_3**	**G_3**	**H_3**	**I_3**	**J_3**
S_1, LUSAS (MPa)	1.735	1.632	1.591	1.570	1.584	1.342	1.226	1.162
Reduction in S_1 (%)	14	19	21	22	22	33	39	42
Model name	**K_3**	**L_3**	**M_3**	**N_3**	**O_3**	**P_3**	**Q_3**	**R_3**
S_1, LUSAS (MPa)	1.523	1.181	**0.988**	**0.874**	1.516	1.118	**0.864**	**0.702**
Reduction in S_1 , (%)	25	41	51	57	25	45	56	65
Model name	**C_4**	**D_4**	**E_4**	**F_4**	**G_4**	**H_4**	**I_4**	**J_4**
S_1, LUSAS (MPa)	1.179	1.114	1.086	**1.070**	1.109	**0.963**	**0.887**	**0.842**
Reduction in S_1 (%)	10	15	17	18	15	26	32	36
Model name	**K_4**	**L_4**	**M_4**	**N_4**	**O_4**	**P_4**	**Q_4**	**R_4**
S_1, LUSAS (MPa)	1.089	**0.893**	**0.771**	**0.693**	1.098	**0.882**	**0.732**	**0.612**
Reduction in S_1 (%)	17	32	41	47	16	33	45	53

3.5.1 Variation of b, c for aCertain h

The maximum principal stresses results of analysis models with haunches by LUSAS Software indicate that for a certain h value when b and c increase, the maximum principal stress, (S_1), decreases as illustrated in Figure 9.

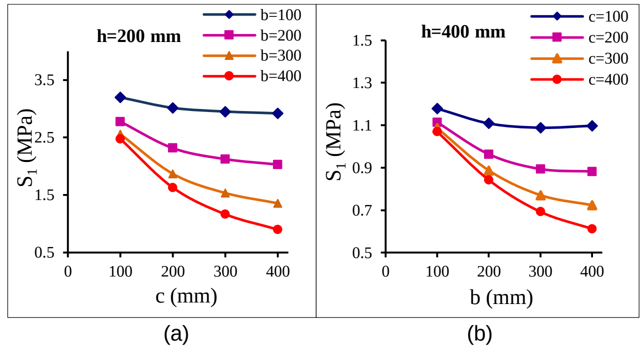


Figure 9 Maximum principal stress versus (a) b and (b) c for a certain h

The effective length of the opening decreases when b increases and causes reduction in L/h ratio. Therefore by considering equation 3, the lessening in the maximum principal stress value at the mid-span of the wall model above the opening is unavoidable. Also, for a certain h value in a higher c (red line), increasing in b, has more effect on decreasing the maximum principal stress value than in smaller c (blue line) i.e. 43% compare to 7%.

When c raises the effective length of the wall above the opening (h) increases, thus L/h ratio decreases and according to equation 3 ($S^*_1=\omega[0.275(L/h)^2+0.0892(L/h)+0.977]$) the maximum principal stress value lessens. More attention shows that for a bigger b (red line) the slope of the diagram is more than for smaller b (blue line) i.e. 64% compare to 9% slope.

3.5.2 Variation of c, h for a Certain b

Figure 10 demonstrates the results of the maximum principal stress for a certain b when c is varied for different h values. It can be seen that for all h values, increasing in c causes reduction in the maximum principal stress at the mid-span of the wall model above the opening.

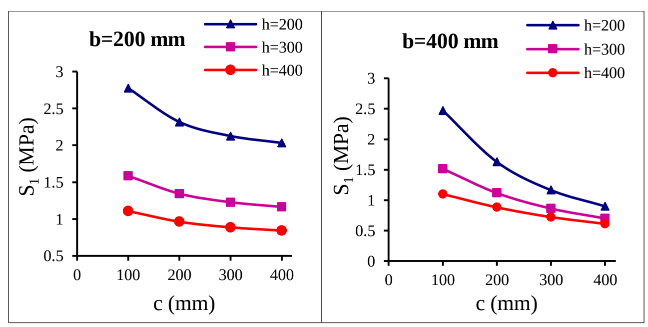


Figure 10 Maximum principal stress versus c for a certain b

More attention to the figure reveals that in higher b values (b=400mm), the rate of decreasing the maximum principal stress is much more than in smaller b values (b=200mm). In addition in a certain b, for example in b=400mm the reduction rate in smaller h value (blue line) is significantly more than in bigger h value (red line) i.e. 64% compare to 44%.

3.5.3 Variation of b and h for a Certain c

Figure 11 shows the results of the maximum principal stress for a certain c when b is varied in different h values. It can be noticed that for all h values, increasing in b causes decrease in the maximum principal stress at the mid-span of the wall above the opening with haunches.

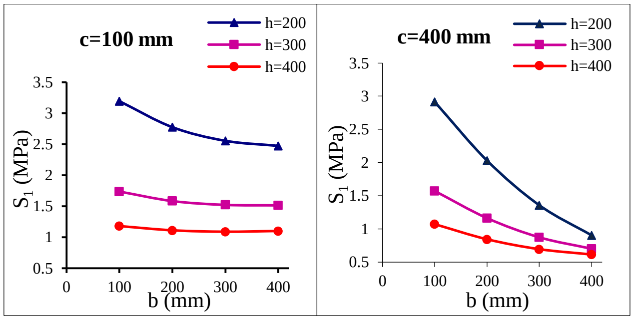


Figure 11 Maximum principal stress versus b for a certain c

More observations can be made from assessing the figures and indicate that in higher c values, the rate of decreasing the maximum principal stress value is much more than in smaller c values. In addition in a certain c, for example c=400mm, the reduction rate of the maximum principal stress in smaller h value (blue line) is more obvious than in bigger h value (red line) i.e. 69% compare to 43%.

4.0 CONCLUSION

In this research a finite element elastic analysis was carried out using LUSAS software to investigate the maximum principal stress values and locations in the load bearing wall with openings for a double story houses. The openings were in the shape of rectangular or with haunches.

This study showed that the most critical principal stress is maximum principal stress (S_1) which occurs almost at the lowest parts of the mid-span of the wall above the openings. Also, in load bearing concrete wall with rectangular opening, decreasing the length of the opening and/or increasing the height of the wall above the opening (h) significantly lessens the maximum principal stress value at the mid-span of the wall above the opening. This decline, for lower height of the wall above the opening (h) and bigger length of the rectangular opening (L) is some more apparent.

A simple equation is proposed to calculate the maximum principal stress at the mid-span of the wall above the rectangular openings based on (L/h) ratio as follows:

$S^*_1=\omega[0.275(L/h)^2+0.0892(L/h)+0.977]$

S^*_1: Maximum normal stress at the mid-span of the wall above the rectangular opening (MPa)

ω : Load applied on the wall in N/mm²

For a certain h value, when the dimensions of haunches (b and c) increase, the maximum principal stress at the mid-span of the wall above the opening decreases. The reduction is more evident in higher b and c values. In other words, for smaller b or c, the variation in c or b value does not have much effect on the maximum principal stress values.

For a certain b or c, the reduction rate of the maximum principal stress value in smaller h value is significantly more than in bigger h value when c or b varied from 100mm to 400mm. In other words, in smaller h values and higher b or c, the effect of c or b variation in changing the maximum principal stress value is much more visible.

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