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A NUMERICAL MODEL FOR CRACKING IN MASONRY FOR USE IN RELIABILITY MODELLING

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ABSTRACT

A finite element model for the prediction of crack sizes in masonry wall panels due to foundation movements is presented. The model is specifically designed for use in reliability studies. Model simplicity and rapid solution speed are key features while still maintaining the flexibility to investigate a wide range of scenarios for cracking in the wall panels. Crack widths are obtained essentially by studying relative movements between intact blocks of masonry and the footing beam (which are separated by cracks) due to various deformed ground profiles.

INTRODUCTION

Reactive soil movements, mine subsidence and differential settlement are some of the sources of structure foundation movements which have historically caused widespread problems with respect to the serviceability performance of masonry structures. The most obvious problem is that of cracking in masonry walls supported by footings. The types of cracks typically observed are rarely significant from a structural safety viewpoint. Concern lies more with serviceability issues such as aesthetics and water tightness.

The literature reveals that this problem has been addressed in part previously by various researchers. The likely causes for cracking have been established and various techniques for the prevention of cracking have been proposed (Cement and Concrete Assoc. of Aust. 1991, Cameron & Walsh 1984, Page 1993, Grimm 1997).

However. previous research has been largely empirical. based on observations of the performance of structures in service (Skempton & MacDonald 1956). This has resulted in the serviceability provisions in design codes containing very general clauses which offer little detailed guidance to designers.

There is therefore a need to produce rational design criteria for the serviceability design of masonry structures using reliability based structural design (Melchers 1996, Ellingwood & Tallin 1985).

This is currently the focus of an ongoing group research project at the University of Newcastle.

Overview of the Project

The project is confined to one and two storey domestic or commercial construction in either unreinforced cavity brick or unreinforced brick veneer. This is one of the major areas of masonry use in Australia. The project has been divided into three main strands.

1. The first is the establishment of the types and range of external effects likely to influence the cracking of masonry. This work has involved the development of a model to predict expansive soil movements due to various factors. (i.e. soil movement model) (Muniruzzaman & Totoev 1998, Totoev & Kleeman 1994).

2. The second strand requires determining the masonry structure response to these foundation movements. This has involved extensive full scale testing of masonry wall panels in the laboratory. This testing is now complete (Bryant 1993, Muniruzzaman 1997).

Also important in this strand is the development of numerical models capable of duplicating the structure response observed in the experiments so as to reduce the number of laboratory experiments required to investigate a full range of scenarios for wall movement. The experiments indicate that such models need to allow for cracking with frictional sliding along crack interfaces.

3. The third strand will bring together the numerical models for soil movement and structural response to develop a probabilistic model for the prediction of cracking in masonry. The aim of this model is to predict the likelihood of cracking, its probable extent and its likely size.

Rational procedures should then follow for developing serviceability criteria for cracking in masonry structures allowing for the variability in both external effects and structural response.

This paper presents a finite element model for the prediction of crack sizes in masonry wall panels due to foundation movements. The model represents part of the strand 2 work and is specifically designed for use in reliability studies. Model simplicity and rapid solution speed are key features while still maintaining the flexibility to investigate a wide range of scenarios for cracking in the wall panels. Crack widths are obtained essentially by studying relative movements between intact blocks of masonry and the footing beam (which are separated by cracks) due to various deformed ground profiles. Frictional sliding is included.

The proposed reliability work of strand 3 is outlined elsewhere (Melchers 1996).

THE FINITE ELEMENT WALL MODEL (STRUCTURE RESPONSE MODEL)

Purpose of the Model

A numerical model able to be used in predicting crack displacements in a masonry wall panel subject to a set of internal and external variables forms one of the basic tools for the proposed reliability analyses. Such a model not only needs the flexibility to randomly vary the boundary conditions and a range of other influencing parameters, but also requires rapid solution speed for simulating a large range of scenarios.

Numerical modelling of the masonry wall panel experiments conducted at the University of Newcastle has been performed by the associated researchers (Bryant 1993, Muniruzzaman 1997). These models have generally made use of commercial finite element software. Although the experimental observations have been successfully reproduced, these models do not exhibit the required solution speed or flexibility for use in reliability modelling (Melchers 1996).

These requirements have necessitated writing a finite element program which avoids the large time cost associated with the extensive graphical interface and generality of the commercial software.

Components of the Model

The current wall model is two dimensional and consists of a masonry wall panel supported by a reinforced concrete beam (Fig. 1). The beam is representative of a typical strip footing in domestic construction and can in turn be supported at a number of nodal points along its length.

