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SEISMIC BEHAVIOUR OF AUSTRALIAN MASONRY VENEER

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ABSTRACT

The seismic behaviour of masonry veneer in Australia is largely unknown. A nonlinear finite element model simulating masonry veneer under both static and dynamic loads has been developed in order to determine whether current design procedures in Australia are adequate. Results of static analyses using the model are presented along with results from nonlinear dynamic time domain analyses. The important role of wall ties is emphasised.

INTRODUCTION

Australia has long been regarded as an earthquake free continent as it is not near any inter-continental plate boundary. Earthquakes have occurred in the past, but until recently few had been located close enough to populated areas to cause significant damage. The 1989 Newcastle Earthquake caused widespread damage to the city and surrounds (13 deaths and damage estimated between 1.1 and 1.5 billion dollars U.S.) and graphically illustrated that even moderate earthquakes can cause significant damage if buildings are not designed for seismic effects. Much of this damage was to structural and non-structural unreinforced masonry and emphasised possible inadequacies with current design and construction methods for masonry veneer, particularly related to the detailing of the structural elements and their connections [Page 1993]. With the publication of the new Earthquake Loading Code AS1170.4 [Standards Australia 1993], and its subsequent adoption by the Building Code of Australia in 1995, it is now mandatory to consider seismic effects for all structures including housing.

Unreinforced masonry veneer is widely used in Australia particularly for domestic construction. Since unreinforced masonry veneer is so widely used, there is an obvious need for research into its seismic behaviour to ascertain if current details and design procedures are adequate.

In the past in Australia, housing has been designed for wind load with no consideration of earthquake loading. Details that have been developed for wind effects are not necessarily suitable for earthquake due to the differing nature of the loads. with earthquake load more dependent on the mass of the structural elements. This therefore makes unreinforced masonry veneer with its high mass and brittle behaviour, particularly susceptible to damage from earthquake loads. A preliminary study of these aspects has been previously reported [Kautto & Page 1995]. Some other studies of the performance of housing under seismic loading have also been presented [Gad et al 1995], but the emphasis has been on the performance of the back-up frame rather than the veneer.

This paper presents an overview of current and future research at The University of Newcastle, Australia into the behaviour of masonry veneer under seismic loads, together with the results of some preliminary analyses. In this research particular emphasis has been placed on the analytical modelling of masonry veneer in an effort to determine its performance under both static and seismic or dynamic loads.

AUSTRALIAN SEISMICITY AND EARTHQUAKE DESIGN REQUIREMENTS

Because of its location on a tectonic plate, Australia is subjected to intraplate rather than interplate earthquakes. The earthquakes are generally smaller in magnitude and less frequent than those which occur in interplate regions. They are also more randomly distributed. Earthquakes of magnitude 5 are experienced on average every two years, and larger earthquakes have been recorded [Hutchison et al 1994]. Fortunately damage from these and other similar events was limited due to the remoteness of their locations. However, the Newcastle earthquake of 1989 demonstrated that even moderate earthquakes have the potential to cause major damage and loss of life. In this case other factors such as soft soils, poor design and detailing of structures, building deterioration, and lack of consideration of earthquake effects in design also played a major role.

Because of the relative lack of seismic activity, the common perception in Australia has been that the risk from earthquakes was low and seismic forces need not be considered in design. As the result of a general review (accelerated by the Newcastle earthquake), a new standard AS1170.4 was issued in 1993. The code provisions are generally consistent with the recommendations made by the United States Applied Technology Council [Applied Technology Council 1988]. The standard has been included in the Building Code of Australia and therefore it is now mandatory to consider seismic effects for all structures including housing. The impact of this on the design of masonry housing has yet to be established.

For use in limit states design codes, the ultimate limit state load corresponds to an earthquake event with a return period of 500 years [Hutchison et al 1994]. An equivalent static or dynamic analysis can be performed, depending on the design category, the structural configuration, and the building ductility. The requirements apply to all buildings and their components, including domestic structures.

