Evaluation of Earthquake Risk Buildings with Masonry Infill Panels

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ABSTRACT:
Structural frame buildings with masonry infill panels make up a significant portion of the buildings constructed in New Zealand prior to the development of comprehensive seismic design standards. These structures may be regarded as 'Earthquake Risk' buildings, therefore an evaluation of their level of seismic performance may be required. There is however limited guidance in New Zealand on the seismic evaluation of infilled frame buildings.

This paper reports on the evaluation of a reinforced concrete frame building with brick infill panels on the exterior walls. The evaluation uses an equivalent strut approach for modelling the infill panels. Reference is made to international studies and guidelines, including FEMA-273 and Eurocode 8.

1 INTRODUCTION

Reinforced concrete frame buildings with masonry infill panels are generally regarded as 'Earthquake Risk' buildings. As such there is a growing need to carry out an evaluation of their level of seismic performance. In recent years there has been a good deal of research in the area of infill-masonry buildings. Guidelines have also been published recently for the seismic evaluation of these structures. A literature review indicated that the current 'state-of-the-art' in practice is to account for infill panels by including an equivalent strut to represent the stiffness of the panels. There are however a range of proposed modelling methods. A selection of the reviewed procedures are presented in the following section. The focus of the review was on buildings with full height infills with regular distribution over the height of the structure. The cases of buildings with partial height infills or open ground floors, where there is a high potential for soft storey mechanisms, are relatively well understood. Using the knowledge gained form the literature review an evaluation of an existing building in Auckland was performed. A summary of this evaluation is presented.

2 ELAVUATION METHODS

2.1 *New Zealand Procedures*

The NZNSEE draft Earthquake Risk Building (ERB) Document "The assessment and improvement of the structural performance of earthquake risk buildings" [NZNSEE ERB 1996] may be viewed as the standard New Zealand guideline for the evaluation of earthquake risk buildings. Section 6.3 of the ERB Document addresses moment resisting frame elements with masonry infill panels. The main thrust of the ERB Document is that if the infill panels have a significant affect on the seismic response and are expected to suffer damage without collapse, then it is likely that a soft storey mechanism will form. Diagonal failure modes can be expected to degenerate into a sliding shear failure mode, leading to hinging of columns between floors.

This is illustrated in figure 1. The ERB document states that for exterior columns, hinges form top and bottom and at mid-height, while for interior columns, hinges form close to quarter points. In both cases the effective height of the columns is h/2. Ductility capacity and demand may be assessed as for a column sway mechanism with the reduced column height. Methods for accounting for the infill panel in the building analysis for this scenario are not discussed.

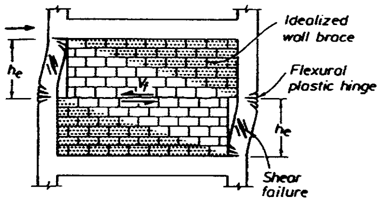
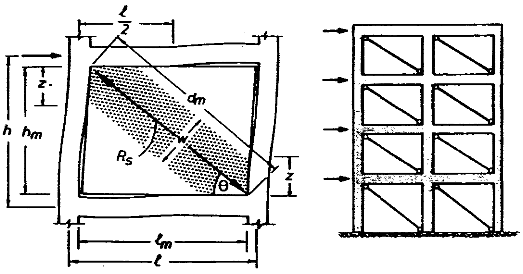


Figure 1 Knee-braced frame model for sliding shear failure of Masonry infill (Pauley & Priestly 1992)

An expansion of the ERB document provisions may be found in “Seismic design of reinforced concrete and masonry buildings” [Pauley & Priestly 1992], a widely used reference text. This provides guidelines on modelling panel stiffness. The recommendation is that Masonry infill panels be modelled as equivalent concentric diagonal struts, based on an effective width of 0.25 times the diagonal length (a conservative estimate). This is illustrated in figure 2. It is recommended that where sliding or diagonal compression failure may occur, frames should be designed elastically due to the concentration of deformation in the first storey.