During model development, wall panel dimensions of storey height (2.5m) by control joint spacing (6.0m) width were adopted. These dimensions, as well as the adopted footing dimensions and support arrangement, are consistent with those used in the associated laboratory testing.

It is common practice in domestic construction to include a damp proof course (dpc) in the external skin of masonry walls either at the footing/masonry interface or, more commonly, in a masonry bed joint close (say two courses) to the footing/masonry interface. The experimental results indicate that the presence of the dpc has a significant influence on wall behaviour (Page et al. 1994) and so a dpc is included in the model. The way in which the dpc is modelled is discussed in a later section.

Structure loading is by self weight of the wall and beam and top plate point loads due to rafters and/or a second storey can be included. Wall deformation and cracking is then simulated by imposing a deformed profile to the footing beam. This is done either by using prescribed displacement supports at various points along the beam or by imposing external point loads to the beam with simple supports at each end.

The model will be expanded later to include a soil layer beneath the footing beam to simulate ground movements more accurately.

Flexibility of the Model

As presently implemented the model allows only two dimensional plane stress analysis. Extension to an equivalent three dimensional model is the subject for future research. The model allows the flexibility to study cracking in masonry panels with:

- Any length, height and thickness of masonry panel or reinforced concrete footing beam.
- Any material properties for the masonry or reinforced concrete. Note that to date both materials have been assumed homogeneous and isotropic, although homogeneous, orthotropic behaviour could be relatively easily included.
- Horizontal, vertical or stepped cracking or a combination of these.
- Any imposed deformed footing profile.
- Window and /or door openings of any size in any location.
- The inclusion of a timber top plate. The presence of the top plate has been found to significantly affect the behaviour for loadbearing walls with openings (Page et al. 1994).

Minimising Solution Time

Considerable emphasis has been placed on minimising solution time for the program. To achieve this the model has been kept as simple as possible.

- 4–noded and 8–noded plane stress finite elements have been used throughout. The assumption of plane stress in modelling elastic behaviour for masonry walls has been validated by others (Anthoine 1997).
- Crack locations and configurations are able to be prespecified so that no modelling of crack propagation is required.
- The intact masonry between the cracks as well as the reinforced concrete footing beam have both been macro–modelled as homogeneous, isotropic composite materials and are assumed to behave linearly elastically. These assumptions have been shown to enable reproduction of the actual wall behaviour at serviceability loads (Page et al. 1994, Muniruzzaman 1997).

The assumption of linear elastic behaviour in the structure between crack lines has allowed the solution speed to be enhanced by the use of static condensation to reduce the total number of degrees of freedom (dofs) in the iterative procedure for adjusting crack contact lengths and to allow sliding. Only the dofs associated with the crack interface are retained as it is only the crack opening/sliding displacements and contact lengths and forces which are of interest at each iteration (Fig. 2).

The complete structure has been treated as a single 'superelement' for the condensation process. This was considered to be simpler and more efficient than adopting the usual technique of breaking the structure into a number of substructures (superelements) and performing static condensation for each before assembling the global condensed stiffness equations (Ali & Page 1987).

Run time comparisons using versions of the wall model program with and without static condensation indicate that significant time savings can be achieved. The time for solution of the global stiffness equations for crack displacements for a single iteration prior to static condensation is approximately 7.5 times longer than that after static condensation. The time taken to perform the condensation starting with the uncondensed stiffness equations is approximately 6 times a single solution time for the uncondensed equations. The considerable time taken for the condensation procedure was noted by Stavroulakis (Stavroulakis 1990). However the time savings for the subsequent condensed solutions for displacements result in significant overall savings.

Modelling the Masonry Cracks

Cracking in the wall panels is modelled using a prespecified crack location. Likely initiation points of cracks can be determined from analyses of uncracked panels subjected to appropriate footing deformations. The input to the finite element program contains information defining the cracking paths across the wall panel.

The program therefore does not locate a crack or determine a crack path but rather calculates the crack opening widths due to relative movements between the intact blocks of masonry and the footing beam arising from the imposed soil deformations.

The selection of the type and configuration of cracking for the given deformed footing profile is based on experience gained from experimental work and parametric studies conducted at the University of Newcastle (Bryant 1993, Muniruzzaman 1997). This research, together with observations of structures in practice, indicates that the range of possible crack locations and configurations which occur in practice is quite small. During model development the crack configurations observed during particular laboratory experiments are being used as model input.