The requirements for domestic structures are fairly nominal. They range from no design or detailing requirements for ductile structures in low risk areas to an equivalent static analysis and detailing for non-ductile full masonry structures located in high risk areas. However with this study both a static and full dynamic analyses have been performed in order to more realistically simulate the structural response of masonry housing to earthquakes, and to determine the validity of the equivalent static procedure specified in AS1170.4.

MASONRY VENEER CONSTRUCTION

Masonry veneer construction with either a flexible or stiff back-up is widely used for domestic construction in Australia. Masonry veneer with a flexible back-up consisting of a timber or steel framing system is commonly used in most areas of Australia. Masonry veneer with a stiff back-up (conventional cavity brick construction) forms a smaller percentage of new housing in some states, but is widely used in Western Australia.

Masonry veneer consists of an outer non-loadbearing leaf of masonry attached to an inner loadbearing masonry leaf or structural timber or steel back-up frame. The veneer provides an external weather barrier, whilst at the same time adding to the aesthetics of the structure. A cross section of typical Australian veneer with flexible back-up is shown in Fig. 1.

The structural back-up serves to laterally support the veneer (via the wall ties) and usually spans vertically from the footing to the ceiling/roof system which acts as a diaphragm. The back-up can be classed as either flexible or stiff, with a flexible back-up having a stiffness far lower than the veneer it is supporting, and a stiff back-up having a stiffness comparable to the veneer. This paper concentrates on masonry veneer with flexible back-up, however the complete study also includes masonry veneer with stiff back-up.

Wall ties attach the otherwise free-standing veneer to the structural back-up and therefore play a crucial role in the adequate performance of the masonry veneer. The wall ties are formed from light gauge steel plate, wire or plastic and nailed or secured to the back-up frame and embedded in the mortar joints of the veneer. Fig. 2. shows two of the most common forms of wall ties for use with timber back-up, the side fixed tie and the face fixed tie. Unfortunately the wall ties are usually the most neglected component in such walls and are often installed incorrectly, thus directly affecting the performance of the assemblage.

Structural Behaviour of Masonry Housing

The structural behaviour of a domestic house subjected to lateral loading is extremely complex. This is mainly due to the high degree of redundancy in such structures and the lack of knowledge of the structural response of the components and their connections. The overall behaviour can be summarised in the following manner (see Fig. 3):

i. Out-of-plane loading on veneer walls is transmitted to the supporting back-up by the wall ties
ii. The back-up walls then span vertically between the foundation and the ceiling/roof diaphragm. In some cases, walls may also span horizontally between returns and/or cross walls.
iii. The ceiling or roof diaphragm then transmits the forces to the walls aligned parallel to the direction of loading. These walls (or appropriate bracing systems) then transfer the load to the foundation by in-plane action.

Observation of damage resulting from the Newcastle earthquake [Page 1993] has shown that the walls loaded out of plane are the most prone to damage from dynamic loads, with satisfactory performance of the wall ties being crucial to the overall behaviour of the wall.

From preliminary studies, a masonry veneer wall loaded out-of-plane was deemed to be the most critical component in a domestic house. Research has therefore concentrated on this component with a finite element model being developed to simulate unreinforced masonry veneer loaded out-of-plane.

ANALYTICAL MODEL OF VENEER BEHAVIOUR

A finite element model was used to simulate the behaviour of the masonry veneer subjected to lateral (face) loading. Both static and dynamic analyses were performed so as to allow comparison of the results from each. The properties of the model are outlined below (see Fig. 4).

Masonry

The masonry veneer and rigid back-up walls (where appropriate) were modelled using orthotropic elastic plate bending elements (although in most cases isotropic behaviour was assumed). Typical elastic properties were assumed for the masonry (Ex=8000MPa, Ey=8000Mpa, Poisson's Ratio = 0.2). The mesh geometry was chosen to suit the layout of the wall ties which are typically located at 600mm centres [Draft AS3700- 1998] in the vertical direction and in line with each row of studs. A more refined mesh could have been accommodated but was deemed unnecessary for the problem. Provision for the insertion of both horizontal and vertical cracks in the masonry was also included in the program by de-coupling the appropriate plate bending elements when bending moments exceeded values corresponding to the flexural strength of the masonry in the appropriate direction. Inclined cracks could also be incorporated as appropriate by modifying the relevant plate bending element stiffness matrix. For static analysis cracks were inserted into the model manually. For dynamic analysis cracking of the masonry was automated, although in the study reported here, cracking of the masonry was suppressed.