(a) Deformation under shear load

(b) Equivalent braced frame for 2 bay, 4 story infilled wall

Figure 2 Equivalent bracing action of Masonry infill (Pauley & Priestly 1992)

A recent NZSEE Bulletin article, “Analytical modelling of infilled frame structures” [Crisafulli et al 2000] provides a review of macro (equivalent strut) and micro models, and reports on some comparative studies between equivalent strut models and FEM (‘solid’ element) models. Amongt the conclusions were that single strut models can provide an adequate estimation of stiffness of the infilled frame, however multi-strut models are required to obtain realistic values of the bending moments and shear forces in the frames. Strut models included in the study are presented in Figure 3.

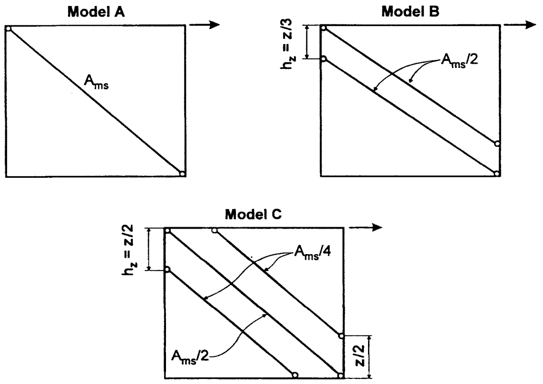


Figure 3 Different strut models considered in the study (Crisafulli et al 2000)

2.2 *United States Procedures*

2.2.1 *FEMA-273*

The NEHRP Guidelines for the seismic rehabilitation of buildings [FEMA-273 1997] is an extensive document for use in the design and analysis of seismic rehabilitation projects. FEMA-273 includes design criteria, analysis methods, and material specific evaluation procedures. Section 7.5 addresses masonry infills systems.

FEMA-273 specifies that masonry infill panels shall be represented as equivalent diagonal struts. The struts may be placed concentrically across the diagonals, or eccentrically to directly evaluate the infill effects on the columns. This is illustrated in figure 4.

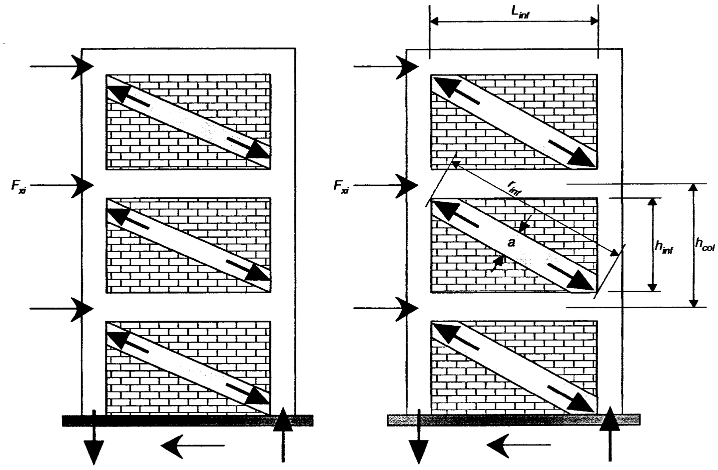


Figure 4 Compression Strut Analogy – Eccentric and Concentric Struts (FEMA-273 1997)

The shear behaviour of masonry infill panels is considered as a deformation controlled action. FEMA-273 provides deformation acceptance criteria. The linear procedure involves comparing the design elastic shear force in a panel (QUD) with the factored expected shear strength of the panel (QCE), m□QCE ≥ QUD; where m is the element demand modifier to account for the expected ductility of the deformation, and □ is the knowledge factor. Typically the knowledge factor would be taken as 0.75, while the demand modifier for the life safety performance level (comparable to ultimate limit state design earthquake) varies from 3 to 8 depending on geometry and the relative strengths of the infill panels and frames. Panel strength is given by the shear sliding (bed-joint) strength with no enhancement for axial stress.

