

A Review of the Seismic Behaviour of RC Frames with Masonry Infill

Alireza Mohyeddin-Kermani¹, Helen M Goldsworthy² and Emad Gad³

1. PhD student, Dept of Civil and Environmental Engineering, The University of Melbourne, Parkville, VIC 3010, Australia. Email: amk@civenv.unimelb.edu.au
2. Senior Lecturer, Dept of Civil and Environmental Engineering, The University of Melbourne, Parkville, VIC 3010, Australia. Email : h.goldsworthy@civenv.unimelb.edu.au
3. Senior Lecturer, Dept of Civil and Environmental Engineering, The University of Melbourne and Swinburne University of Technology, Victoria, Australia. Email: e.gad@civenv.unimelb.edu.au

Exterior masonry walls and/or interior partitions built as an infill between a reinforced concrete frame's beams and columns are usually considered to be non-structural elements in design. The interaction between the frame and infill is often ignored. However, the actual behaviour of such structures observed during past earthquakes shows that their response is often wrongly predicted during the design stage. Real interaction between the infill panel and frame results in premature failure of the frame in some cases, and in improved performance in others. With the aim of better understanding the interaction between the primary structure and infill panels, this paper reviews research performed on the structural behaviour of such buildings under earthquakes. In addition, the predictions of FE models developed here will be compared with the results of some laboratory tests that were previously conducted at the University of Melbourne on masonry specimens. The modelling techniques developed in this work will be useful in constructing future larger FE models to evaluate the real performance at the key displacement limit states of infill-frames when subjected simultaneously to seismic in-plane and out-of-plane loads.

Introduction

Infill-frames have been used in many parts of the world over a long time. In these structures, exterior masonry walls and/or interior partitions, usually regarded as non-structural architectural elements, are built as an infill between the frame members. However, the usual practice in the structural design of infill-frames is to ignore the structural interaction between the frame and infill. This implies that the infill has no influence on the structural behaviour of the building except for its mass. This would be appropriate if the frame and infill panel were separated by providing a sufficient gap between them. However, gaps are not usually specified and the actual behaviour of infill-frames observed during past earthquakes shows that their response is sometimes wrongly predicted. Infill-frames have often demonstrated good earthquake-resistant behaviour, at least for serviceability level earthquakes in which the masonry infill can provide enhanced stiffness and strength. It is expected that this structural system will continue to be used in many countries because the masonry infill panels are often cost-effective and suitable for temperature and sound insulation purposes. Hence, further investigation of the actual behaviour of these frames is warranted, with a goal towards developing a displacement-based approach to their design.

Masonry panels, which contribute a large proportion of the mass of the infill-frame, normally consist of anisotropic materials with a wide range of strength, deformation and energy dissipation properties. Unlike other conventional materials such as concrete and steel which have, to some extent, standard properties regardless of the region (country) in which they are produced, masonry materials vary significantly from one country to another based on the local constituent materials (the bricks and the mortar) and workmanship. Different local materials are used to produce masonry units with different shapes; they might be solid or hollow units with different hole-sizes and hole-arrangements.

The structural behaviour of an infill-frame can be divided into two parts, in-plane and out-of-plane. The simultaneous effect of in-plane and out-of-plane loading has usually been ignored in the research conducted to date, although in actual earthquakes this effect will usually be present. This paper reviews previous research on the behaviour of infill-frames and outlines the research which is currently being conducted at The University of Melbourne.

In-plane behaviour of infill-frames

The masonry infill changes the mass, damping, stiffness and strength properties of the whole integrated structure. Some design codes acknowledge the difference between a bare frame and an infill-frame, however these provide recommendations mainly on the global behaviour of the structure such as the natural period or the reduction factor (Hemant et al. 2006). FEMA 306 (ATC 1998) identifies the difficulty in considering the behaviour of infill-frame to the following:

- a) Discontinuity of the infill resulting in a soft storey;
- b) Various cracking patterns and concentration of forces in structural components;
- c) Large variation in construction practice in different regions;
- d) Changes in materials over time: brick, stone, concrete masonry or concrete panels, reinforced/unreinforced masonry, grouted/un-grouted masonry, steel and concrete frames.

However it is important to realise that there can be some undesirable effects from the structural interaction between the infill and frame such as:

- a) Brittle shear failure (either in the frame members or the infill);
- b) Altering in-plane stiffness distribution in plan and elevation due to the provision of an irregular arrangement of infill panels leading to a soft-storey and/or a magnified torsional effect;
- c) Infill collapse which can cause loss of life and an increase in the number of casualties;
- d) Short-column effect, especially in the case of mid-height infill or infill with an opening (partial infill) leading to unexpected ductility demand in columns.

Based upon truss action (interaction) in an infill-frame system as shown in Figure 1, the idea of a strut model was first proposed by Polyakov (1956). In this method, the infill panel is replaced by one (or more) compressive diagonal(s) in the frame as shown in Figure 2. Opposite diagonals represent the infill panel as the direction of the lateral load changes. The concept of diagonal struts has been widely investigated by researchers (including Paulay and Priestley 1992, Liauw and Kwan 1984, Decanini and Fantin 1986, Dawe and Seah 1989, Durrani and Luo 1994, Stafford Smith 1962) and a variety of models have been proposed. It is important to note that the diagonal properties are heavily empirical. A comparison between different strut methods and equations regarding calculation of the width of the diagonals, relative stiffness and/or strength of the infill and the surrounding frame can be found in the previous research by Al-Chaar (1998), Crisafulli et al. (2000) and Mehrabi (1994). FEMA356 (2000) allows a single concentric strut to be used for global building analyses. In order to consider the local effects of the infill on the frame, e.g. shear and moment actions in beams and columns, the triple strut model and the single eccentric strut model are recommended by Crisafulli et al. (2000) and FEMA356 (2000) respectively.

