3D FINITE ELEMENT MODELS OF PLAIN AND BOND-BEAMED HOLLOW MASONRY WALLS SUBJECTED TO CONCENTRIC AND ECCENTRIC CONCENTRATED LOADS

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ABSTRACT

3-D finite element models have been constructed for plain and bond-beamed hollow concrete masonry walls, capable of simulating their structural behaviour when subjected to concentric and eccentric concentrated loading. The models utilized the smeared crack method for predicting cracking under load. The hollow block units, mortar, grout and bond-beam blocks of the walls were modeled separately. Shell elements were used to model the hollow concrete blocks and mortar, and solid elements were used to model the grout and bond-beam blocks. Multiple-point constraints were used between the shell and solid elements. Geometric and material non-linearity as well as damage due to progressive cracking are taken into account in the models. The models predicted failure modes and loads generally in excellent agreement with those observed in the small number of available experiments. The failure mechanism is by progressive web splitting of the hollow concrete units in the region beneath the load, followed by spalling of face-shells or crushing of mortar. For walls with bond-beams, grout strength only influences the ultimate capacity of the walls marginally, if crushing immediately beneath the steel loading plate is not critical. When the eccentricity is increased, the models predicted a similar failure mechanism but lower failure loads. Comparisons with available experimental results were made, and failure mechanisms explored.

Keywords: 3D, finite element model, plain, bond-beamed, hollow masonry wall, concentrated load, concentric, eccentric

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INTRODUCTION

In recent decades, the thickness of load-bearing masonry walls has decreased. This has been made possible through improved methods of analysis, improved materials and the use of grout and steel reinforcing. However, innovative applications of structural masonry are hindered by the fact that the development of design rules have not kept pace with changes in industry products and practice. One underlying reason is the lack of insight into the complex behaviour of units, mortar, joints, and masonry as a composite material. The geometry of masonry construction varies tremendously. Mortar can be applied to the whole bedding of hollow units (full bedding) or only as a strip along the units' edges (face-shell bedding). The units can be manufactured in different geometric configurations and dimensions, containing cores and webs of irregular geometry. In North America and Australia, a common form of structural masonry is hollow concrete blockwork, typically constructed with mortar applied to the face-shells of the units only (face-shell bedding).

Concentrated loads are often applied to masonry walls through various structural elements such as cross beams, roof trusses, joists, and prestressing anchorages. For solid masonry, the state of stress immediately under a concentrated load is one of biaxial compression and the effective compression strength within the local bearing area is increased. As a result, enhancement of masonry strength is usually allowed for the masonry immediately under the load. In the case of hollow masonry, however, this enhancement is open to question because of the complex stress distribution under the concentrated load and the lack of the knowledge on the hollow masonry behaviour. Despite the wide use of hollow masonry, only a little is known about its behaviour when subjected to concentric concentrated loads (Page and Shrive 1990; Shrive and Sayed-Ahmed 1997), and virtually nothing when subjected to eccentric concentrated loads (Xie et al. 1993; Yi and Shrive 2000).

To investigate the mechanical behaviour of hollow masonry such as its failure mechanisms and strength when subjected to concentrated loads, a large number of analytical studies and experiments are required because of the large number of geometric, material, and load variables involved. It would be distinctly advantageous if this research could be performed with finite element modelling. Realistic finite element models capable of simulating the mechanical behaviour of hollow masonry would save the cost of a large experimental program. Satisfactory results can be obtained provided that the material constitutive laws are adequate to simulate the failure mechanisms observed experimentally, the geometric shape is modeled accurately, and the models are verified by specific tests.