Automatic crack propagation was not included for a number of reasons:

- Numerical solution is much faster and more stable given a prespecified crack.
- Crack locations and configurations due to a range of foundation deformations have already been determined by previous research.
- The use of a prespecified crack configuration allows the model to be used to investigate opening displacements due to foundation movements in existing cracks which were not originally caused by foundation movements or were caused by foundation movements of a different nature to those currently being imposed on the footing.

The crack paths are defined by specifying the nodes of the f.e. mesh along which the crack paths lie. It is therefore convenient to adopt rectangular finite elements for the masonry with dimensions not too far different from those of the masonry units so that stepped crack paths can be modelled reasonably accurately (Fig. 3a).

The crack opening and sliding displacements are modelled by introducing additional dofs at each node on a crack path (Fig. 3b). By including separate sets of horizontal and vertical translation dofs for either side of the crack at each node on the crack path, the relative movements perpendicular to the crack (crack opening/closing) and parallel to the crack (crack sliding) can be computed.

Contact across the crack .that is, where separate intact blocks of masonry or the footing beam touch each other, is incorporated by the use of link elements. These are used to assign a connectivity of specified stiffness between the separate sets of horizontal and vertical dofs on either side of the crack. The program is initially provided with crack contact information. An initial guess is made for the lengths of crack over which adjacent regions of intact masonry and/or footing beam will be in contact. The program then performs iterations to adjust crack contact lengths until equilibrium is satisfied .that is, until there exists only compressive normal contact forces across the crack and the values for displacements at all dofs have converged. If, during iterations, the normal contact force across the crack at a node becomes tensile, normal and shear contact is released by setting the associated link element stiffness coefficients to zero.

The above approach differs from that generally adopted in the literature which involves the introduction of additional nodes along the crack (Kodikara & Moore 1993, Stavroulakis 1990). The current approach was selected so that the same finite element mesh could be used when modelling different crack configurations in any given wall panel without the need to introduce new nodes and renumber existing nodes for each new crack configuration.

Experimental results have shown that for certain deformed footing profiles relative sliding along the crack interfaces, particularly the damp proof course, is common (Fig. 4). Accurate modelling of the associated friction is an important factor affecting the calculated crack size (Bryant 1993, Muniruzzaman 1997).

Two slightly different approaches have been developed for modelling the frictional resistance to relative sliding along the crack interfaces both being similar to that adopted by Cundall for simulating movements in rock systems (Cundall 1971). Both techniques require the shear link force ($F_s=k_s\Delta u_s$) across the crack at each contact node to be investigated at each iteration. If the shear force exceeds the limiting friction value (μF_n) at the node, the shear link element stiffness is reduced to simulate a shear release.

Note that F_n, F_s = Normal and shear contact forces across the crack ($F_n=k_n\Delta u_n$)
Δu_n, Δu_s = Relative normal and shear displacements across the crack
k_n, k_s = Normal and shear contact link element stiffness values
μ = Coefficient of friction for the crack interface

In the first of the two approaches, the reduced shear link stiffness is fixed for all subsequent iterations. Equal and opposite external forces are imposed either side of, and parallel to, the crack in such a way that the combined effect of the reduced shear link force and the external forces is equal to the limiting friction value. The shear link stiffness value can not be reduced to zero because of the possibility of introducing a mechanism into the model.

In the second approach, the reduced shear link stiffness value is adjusted at each iteration (rather than being fixed) so that the shear link force (Fs) across the crack is equal to the limiting friction value. This removes the need for the equal and opposite external forces.

Test runs conducted to date show that both techniques produce exactly the same results for nodal displacements. The first approach converges more rapidly than the second for most cases, but is numerically less stable and for some crack configurations it fails to converge. Future work will aim at improving the stability of this first approach.

It should be noted that since the model considers movements in fully propagated cracks, consideration of time dependent effects on cracking and fracture mechanics behaviour are neither necessary or appropriate. Previous studies of fracture and crack propagation such as those by Lotfi & Shing (1994), Cormeau & Shrive (1996), and Rots (1991) to name a few may be taken into account when choosing the likelihood and location of cracks.

The Footing Beam

The footing beam is modelled using two layers of 8–noded rectangular plane stress finite elements (Fig. 5). Comparisons using a commercial finite element package show that the deflected shape obtained using this discretisation agrees well with that obtained using beam elements and also with that obtained using hand calculations.