Flexible Back-up

Flexible back-up systems were modelled as simple beam elements. Since only the nodal translations were required, to reduce the total number of degrees of freedom at each node, the beam rotations were eliminated by static condensation. The stiffness properties were determined from typical timber stud wall systems using an elastic modulus of 6.9 GPa (typical for F5 Radiata Pine). The stiffness of steel stud wall systems was similar to that of timber.

Cyclic Behaviour of Wall Ties

In the preliminary static and dynamic analyses wall ties were modelled as simple linear springs. This simple linear model was deemed satisfactory for static analysis, however for dynamic analysis a nonlinear model was required [Kautto et al 1997]. Cyclic testing of typical Australian wall ties was carried out in order to determine their hysteretic behaviour. Fig. 5a shows a hysteresis loop for a commonly used face-fixed tie (see Fig. 2b). This tie is attached to the front face of the timber stud via a clout (short nail) before the wall is laid, with the other end of the tie being embedded in the appropriate mortar joint as the wall is constructed. This nail is crucial as the tests revealed that under cyclic loading the nail gradually pulls out of the timber under the tension cycle. Hence the degradation of the tie occurs on the tension side of the loop, whilst under compression the tie essentially behaves as a linear elastic spring. Fig. 5b shows the idealised hysteresis loop adopted for a face fixed tie in the finite element model. Nonlinear models for other tie types such as the side fixed tie are also being developed.

Supports

The top of the back-up frame in veneer construction is usually supported by the roof/ceiling system (see Fig. 1) which acts as a diaphragm and spans horizontally between the side walls. Since the diaphragm may have some flexibility, the top support for the back-up was modelled using a linear spring to allow this effect to be simulated. It should be noted that the ceiling diaphragm is likely to behave in a nonlinear manner, although this has not yet been incorporated into the model. Due to the lack of fixity at the base of the veneer and its back-up frame, the relevant degrees of freedom for these support points were maintained in the global stiffness matrix so that if a rigid support was required, a large spring stiffness could be inserted. This strategy was adopted in order to keep the boundary conditions as general as possible.

In the analyses reported in this paper, the veneer and the back-up were assumed to span in the vertical direction only with no two-way plate action. This is the most critical orientation with regard to the veneer and the structural back-up. In modelling this behaviour, a representative vertically spanning strip encompassing one stud and the corresponding masonry and wall ties was therefore used. The typical arrangement is shown in Fig. 4.

It is common practice for both wind and seismic analysis to simulate these actions by applying equivalent static forces. Both equivalent static and dynamic analyses were performed for the vertically spanning veneer systems subjected to lateral load effects. This allowed direct comparison of the results.

STATIC ANALYSIS

The wall was assumed to behave in a linear elastic manner under static loads. The loads were applied as either pressures or suctions to both the veneer and back-up. Detailed results for these analyses have been previously reported [Page et al 1996]. Results for a typical one-way analysis indicated that the topmost tie was the most heavily loaded if the veneer remained uncracked. If cracking was allowed to occur at approximately mid-height (where masonry stresses were greatest) the tie force distribution changed (see Fig. 6). The ties closest to the crack now became more heavily loaded along with the topmost tie. The results from this simple static analysis showed that it is erroneous to calculate the forces in the wall ties based on a local tributary area as is commonly done in practice.

New design procedures have been developed based on this more representative distribution of tie forces and are currently being incorporated into the latest revision of the Australian Masonry Standard [Draft AS3700- 1998]. Included are;

i For masonry veneer with flexible back-up, the maximum tie force is calculated using a tributary area of 40% of the wall height multiplied by the horizontal tie spacing.

ii For a masonry veneer with stiff back-up, a tributary area based on 1.3 times the nominal tributary area for a wall tie is used in calculating the maximum tie force.