Two-dimensional finite element models can generally be used to simulate the mechanical behaviour of solid masonry subjected to concentrated load, as the failure mechanism is vertical cracking in the plane of the wall. Many numerical models for solid masonry have been described and have led to an excellent understanding of behaviour (Khoo 1972; Ganju 1977 and 1981; Page 1978; Ali and Page 1987, 1988, 1989; Riddington and Naom 1994; Lotfi and Shing 1994). However, the failure mechanism of face-shell bedded hollow masonry is by progressive splitting of the webs, followed by spalling of face-shells or crushing of mortar. This mechanical behaviour needs to be simulated by a three-dimensional numerical model. Linear elastic analysis shows that the stresses in the mortar and some locations in the blocks are high enough for non-linear behaviour to occur in both materials. Hence, ultimate compressive strength would be overestimated when material non-linearity was not included

(Riddington and Naom, 1994). On the other hand, progressive web cracking causes the face-shells to rotate and thus geometric non-linearity occurs. Therefore, non-linear finite element modelling is required to predict realistic behaviour of the failure of hollow masonry. Sayed-Ahmed and Shrive (1995, 1996) developed a three-dimensional non-linear finite element model for face-shell bedded hollow masonry, with concrete block units and mortar being modeled separately and the face-shell taper included. The non-linear behaviour of the masonry in compression due to progressive web cracking and the geometric and material non-linearities is monitored in this model. The model showed the ability to track the behaviour of face-shell bedded hollow masonry from the first appearance of web cracking almost to final failure under concentric load. However, the use of symmetry limited this model only to be able to simulate the behaviour of hollow masonry under axial concentric load.
In practice, compressive loads may not be applied uniformly and may be applied with out-of-plane eccentricities. Therefore, in order to design concentrated load-bearing details safely, it is necessary to understand the mechanical behaviour of hollow concrete masonry subjected to eccentric loading. A more general three-dimensional non-linear finite element model for hollow masonry needs to be developed to simulate behaviour when subjected to both eccentric and concentric compressive loading.

NUMERICAL MODELS

Numerical models of hollow masonry for which some experimental results are available have been developed. PATRAN was used for pre- and post-processing for the models, while the numerical computation was performed with ABAQUS. Geometric and material non-linearities as well as damage due to progressive cracking have been taken into account. Comparison of the model and experimental results has verified that the models are capable of simulating the mechanical behaviour of hollow masonry subjected to both concentric and eccentric concentrated load.

General

When the principal stress components are dominantly compressive, both mortar and blocks are modeled by elastic-plastic theory. The smeared cracking method has been used to model cracking. Cracking is assumed to occur when the stress reaches a failure surface called the crack detection surface. The cracked material remains as a continuum with a reduced modulus simulating the crack being “smeared” over the whole element. Each such cracked element thus represents an infinite number of parallel fissures. Shell elements were used for hollow concrete block and mortar, and solid elements were used for steel plate, grout and bond-beam blocks (if any). Multi-point constraints were used for transition from shell element modelling to solid element modelling. The ″modified Riks method″ was used to obtain non-linear static equilibrium solutions. Load was applied incrementally by specifying a set of prescribed displacements on the loading plate.
For each load increment, iterations allowed for material non-linearity and progressive cracking. Iteration continued until the solution converged. The next load increment was then applied and the procedure repeated. Final failure was indicated by the lack of convergence in

the calculation. Since the load was produced by an equivalent prescribed displacement, the behaviour of the models could be studied from the first appearance of web cracking to final failure (face-shell spalling or mortar crushing).

Geometry

The plain walls modelled are shown in Fig. 1 and 2. Three loading locations were modeled: over the central web of a unit; over two end webs and a vertical mortar joint; and over the core. The loading plate length was 160mm. Models of walls with one-course and two-course bond-beams are shown in Fig. 3 and 4 respectively. Three loading plate lengths were used: 160mm, 240mm and 320mm. The model details of the connection between face-shells of hollow blocks and bond-beam are shown in Fig. 5. After processing the original mesh once, the substructuring technique was used where low stress zones were modeled using super elements.

