CRACKING OF LATERALLY LOADED MASONRY WALLS WITH OPENINGS

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ABSTRACT

The approach of Monte Carlo simulation combined with the finite element method is applied to predict the development of the first crack in laterally loaded masonry panels with various configurations of door and window openings. The effect of various sizes and locations of openings on the cracking loads of panels has been studied. The influence of self-weight is included. The principal moment failure criterion is used to determine when cracking occurs in the masonry material.

The study was carried out for two common practical support categories, namely panels supported on all four edges and panels simply supported along the bottom and two sides but free at the top. Comparisons are also made between the analytical predictions and some available experimental results.

INTRODUCTION

The Australian Masonry Code\(^1\) uses an empirical method called the strip method for design of unreinforced non-loadbearing masonry walls subjected to lateral out-of-plane loading. The method has been derived from extensive testing in Australia of both clay and concrete masonry panels and agrees well with the experimental results for a practical range of panel sizes where door and window openings are not present. However, practical panels usually have door and window openings and there is therefore a need for a rational method of calculation capable of predicting the strength of panels having openings of various sizes and configurations.

The strength properties of masonry exhibit a high degree of randomness\(^2\) because of variable factors such as natural variation in materials, variation in the manufacturing process, variation in the quality of site workmanship, the difficulty of controlling site-batched mortar and so on. It has been shown\(^3\) that this random variation can have a significant effect on the strength of masonry structures which depend on the tensile strength of the material. It is therefore necessary to account for the inherent random variation in any theoretical analysis of non-loadbearing panels under lateral load.
Finite element analysis can readily model the physical aspects of masonry wall panels subjected to wind pressure. It is particularly suited to modelling panels with various configurations of door and window openings. Consideration of random variability can be made by combining a Monte Carlo simulation approach with a finite element model. The analytical results from such a finite element analysis of plain panels have been compared previously with those from an isotropic elastic plate analysis based on conventional elastic plate theory combined with Monte Carlo simulation. The almost identical results from both approaches verify the feasibility and accuracy of the finite element program. The method is here employed to study the behaviour of masonry walls with openings.

THE METHOD OF ANALYSIS

Masonry is an orthotropic material because of the planes of weakness inherent in its construction. Experimental work on large numbers of horizontal and vertical brickwork beams has shown that the ratio of elastic moduli vertically and horizontally is not large and could therefore be expected to have little influence on the plate bending moment distributions. Isotropy is therefore assumed in the finite element solutions to simplify the problem. Seward adopted an orthotropic stiffness ratio of 1:1.4 and showed that the effects of its inclusion are small.

The analysis is based on the assumption that a masonry panel behaves in a linear elastic fashion prior to the first crack. This type of behaviour is supported by detailed studies of beams in flexure and the early load-deflection behaviour of panels under lateral load which showed that first cracking occurs at very low deflections - of the order of span over 5000.

The Monte Carlo simulation approach is well established as a method of dealing with random variability and has been successfully applied to simple problems of brittle masonry behaviour. Given a model of behaviour, it only requires that the model be solved many times with randomly selected input parameters. The result is a picture of the full probability density function for the phenomenon under investigation. It is then a simple matter to study the effects of changing the form and magnitude of random variation in the basic parameters, as well as the type of material model used.

A laterally loaded masonry wall panel is analysed by subdivision into four-node rectangular plate elements, corresponding in size to the module size of the masonry units. The centres of these elements are used as the points of comparison between applied moments and material strengths. At each of these points the horizontal, vertical and twisting moments are calculated and stored for later use. Random horizontal and vertical flexural tensile strengths are then assigned to each point by sampling a probability distribution with given mean and coefficient of variation (CV). For the present study a log-normal distribution is used, based on the results of earlier studies. A ratio of mean horizontal strength to mean vertical strength of two is adopted, based on the average strengths obtained from tests on vertical and horizontal beams. Cracking is assumed to occur when the first point reaches its moment capacity determined by
a chosen failure criterion. That is, all points are assumed to act independently and the failure of the first point constitutes cracking in the panel. This is equivalent to a 'weakest link' or 'links in series' model.

A uniformly distributed load (such as wind) acting normal to the surface of a brickwork wall produces a combination of biaxial bending moments and twisting moments which are superimposed on the vertical compression due to self weight. A failure criterion must be chosen to consider the interaction of these bending and twisting moments about the major axes and to determine the point at which cracking initiates. A principal moment criterion (an elliptical interaction between moments in the two inclined principal directions) is applied in this study.

The principal moment failure criterion is applied by calculating the principal moments at the centre of each element from the vertical, horizontal and twisting moments. Then, from the assigned vertical and horizontal strengths, the moment capacities about the inclined principal axes are determined using the interaction proposed by Baker. Although this interaction relationship is based on very little experimental data there is no alternative available at the present time. The ratios of strength to applied moment (on the inclined axes) are then calculated and a cracking load for each element thereby determined. The lowest of these cracking loads is taken as the load to cause first cracking in the panel.

Once the cracking load of the panel is determined in this way it is stored, along with the location of the first crack, and the whole process is repeated with another set of random strengths assigned to the points. By repeating this process many times a distribution of wall strengths is developed.

For this analysis the subdivision into finite elements is based on the unit size of the masonry. That is, there are approximately the same number of four node rectangular elements in the model as there are masonry units in the wall. This is not to say that the elements are intended to physically model the masonry units and mortar joints, it is merely to give the correct number of contributory elements for dealing with the random strength variation from point to point.