The above design procedures agree well with those proposed in the Canadian Masonry Design for Buildings [s304.1-1994 Canadian Standards Association]. It should also be noted the above design procedures refer to wind loads, however they are equally valid for equivalent static earthquake loads once the loading distribution has been calculated.

DYNAMIC ANALYSIS

The dynamic analysis was performed in the time domain (only a small time-history was required), and to keep the model as simple as possible a lumped-mass system was utilised (see Fig. 7a.). This allowed static condensation of the global stiffness matrix to remove the rotational degrees of freedom and therefore reduce the overall size of the problem [Clough & Penzien 1975]. The seismic effects were applied as ground accelerations obtained from suitable earthquake traces. The input for the dynamic analysis was in the form of an earthquake trace obtained from the 1982 Miramichi earthquake, recorded at Loggie Lodge in Canada (see Fig. 7b.). This input was chosen as it was considered to reasonably represent the form of earthquake that occurs in Australia [Melchers & Morison 1995], although what constitutes a "typical" Australian earthquake is still open to debate. This earthquake has a very short time-history and is quite similar to that produced by an explosion. A slightly longer less severe input may be more appropriate, and numerous results from various input traces are currently being obtained. Two different analyses were carried out, the first one assumed the wall ties behaved in a simple linear fashion, whilst the second assumed they behaved in a nonlinear fashion as prescribed by Fig. 5b.

In both cases, for linear and nonlinear wall tie behaviour, the direct integration solution technique was adopted. The Newmark integration scheme with constant time stepping was utilised [Bathe & Wilson 1976]. Rayleigh damping was assumed in the calculation of the damping matrix based on the first two mode shapes and their respective percentages of critical damping (5%). The results were presented as time histories of displacements, tie forces, and back-up and masonry bending moments.

RESULTS OF DYNAMIC ANALYSIS

Tie Forces

In the dynamic analysis one-way bending was considered most critical in terms of wall performance. Fig. 8 shows the variation of force in the topmost tie with time for a strip of wall 1.8m wide by 2.4m high with a flexible back-up (the nonlinear wall tie model was only relevant to flexible back-up). It can be seen that the masonry veneer reacts almost instantaneously to the dynamic input which is of a similar frequency to the fundamental frequency of the veneer. It should also be noted in Fig. 8a that if the tie is assumed to behave as a simple linear spring the forces cycle rapidly from tension to compression and are initially quite large. In fact when compared to the static results (Fig. 6) the forces are initially much larger for the dynamic loads (approximately 50% larger). If the ties are assumed to behave in a nonlinear fashion as per Fig. 4b then the load/time history is quite different (Fig. 8b). The tie forces are much smaller in tension (limited by the pull-out capacity of the nail- timber assemblage) and much larger in compression. Degradation of the wall tie also occurs due to pull out of the nail from the timber, resulting in a zone of 'play' developing with time. Screwing the tie to the timber stud rather than using nails might alleviate this problem. Such a large difference between the linear and nonlinear tie models indicates that it is crucial to model the ties as nonlinear springs with realistic properties if the overall behaviour of the wall is to be correctly simulated. For this reason, a comprehensive series of cyclic tests on a range of tie assemblages is being performed.

Masonry Moments

Although cracking of the masonry was suppressed in this study, the results indicate that the masonry moments and therefore stresses were higher when the nonlinear tie model was utilised. This was the result of the higher compressive tie forces compared to the linear tie model. Indeed both cases the masonry veneer is likely to crack at mid height. This does not necessarily mean the wall will collapse, as the wall, although cracked, is likely to retain its integrity so long as the wall ties do not completely fail.