The beam is discretised in this way so that the effects of localised flexural tensile cracking in the real beam can be modelled by using reduced stiffness (E) values for the finite elements in regions of suspected flexural cracking. This allows the deflected shape of the footing beam to be modelled more accurately.

The Damp Proof Course

The experimental results of Bryant (Bryant 1993) and Muniruzzaman (Muniruzzaman 1997) both show that a small degree of deformation of the foundation soil will result in deflections in the footing beam sufficient to break the relatively weak bed joint bond at the dpc level (Fig. 6). The dpc is therefore most easily represented by specifying a horizontal crack path along its full length.

Panel Openings

To avoid altering the finite element mesh used for any particular wall panel study, openings are included simply by using much reduced stiffness and unit weight values for the finite elements representing the masonry in the region of the wall panel occupied by the opening.

VALIDATION OF THE WALL MODEL USING EXPERIMENTAL DATA

The reason for developing a numerical model for the wall behaviour is to reduce the number of costly and time consuming experiments that would otherwise be required to study a full range of scenarios for the wall. For such a model to be useful it must be able to duplicate the results observed during a limited number of actual experiments.

For the purpose of validation and calibration of the wall model the results of experiments conducted by Bryant (Bryant 1993) and Muniruzzaman (Muniruzzaman 1997) at the University of Newcastle are available.

The current wall model is capable of reproducing the essential features of wall behaviour observed in the two dimensional tests (Bryant 1993).

Example. Dishing ground curvature with central vertical crack and horizontal crack along dpc (Fig. 4) – The model has been used to reproduce the experimentally observed behaviour of separation along the dpc and simultaneous sliding at each end of the dpc, allowing the intact masonry wall segments to rotate and contact the beam at midspan. The resulting crack opening and relative sliding displacements are consistent with experimental observation. Similar results have also been achieved with a vertical crack off centre.

CONCLUSIONS AND FUTURE DIRECTION

A finite element model for the prediction of crack sizes in masonry wall panels due to foundation movements has been presented. The model successfully captures the essential features of wall behaviour as observed in numerous experiments conducted at the University of Newcastle. The model will be used in reliability studies and so development has focused on model simplicity, rapid solution speed and flexibility to study a full range of scenarios for cracking in masonry wall panels.

The next step in the project is to combine this structure response wall model with the soil movement model developed in strand 1. From this will be derived a probabilistic model for predicting the likely location, extent and size of cracking in masonry wall panels based on expected variability in both the external effects and structural response. The development of this probabilistic model is outlined elsewhere (Melchers 1996).

Reliability based structural design for the serviceability limit state requires not only this probabilistic model for cracking but also criteria on which can be based decisions about cracking acceptability. Cracking acceptability criteria need to consider the specific uses of a structure and therefore its likely serviceability requirements.

The ultimate aim for the project is to use the probabilistic cracking model together with such cracking acceptability criteria to develop rational design criteria for serviceability design. This can then be used to verify and/or modify current Australian Standard code provisions for serviceability design of masonry in a limit states framework.

The scope also exists for the development of highly simplified numerical crack models for use by designers in designing and/or assessing masonry structures.

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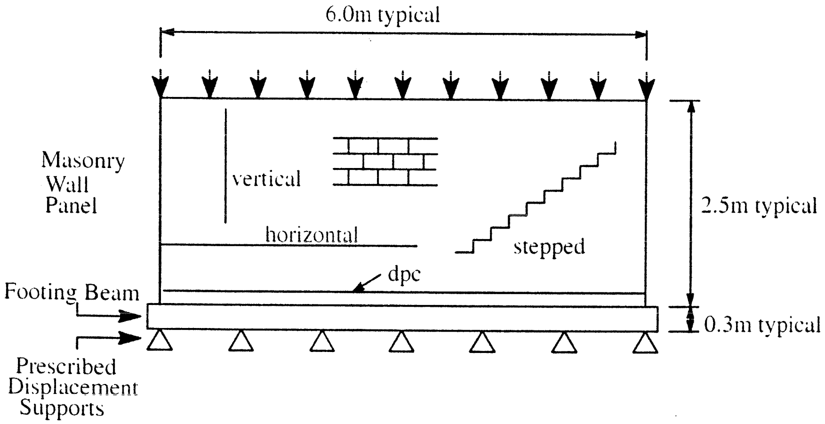
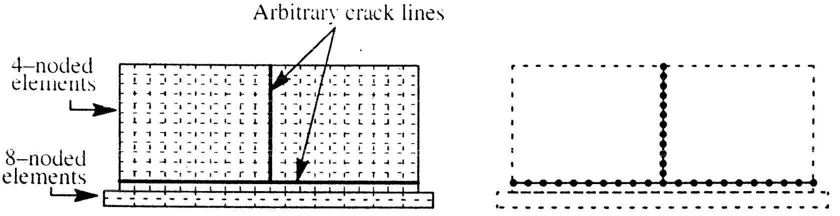
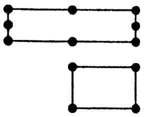