FEMA-273 specifies strength requirements for column members adjacent to infill panels. Column actions may be evaluated through the application of the horizontal component of the expected infill strut force at a specified distance from the columns ends. This is illustrated in figure 5. Shear force demand may however be limited by the moment capacities of the column of reduced length, l_{eff}.

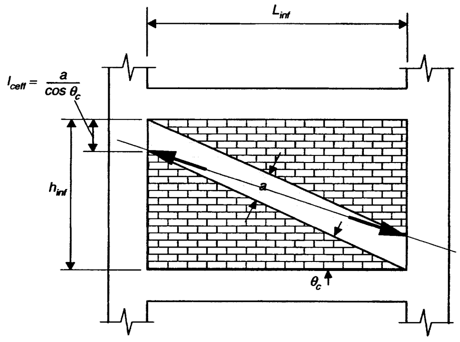
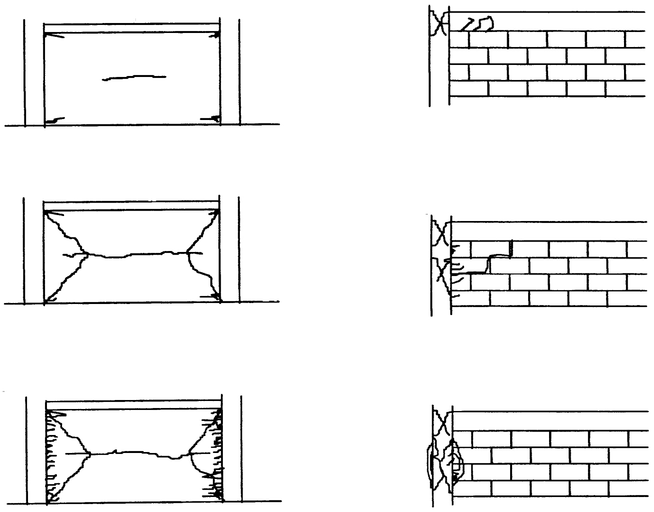


Figure 5 Estimating forces applied to columns (FEMA-273 1997)

2.2.2 *FEMA-306,307*

FEMA publications on the "Evaluation of Earthquake damaged concrete and masonry wall buildings" [FEMA-306 1999, FEMA-307 1999] were developed to provide practical criteria and guidance. FEMA-306 recommends that infill panels may be modelled as equivalent struts in accordance with FEMA-273. Deformation capacity guidelines are given in the form of interstorey drift ratios. These vary from 1.5% for brick masonry to 2.5% for ungrouted concrete block masonry. As diagonal cracking is initiated at drifts of 0.25% and essentially complete by about 0.5% this represents a high level of ductility in the panel system.



Bed joint sliding

Column shear failure

Figure 6 Component Damage (FEMA-306 1999)

For the concrete-frame components, shear demand is evaluated for short columns as specified in FEMA-273. FEMA-306 also provides an infilled frame component damage guide. Two topical behaviour modes are illustrated in figure 6. The bed joint sliding mode involves diagonal cracks from the corners intersecting horizontal cracks in centre of the panel and is associated with large displacements as may be found with flexible steel frame. The reinforced concrete column shear failure mode typically occurs near the frame joints and is associated with stiff and/or strong infills.

2.3 *European Procedures*

2.3.1 *Eurocode 8*

Eurocode 8 (EC8) [DD ENV 1998-1 1996] contains provisions for the design of infilled RC frames (section 2.9). EC8 specifies that the period of the structure used to evaluate seismic base shear shall be the average of that for the bare frame and the elastic infilled frame. Frame member actions are then determined by modelling the frame without the struts. Irregular infill arrangement in plan and elevation are addressed.

2.3.2 *European Studies*

Recently a number of papers have been published reporting on studies of the behaviour, design, and analysis of infilled frames. Those making reference to EC8 generally conclude that Eurocode 8 is overly conservative by not modelling the infill panels when evaluating member actions.