MODELLING OF COMPONENTS

The effect of the ceiling/roof diaphragm could be significant as it not only adds mass to the top of the back-up in a veneer wall but, the diaphragm itself could also behave in a nonlinear fashion. Additional mass at the top of the back-up could significantly alter the response of the wall. Inertial load would not only be induced by the masonry veneer itself but also by the ceiling diaphragm. This effect has been illustrated in full scale shaking table tests of a portion of house at The University of Melbourne [Gad et al 1995]. This, along with the nonlinear response of the ceiling diaphragm, is currently being investigated. A more complete comparison between the static and dynamic behaviour of an unreinforced masonry veneer wall will then be carried out, from which design procedures for earthquake loads will be developed.

SUMMARY & CONCLUSIONS

Australia is not traditionally regarded as a country in which earthquakes are a problem. However the Newcastle Earthquake highlighted the fact that earthquakes do need to be considered in design especially for unreinforced masonry which is widely used. The latest Earthquake loading code AS1170.4 also requires that all new structures in Australia be designed at least nominally for earthquakes. There is therefore the need for research into the behaviour of masonry structures under dynamic loading conditions. Of particular interest is unreinforced masonry veneer which forms a large part of domestic housing in Australia . A nonlinear elastic finite element model simulating masonry veneer under both static and dynamic loads was developed in order to determine its performance under such loads.

Dynamic analysis was in the time domain using both a linear and nonlinear behaviour of the wall ties. It was found that the response of the veneer wall system was critically dependent on the tie properties. Hence it is crucial to correctly model the wall ties as nonlinear springs with properties determined from realistic tests on tie assemblages. The effect of other components such as the ceiling diaphragm is also being investigated. Masonry stresses were found to be high enough to cause cracking. However if the wall ties do not completely fail, it is unlikely that the wall will collapse, again stressing the importance of wall ties in the overall behaviour of a masonry veneer wall under dynamic loading.

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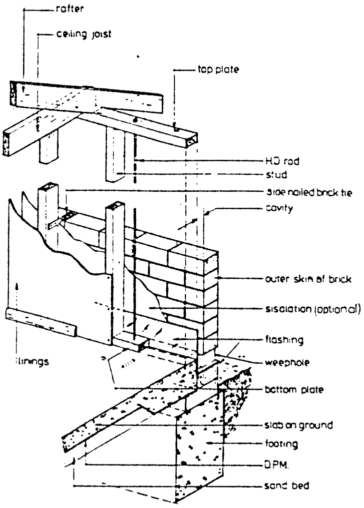
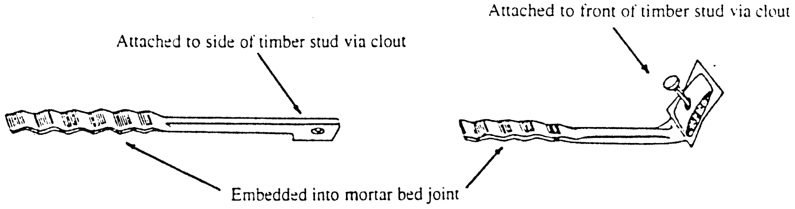


Figure 1. Typical Masonry Veneer Construction [ADCM 1993]



a) Side fixed

b) Face fixed

Figure 2. Typical Wall Ties for Timber Back-up [ADCM 1993]

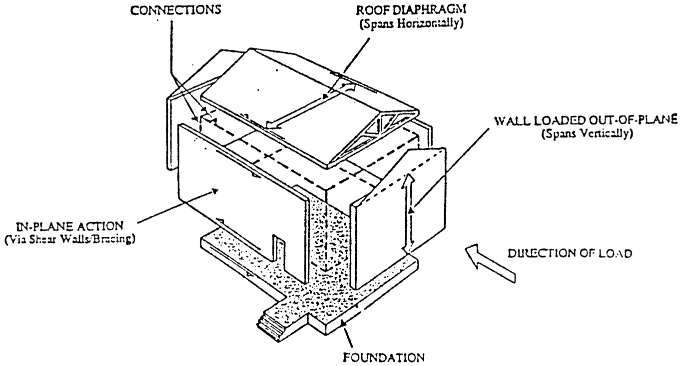


Figure 3. Structural Behaviour of House Subjected to Lateral Loads [Yanev 1974]