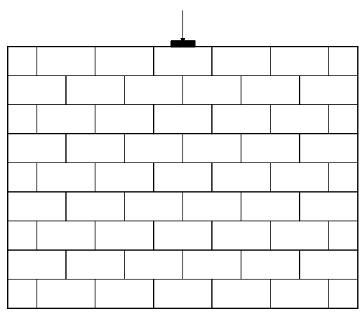


Fig. 1. Plain hollow concrete masonry wall (load over central web)

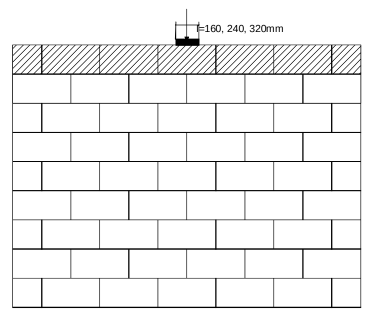


Fig. 3. One-course bond-beamed hollow concrete masonry wall

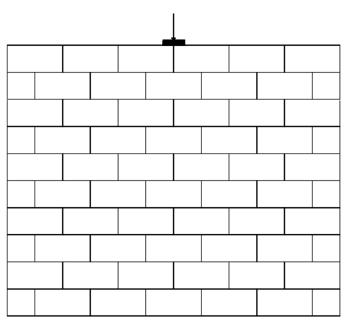


Fig. 2. Plain hollow concrete masonry wall (load over two end webs)

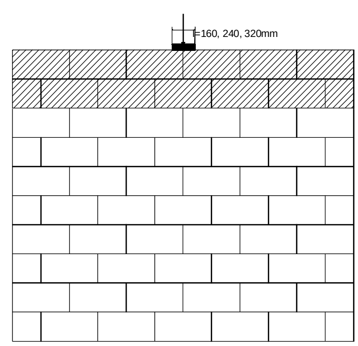


Fig. 4. Two-course bond-beamed hollow concrete masonry wall

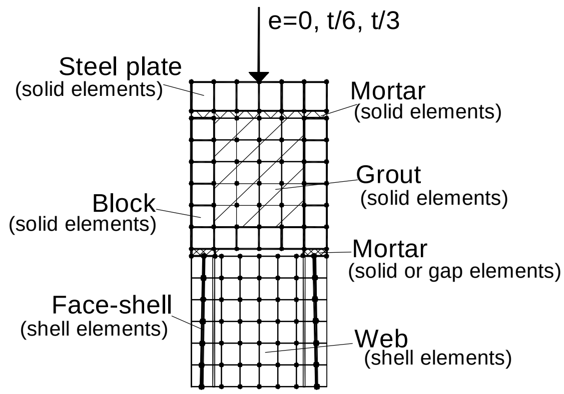


Fig. 5. Connection details between hollow block and grouted bond-beam block

RESULTS

Failure Loads

The failure loads from predicted results and experiments for plain, one-course and two-course bond-beamed walls subjected to concentrated load are included in Tables 1, 2, and 3, respectively. There is excellent agreement between the predicted results and the available experimental results, as can be seen. As the eccentricity increased, the models predicted a similar failure mechanism but lower and lower failure loads. However, the idealization of the models might overestimate the failure loads of hollow concrete masonry walls subjected to eccentric loads, as instability develops in practice when loaded under large eccentric loads (Yi and Shrive 2000).

Failure Modes

For plain walls subjected to concentrated load, the failure modes are as follows:

1. Concentrated load over central web:
Under concentric load, at about 50% of the ultimate load, cracking appeared in the middle of the top of the central web directly beneath the loading plate. At about 80% of the ultimate load, cracking appeared at the two sides of the top of the central web, and also in the face-shells at the edges of the loading plate. At about 90% of the ultimate load, cracking formed in the middle of the bottom of the central web directly beneath the loading plate. Finally, cracking occurred at the top of the two end webs in the second course below the loading plate (running bond), and a vertical crack formed in the face-shell of the unit directly beneath the loading plate and in the mortar one course below in line with the load, similar to a crack that would form in a solid wall loaded in this manner. A typical predicted cracking pattern is shown in Fig. 6(a).

Under eccentric load, the first cracks still appeared at the top of the central web directly beneath the loading plate, but on the lightly-loaded side, rather than the middle. As the load increased, cracking developed on the heavily-loaded side of the bottom of the central web, and the top of the two end webs in the same unit. And at the same time, a vertical crack developed in the face-shell in line with the load. Final failure occurred with cracking on the lightly-loaded side of the top of the two end webs in the second course below the load. As the eccentricity increased, the sequence of cracking and failure was similar except that the top of the central web cracked closer and closer to the lightly loaded face-shell while the bottom of the web cracked closer and closer to the heavily loaded face-shell. A typical predicted cracking pattern is shown in Fig. 6(b).