Experimenting with various numbers of samples in the Monte Carlo simulation has shown that 100 cycles of analysis gives reasonably close approximations (within a few percentage points) but that 500 to 1000 cycles are required for truly consistent results. Because of the time consuming nature of the analysis the results for wall panels with openings presented here are derived from runs of 100 cycles.

**SCHEME OF ANALYSIS**

To investigate the effects of size and location of opening on the cracking load of a panel, sixteen cases of various sizes and positions of openings, as shown in Table 1, have been examined. The sixteen cases are considered for each of two common practical support conditions, namely panels simply supported on all four edges (referred
to as support category 1) and panels simply supported along the bottom and two sides but free at the top (support category 2). Table 1 and Figure 1 show the arrangement and geometrical data for the sixteen cases analysed.

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* S=1 - Simply supported on four sides (category 1)
S=2 - Simply supported on bottom and two sides, free at the top (category 2)

Table 1 Geometrical Data for the Walls Analysed (Refer to Figure 1).

Figure 1. Arrangement of Walls Analysed
The wall panels used for the analysis are all 6000 mm long by 2400 mm high and 190 mm thick. Material properties are - Young's modulus $E = 17.5$ GPa; Poisson's ratio $v = 0.23$; mean flexural strength in the $y$ direction $= 0.44$ MPa. These properties correspond to the average of those for the materials used by Candy et al\cite{9} in obtaining the test data which are used for comparison with the analytical results.

The analysis has been carried out for a range of CV of flexural tensile strength. Variability in this property is typically about 15% to 25% but some samples can give an even wider range of CV. The range included in the analysis is 0.05 to 0.40.

RESULTS AND DISCUSSIONS

Figure 2 shows the mean calculated load to cause cracking (for mean vertical flexural tensile strength of $0.44$ MPa) plotted against the CV of vertical flexural tensile strength, for panels containing openings with various locations and sizes. These panels were simply supported on four sides (support category 1). Similarly, Figure 3 shows results for panels simply supported at the bottom and two sides but free at the top (support category 2).

These results show that, as expected, the existence of openings reduces the cracking loads of panels and that the influence of location is more important than size of the opening. The degree of influence for a particular configuration of opening also depends greatly on the support conditions of the panel.

![Figure 2. Effect of Openings on Cracking Load - Support Category 1](image)
It is noticed from Figure 2 that for support category 1 the reduction in the initial cracking load for a panel with a door shaped opening (case 8) is much less (10%) than that of a panel with a long window-shaped opening (cases 2 to 7) where the reductions are up to 51%. The maximum difference among panels with the same shaped opening but different sizes is 28% at CV = 0.05 and 22% at CV = 0.40.

For support category 2, the load reduction of panels with openings is not as significant as that for support category 1 and the analytical curves for different cases cluster around each other (Figure 3). The exception is case 13 where the opening location is the farthest from the top free edge (largest value of c - see Figure 1) and the reduction in cracking load is pronounced.

To display the significance of location of opening the mean cracking load is plotted against CV in Figure 4 for panels of both support categories containing a fixed size of opening (4000 mm x 600 mm).

The large differences in results - up to 28% for support category 1 and 31% for support category 2 - for panels with an opening of fixed size in various locations demonstrate the significance of location of opening on cracking load.

With a given size and location of opening, the load reduction for panels with support category 1 is larger than for support category 2. Consider for example case 2 and case 10 (which have the same size and location of opening). Compared with the panels without openings (cases 1 and 9) the load reduction for case 2 is 51% whereas for case 10 it is only 10% (Figure 4).
Very few test data are available for walls with openings. For this study, comparisons have been made with the test results reported by Candy et al.[9]. In that work the measured cracking load for a panel with an opening corresponding to case 10 is 1.5 kPa, which falls within the range of analytical results between 1.95 kPa and 1.19 kPa for CV of 0.05 and 0.40 respectively. There is no record in the reference of an initial cracking load for other cases studied. There is an urgent need to obtain more experimental data to verify these analytical approaches. Further theoretical and experimental investigations of the effect of different sizes and locations of openings on the cracking load need to be carried out to formulate design rules for common cases.

**FUTURE DEVELOPMENT OF THE METHOD**

Future work will investigate further the effect of the assumptions regarding failure criterion on the predicted cracking loads, including the possibility of a degree of load sharing between units in a bed joint. Work is required to establish a suitable criterion, supported by test data, which can then be incorporated into the analysis. Experimental data on the performance of panels with openings is also required urgently for comparison with the results of analysis.

The method will then be developed to trace cracking and to model the full range of panel behaviour right up to failure. This will allow the practical cases to be studied in detail and design rules to be formulated.
CONCLUSIONS

By considering the random variation in flexural tensile strength, Monte Carlo simulation combined with finite element solutions can be used to derive estimates of first cracking in non-loadbearing masonry panels under lateral load. This is a useful tool for analysing panels in various configurations, including the presence of door and window openings.

The analytical results for panels with sixteen cases of various sizes and locations of openings show that (as expected) the existence of an opening reduces the cracking load. The reduction for panels with four sides supported is larger than for panels with bottom and sides supported and the top free. In general the cracking load depends more on the location than on the size of opening.

There is an urgent need for more experimental data to verify the analytical approach.

REFERENCES