Figure 1. Components of the wall model



Finite element mesh prior to static condensation

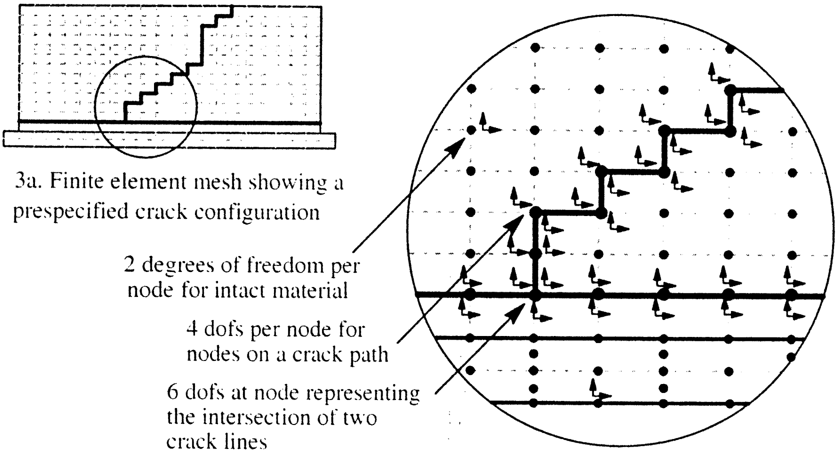
After static condensation all degrees of freedom have been removed except those along the crack interfaces



8–noded plane stress element used to model the reinforced concrete footing beam

4–noded plane stress element used to model the masonry

Figure 2. Use of static condensation



3a. Finite element mesh showing a prespecified crack configuration

3b. Enlargement of the region around the intersection of horizontal and stepped cracks

Figure 3. Modelling the masonry cracks

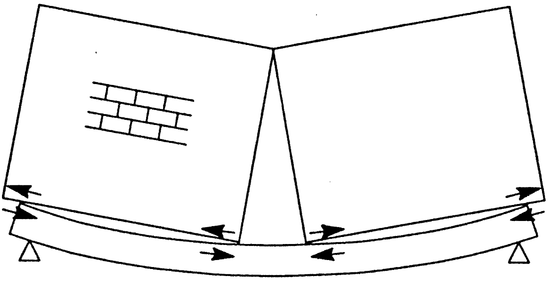


Figure 4. Relative sliding along the damp proof course for a dishing curvature and a central vertical crack

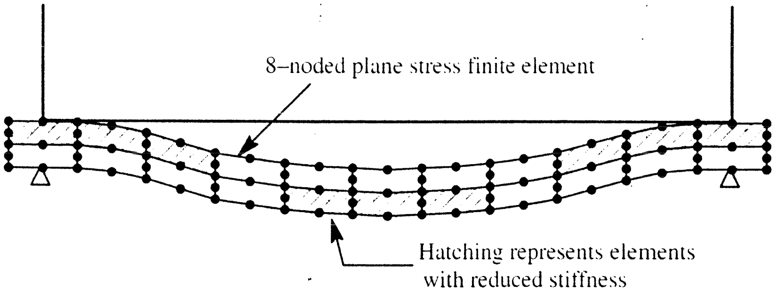


Figure 5. Finite element discretisation for the reinforced concrete footing beam

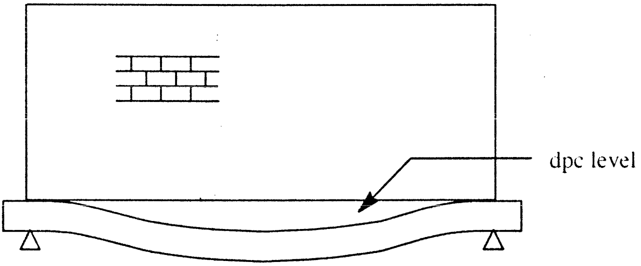


Figure 6. Separation along the damp proof course for a dishing ground curvature