The predicted failure modes compare very well with the available experimental results (Page and Shrive 1990), as depicted in Fig. 7(a).

2. Concentrated load over two end webs:

Under concentric load, at about 55% of the ultimate load, cracking appeared in the middle of the top of the two end webs directly beneath the loading plate. At about 90% of the ultimate, cracking occurred at the two sides of the top of the two end webs, and also occurred in the face-shells at the edges of the loading plate. At almost the same time cracking occurred in the middle of the bottom of the two end webs. Finally, cracking occurred at the top of the central web one course below (running bond), and a vertical crack formed in the bottom part of the mortar in the course directly beneath the load in line with the load, similar to a crack that would form in a solid wall loaded in this manner.

Table 1. Predicted and Experimental Results for Plain Hollow Concrete Masonry Walls Subjected to Concentrated Loads

Loading Position	Eccentricities (mm)	Failure Load (KN)	
		Finite Element Model	Experimental
Load over central web	e=0	236	251
	e=31	185	171*
	e=62	155	
Load over two end webs	e=0	221	219**
	e=31	175	
	e=62	149	
Load over core	e=0	183	181
	e=31	156	
	e=62	127	

Note: Experimental data are from Page and Shrive (1990). * Eccentricity may be 35mm.
** From Shrive and Sayed-Ahmed (1997).

Table 2. Predicted and Experimental Results for One-course Bond-beamed Hollow Concrete Masonry Walls Subjected to Concentrated Loads

Loading Plate Length (mm)	Eccentricities (mm)	Failure Load (KN)	
		Finite Element Model	Experimental
160	e=0	378	395
	e=31	339	313*
	e=62	257	
240	e=0	426	436
	e=31	375	
	e=62	312	
320	e=0	517	530
	e=31	440	
	e=62	407	

Note: Experimental data are from Page and Shrive (1990). * Eccentricity is 35mm.

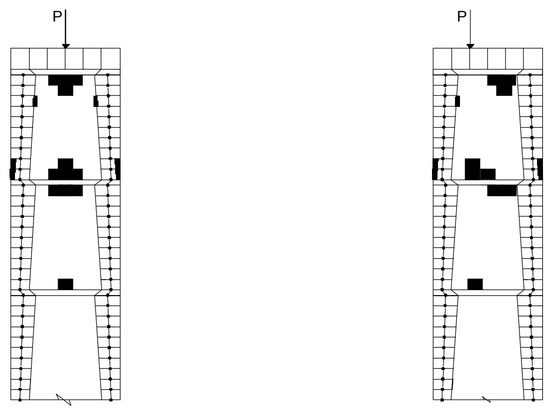
Table 3. Predicted and Experimental Results for Two-course Bond-beamed Hollow Concrete Masonry Walls Subjected to Concentrated Loads

Loading Plate Length (mm)	Eccentricities (mm)	Failure Load (KN)	
		Finite Element Model	Experimental
160	e=0	539	520
	e=31	491	384*
	e=62	406	
240	e=0	588	591
	e=31	538	
	e=62	449	
320	e=0	645	660
	e=31	556	
	e=62	473	

Note: Experimental data are from Page and Shrive (1990). * Eccentricity is 35mm.