Fardis [Fardis 2000] carried out a European Commission sponsored study on the design of infilled RC structures. Conclusions of the study included;

- For Infills with regular distribution, the overall effect of infills is found to be beneficial and designing the structure as bare suffices (their main effect is on energy dissipation and not response period), therefore the provisions of EC8 are too conservative.
- The only adverse effect for regular structures is a tendency for drift concentration in the bottom storey, however deformations in that storey are well below that required for a soft storey mechanism.
- For structures with an open bottom storey the concentration of drift and structural damage of the columns become significant. Alternatives to the EC8 provisions are proposed.
- In structures with infilled panels along two adjacent sides, the response can be quasi-rotational. As a result the far corner columns may need to be designed for the simultaneous peaks for the two directional components. In all other respects the RC frame may be designed as bare.

Kappo and Ellul [Kappos & Ellul 2000] carried out a study evaluating the effect of applying EC8 to RC buildings with infill panels. The study concludes that EC8 is over conservative by disregarding the contribution to strength of the infills. It is proposed that design of frames be based on models which include infill elements using two different stiffness assumptions. Base shear should be calculated assuming the secant stiffness at peak load for the infill panels. Member actions should then be found assuming a lower stiffness of infills (approx. one third).

Combescure and Pegon [Combescure & Pegon 2000] carried out numerical studies and a testing programme on infilled frame structures. Both micro (panel element) and macro (strut element) models were considered. The modelling showed the validity of the diagonal strut model and highlighted the importance of identifying appropriate strut properties. The study found that an effective strut width of approximately 25% of the diagonal length was appropriate for the cracked stiffness and stiffness at maximum strength. Though a concentric strut was used, micro-modelling indicated a concentration of shear at the end of the columns, indicating that an eccentric strut model would be required for the detailed evaluation of member actions.

Bruno et al [Bruno et al 2000] carried out a study on the seismic performance of pre-code RC buildings, including the effects of infill panels. Masonry infills were modelled using concentric equivalent struts. The study indicated that the presence of continuous infill panels significantly enhances the performance of the pre-code buildings.

Murty and Jain [Murty & Jain 2000] carried out experimental testing to study the influence of masonry infills on seismic performance of RC frame buildings. The study found the influence of masonry infills to be beneficial. Infill panels increase strength, stiffness, overall ductility and energy dissipation of the building. Further, they dramatically decrease the deformation and ductility demand on RC frame members. These buildings therefore perform well in moderate earthquakes. Detrimental effects of infills, such as short column effect, soft-storey effect, and torsion, are however a concern.

2.4 *Discussion of Evaluation Methods*

Standard New Zealand evaluation methods essentially involve designing frame members for the full seismic load, with ductility based on a first floor soft storey with a short column of half the panel height (shear slidding mechanism). This can lead to the conception that infill masonry panels will generally have a detrimental influence on the behaviour of RC buildings. However the review of studies and guidelines from the USA and Europe indicate that infill panels, where present in a regular arrangement, do in fact have a significant beneficial influence on the behaviour of RC buildings. There is a possible adverse effect for regular structures in a tendency for drift concentration in the bottom storey, however it is suggested that deformations in that storey are generally below that required for a soft storey mechanism. Studies also indicate that column damage typically occurs in the end regions of the members, due to the concentrated load applied by panel eccentric strut action, rather than the shear slidding mechanism.

The majority of reference sources model infill panels using concentric struts. However there appears to be some inconsistency in using a concentric strut model to determine actions on frame columns when testing and micro modelling indicate that a critical behaviour mode is column shear failure due to the eccentricity of the panel loading. The use of a concentric strut model alone does not accurately model the shear and curvature demand on frame members for ductile behaviour. FEMA procedures recognise the column shear mechanism, specifying that column shear may be evaluated by applying the expected panel forces eccentrically from the joint. However this would tend to be overly conservative in that it would not recognise the distribution of load between frame action and strut action. FEMA also appears to permit eccentric rather than concentric strut models to evaluate column action explicitly. Eccentric strut models have been used in other studies (see Crisafulli et al 2000) and recent New Zealand research indicates that they are required to obtain realistic values of the member actions in the frames. It appears that multi-strut models may be the best solution for infill frame evaluation. However there may need to be further research into the use of these models when panel damage occurs, so as to provide an adequate margin of safety against a column shear mechanism.