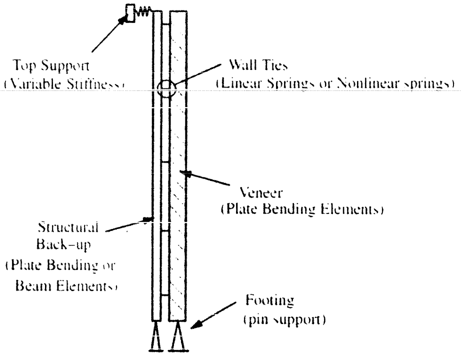
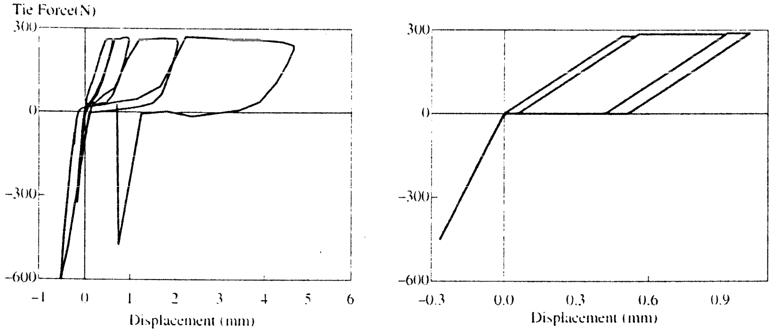


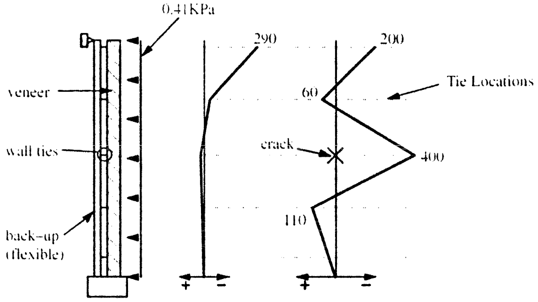
Figure 4. Finite Element Model



a) Experimenatl Results

b) Nonlinear Tie Model

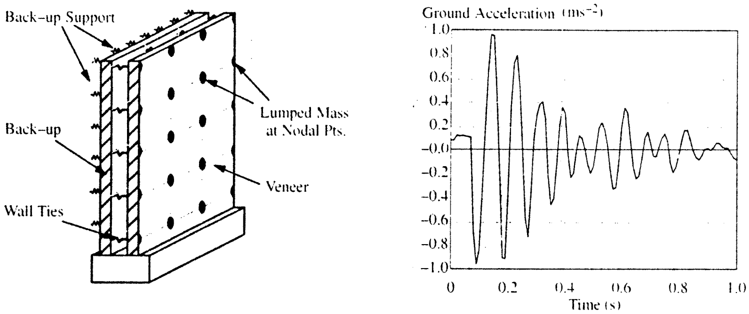
Figure 5. Cylcic Behaviour of Face Fixed Tie



a) Uncracked

b) Cracked at Mid-Ht.

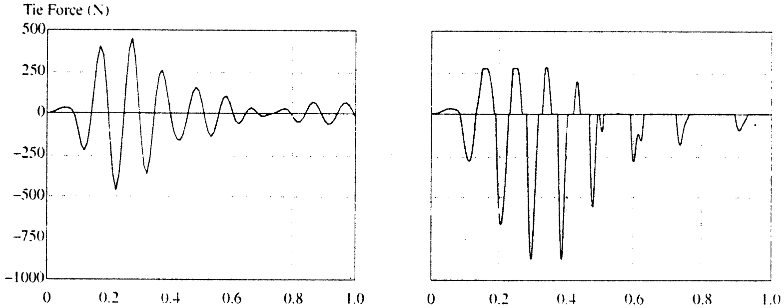
Figure 6. Tie forces(N) under static load (p=0.41KPa) with flexible back-up



a) Lumped–mass system

b) Input earthquake trace

Figure 7. Dynamic Model



a) Linear Ties

b) Nonlinear Ties

Figure 8. Dynamic Results: Top Tie Force versus Time