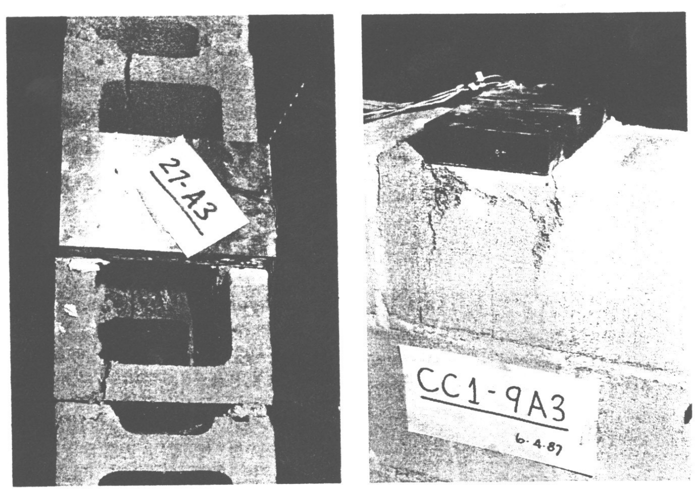
Under eccentric load, the first cracks still formed at the top of the two end webs directly beneath the loading plate, but at the lightly-loaded side. As the load increased, cracking appeared at the heavily-loaded side of the bottom of the two end webs, and a vertical crack formed in the bottom part of the mortar in the course directly beneath the load in line with the load. Final failure occurred when cracks developed on the lightly-loaded side of the top of the central web one course below. As the eccentricity increased, the sequence of cracking and failure was similar except that the top of the two end webs cracked closer and closer to the lightly-loaded face-shell while the bottom of the two end webs cracked closer and closer to the heavily-loaded face-shell.

The failure mode of hollow masonry wall subjected to concentrated load over two-end webs is almost the same as that with load over the central web, except that when the load is over two-end webs, the wall is stiffer.



(a) (b)

Fig. 6. Cracking pattern of plain hollow masonry walls subjected to concentrated load
(a) concentric load (b) eccentric load



(a) (b)

Fig. 7. Failure modes of plain hollow concrete masonry walls subjected to concentrated load
(a) Load over central web (b) Load over core

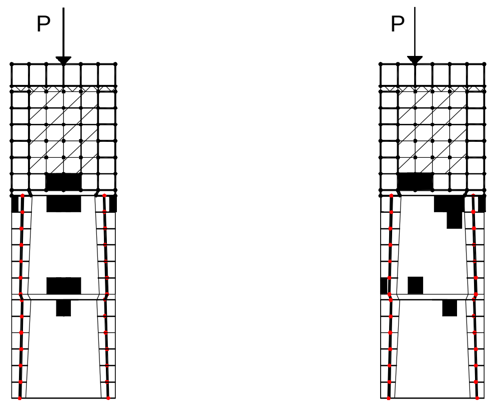
3. Concentrated load over core:
Under concentric load, at about 80% of the ultimate load, mortar connecting the end webs beside the loading plate cracked. Final failure occurred by local splitting of the loaded face-shells directly in line with the edge of the bearing plate, a typical tearing stress failure. As the eccentricity increased, final failure occurred by local splitting of the heavily loaded face-shell directly in line with the edge of the bearing plate, and the ultimate load decreased. The predicted result compares very well with the experimental result of Page and Shrive (1990), as shown in Fig. 7(b).

The failure modes of walls with one-course bond-beams are as follows:

1. Under concentric load, when the plate length is 160mm, at about 40% of the ultimate load, mortar between the bond-beam and the face-shells beneath started to crack. At about 50% of the ultimate load, cracking occurred in the middle of the bottom of the bond-beam directly beneath the loading plate, and web split in the first hollow course immediately below the bond-beam in the region directly beneath the load. At about 60% of the ultimate, a vertical crack formed in the face-shell in the hollow course in line with the load, similar to a crack that would form in a solid wall loaded in this manner. With increasing load, web-splitting progressed along the top of the first hollow course below the bond-beam and into the courses beneath, and vertical mortar joints also cracked due to the combined shear and compressive stress. Final failure occurred when sufficient webs had split and local face-shell spalled and mortar crushed. When the loading plate length was increased (240mm, 320mm), the same cracking sequence occurred again, except that the ultimate loads increased. A typical predicted cracking pattern is shown in Fig. 8(a).

2. Under eccentric load, the first cracks still occurred at the bottom of the bond-beam directly beneath the loading plate, but on the heavily loaded side, rather than the middle. At the same time, cracking appeared at the lightly loaded side of the top of the webs in the first hollow course immediately below the bond-beam. Also the mortar between the bond-beam and the lightly loaded face-shell beneath cracked under combined shear and compression. As the load increased, a vertical crack occurred in the face-shell and mortar in line with the load. Final failure occurred when cracking formed at the bottom of the webs in the first hollow course below the bond-beam at the heavily loaded side, and at the top of the webs in the second course below the bond-beam at the lightly loaded side. As the eccentricity increased, the sequence of cracking and failure was similar except that the predicted ultimate loads were lower and lower, the bottom of the bond-beam cracked closer and closer to the heavily loaded face-shell while the top of the webs in the first hollow course immediately below the bond-beam cracked closer and closer to the lightly loaded face-shell. A typical predicted cracking pattern is shown in Fig. 8(b).