3 PRACTICAL APPLICATION

Compusoft Engineering have performed a Seismic Evaluation of an existing 5 storey building in Auckland as part of a refurbishment program. A summary of the study is presented below.

3.1 *Building Description*

The principal building structure consists of reinforced concrete internal and external frames supporting reinforced concrete floor slabs. Double skin brick infill panels are provided on the two adjacent exterior walls which face neighbouring buildings. The infill panels were typically full height and uniformly distributed.

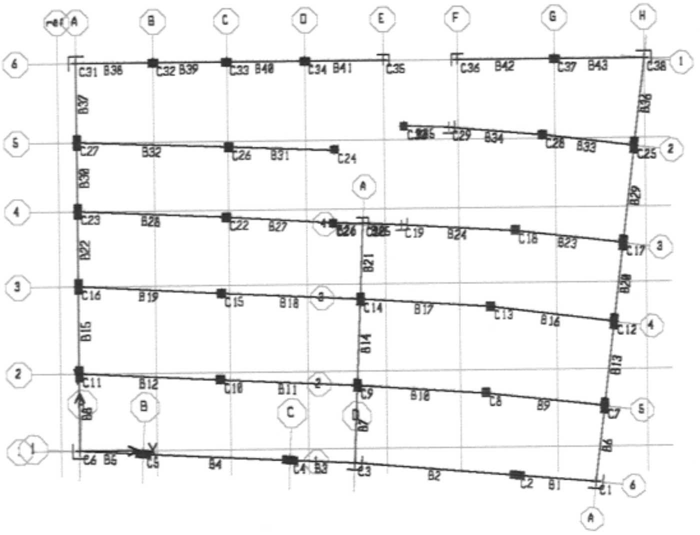


Figure 7 Building Layout

3.2 *Evaluation Procedure*

The seismic performance of the building was assessed following the NZSEE guidelines, with reference to the FEMA-273 guidelines when assessing the affects of the infill masonry panels.

Panels were modelled as single struts eccentric along the columns, typically at quarter points. Where isolated openings occured in upper stories, the upper ends of the struts were lower to mid-height of the columns. The eccentric strut models represent the most severe case for column flexure and shear. The effective properties of the struts were evaluated following FEMA-273. The FEMA-273 method typically gives an equivalent strut stiffness at the lower end of the reviewed studies, however a sensitivity analysis with the stiffness of the struts doubled only resulted in a 5 to 10% decrease in vibration period of the building, therefore the modelling would appear satisfactory. It should be noted that due the presence of internal seismic frames, the affect of the infill panels of the vibration periods was lower than typical.

3.3 *Seismic Analysis:*

The building was analysed using ETABS V7 [ETABS V7 2000], a specialist program for the three dimensional analysis and design of building systems. The building model consisted of the reinforced concrete frame structure and infill struts, with rigid diaphragms at each floor level.

Linear elastic analyses of the building were carried out using the equivalent static method. This method was appropriate as the building is vertically regular, and modal analyses show that despite the presence of infill panels, the building could be classed as horizontally regular. As discussed above the affect of the infill panels on building modes is reduced by the presence of internal frames.

Two building models were used, one with seismic loads applied in the positive directions of the defined horizontal axes, and one with seismic loads applied in the negative directions of the defined horizontal axes. The two separate models were used so to accommodate the infill panel compression struts. For each model three seismic load cases in each of the principal directions were considered to model the range of mass eccentricities specified by NZS4203.

Seismic design actions were evaluated as specified by NZS4203, with a risk factor of 0.5 to account for the lower level of earthquake loading for an existing structure (as specified by the local authority).

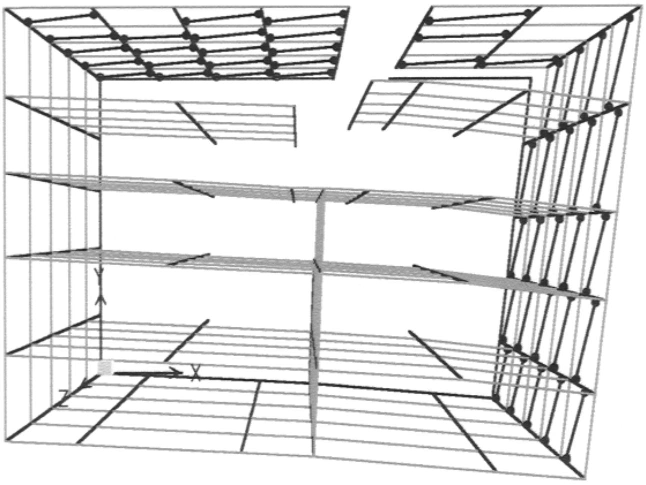


Figure 8 Building model (3D Plan)

3.4 *Seismic Evaluation*

3.4.1 *Frame Member Evaluation:*

Comparisons were made between the frame member capacities and the calculated frame member actions for the design loading. Frame member flexural capacities were evaluated to NZS 3101 using the strength reduction factors as specified for new structures. Frame member shear strengths were evaluated following the provisions of the NZSEE guidelines (6.2.2) for curvature ductility demand of up to 3. Shear strength evaluations conservatively discounted the beneficial effects of the nominal transverse steel provided, or for the case of columns, the beneficial effects of axial loads. The structural ductility factor was selected following the provisions of the NZSEE guidelines. Evaluations indicated that a beam side sway mechanism was likely for y-dirn action, therefore a ductility factor of 2 was selected. For x-dirn action, checks indicated that beams may respond elastically, therefore to protect against a column side sway mechanism, a ductility factor of 1.25 was used for column capacity checks for this loading.

A check of beam members showed that the beams would typically carry the design load elastically for the x-dirn earthquake. For the y-dirn earthquake the beams had sufficient capacity for a structural ductility factor of approximately 2.

Column capacity checks were carried out by the ETABS design module. Column capacity ratios were less than 1 for all columns with one exception, C21 at storey 2. C21 is a small column in the core area. There is a 150 concrete wall in this area (not modelled) therefore the 'overloading' of this column would be inconsequential. Typically the capacity ratio for the building columns were significantly less than 1. Column shear capacity exceeded demand for all columns. The maximum demand/capacity ratio was 0.7, indicating that the columns would essentially carry the design load elastically.

3.4.2 *Evaluation of Infill Walls*

Infill panel walls were assessed following the FEMA-273 deformation acceptance criteria. The ratio of elastic shear force in a panel to the expected shear strength was typically in the range of 1 to 2, indicating that moderate damage would be likely. The FEMA-273 guidelines specified a limiting ratio of approximately 4, therefore the infill panels comply with the criteria.

4 **CONCLUSIONS**

A review of international research and guidelines indicate that infill panels, where present in a regular arrangement, have a significant beneficial influence on the behaviour of RC buildings. This contrasts with New Zealand guidelines which can give an impression that infill masonry panels have a detrimental influence on the behaviour of buildings due to soft storey effects. The reviewed sources indicate that due to stiffness, strength, and damping effects of infill panels, deformations are below that required for a soft storey mechanism.

The current 'state-of-the-art' method in practice to account for infill panels is to model an equivalent strut to represent the stiffness of the panels. A variety of strut models have been developed, however each can be seen to have some shortcomings. The most realistic model appears to be some form of multi-strut representation, however there may need to be further research into the use of these models when panel damage occurs, so as to provide an adequate margin of safety against a column shear mechanism. For the interim, an eccentric strut model would seen to be the most appropriate.

A seismic evaluation of an existing building was carried out employing ETABS analyses with an eccentric strut infill model. The seismic performance of the building was assessed following the NZSEE and FEMA-273 guidelines. The evaluation showed the performance of the building to be satisfactory for the design earthquake.

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