An important point to note is that when the grout strength was increased from 20MPa to 50MPa in the model of a wall with a bond-beam, the predicted ultimate strength increased less than 5% (Yi and Shrive 2001). This is in excellent agreement with the results of Page and Shrive (1990) who found very little variation in wall strength with substantially different grouts. From the sequence of cracking shown by the finite element models, we now recognize that the grout is not involved much in the failure mechanism: its contribution is mainly the distribution of the concentrated load. Hence grout strength will have little influence on overall wall strength. If the plate is full width (over both grout and face-shells of bond-beam blocks, as in the models and the experiments), the face-shells of the bond-beam blocks help to distribute load as well. Grout strength will not be critical as long as the grout is strong enough to resist local crushing beneath the steel loading plate.



(a) (b)

Fig. 8. Cracking pattern of bond-beamed hollow masonry walls
(a) concentric load (b) eccentric load

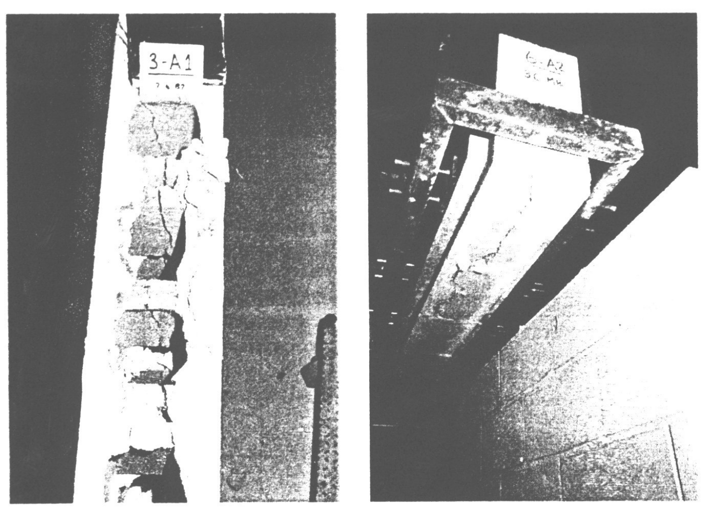


Fig. 9. Failure modes of bond-beamed hollow concrete masonry walls subjected to concentrated load

The failure modes of walls with two-course bond-beams are similar to those with one-course bond-beams, except that the web-splitting progresses wider and deeper, and with higher ultimate capacity or higher strength enhancement. Again the predicted results compare very well with experimental results of Page and Shrive (1990), as depicted in Fig. 9.

CONCLUSION

3D nonlinear elastic-plastic finite element models have been developed and applied to simulate the structural behaviour of plain and bond-beamed hollow concrete masonry walls subjected to concentric and eccentric concentrated load. Hollow blocks, mortar, grout and bond-beam blocks were modeled separately. Geometric and material non-linearities were taken into account. The smeared crack modelling approach was used to model the progressive cracking and damage. Iso-parametric shell elements and solid elements were used. Multiple-point constraints were used between the shell and solid elements.
Some results of the models were compared with those observed in the small number of available experiments. The good agreement confirms that the nonlinear behaviour of hollow masonry walls subjected to concentric and eccentric concentrated load can be successfully modelled. The failure mechanism is by progressive web-splitting of the hollow concrete units in the region beneath the load, followed by spalling of face-shells or crushing of mortar. The grout does not help much in resisting cracking in bond-beamed hollow masonry walls, so grout strength only influence the ultimate capacity of the walls subjected to concentrated load marginally. Local crushing beneath the steel loading plate has to be avoided. When the eccentricity is increased, the models predict basically the same failure mechanism, but with lower failure loads.

ACKNOWLEDGEMENTS

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