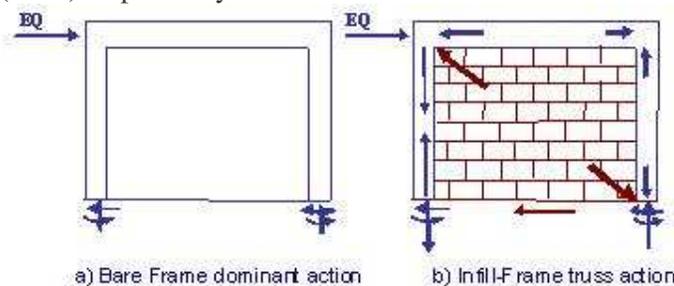


Figure 1: Comparison between the actions in a bare-frame and infill-frame.

The strut model has also been used in nonlinear analyses. Different hysteretic behaviour patterns proposed by various researchers are discussed in Crisafulli et al. (2000). Based on the strut analogy, a nonlinear four-node masonry panel element has been proposed by Crisafulli (1997) and incorporated in the software RUAUMOKO 2000. This is a 2-D compound element consisting of four diagonal struts (two in each direction) to model the diagonal stiffness of the infill confined by an RC frame, and a shear spring between the upper and lower parts of the diagonals to consider the shear capacity of the infill (bed-joint). A hysteretic model proposed by Crisafulli (1997) along with a bi-linear force-displacement model for the spring are considered. The FE formulation of this element can be found in Crisafulli and Carr (2007).

For solid infill panels in which the infill is the controlling structural element, un-cracked infill characteristics govern its behaviour at low levels of loading. Eventually, bed-joint

sliding or diagonal tension failure occur and the infill can be modelled by an equivalent strut model. The beam and column shear capacities should also be investigated. The final limiting condition would often be corner crushing of the masonry which requires the beam to be checked for shear and the column to be checked for shear and tension. Column tensile capacity is usually adequate for steel and reinforced concrete, but may be a limiting factor for lightly reinforced concrete columns.

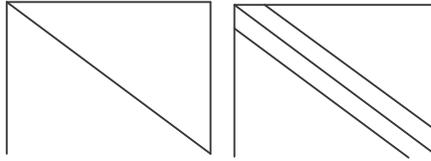


Figure 2: Strut models with different number of struts.

As reported by Crisafulli et al. (2000), the FE technique was first applied to analyse an infill-frame by Mallick and Severn (1967). Different research groups have attempted this type of modelling and a comparison between them can be found in Crisafulli et al. (2000), Mehrabi (1994), Mehrabi and Shing (1997) and Shing and Mehrabi (2002). One of the critical issues in modelling of masonry material arises from the characteristics of the interface between the masonry and the mortar, and that between the infill panel and frame. As shown in Figure 3, three different idealisations may be considered for analytical models of a masonry wall (Lourenco 1996):

- a) masonry as a homogeneous isotropic continuum;
- b) expanded units, mortar and mortar joints as lumped interface;
- c) masonry unit and mortar modelled separately with interface elements in between.

The first approach in modelling a masonry panel is to consider the masonry as a homogeneous material including the masonry units and the mortar together as a continuum (Figure 3a). The interfaces are actually the weakest link in a masonry assemblage and cannot be modelled by smeared crack patterns, since in this case some individual cracks may control the behaviour of the whole panel (Lourenco 1996; Shing and Mehrabi 2002).

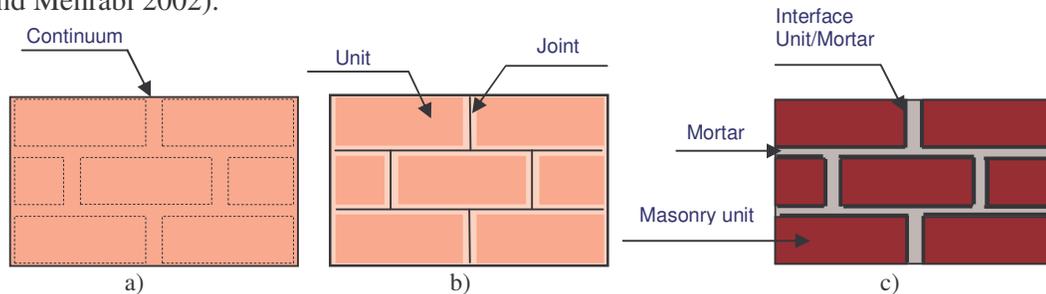


Figure 3: Different masonry modelling strategies recognised by Lourenco (1996).

The second method uses the lumped-interface strategy in which two sets of elements are developed. The first set of elements models the behaviour of the units and second one is to model the behaviour of the mortar and the interface between the mortar and the units (the joints as depicted in Figure 3b). An interface element representing the accumulative effects of shear dilatation, hardening of the interface under compression and normal contraction of the joint under shear force was developed by Mehrabi (1994). In the case of an infill-frame, another set of interface elements are required to model the behaviour of the interface between the frame and infill panel.

The most detailed model considers three different elements representing the units, mortar and the interface between them separately (Figure 3c). Such a detailed model can better represent the de-bonding, slippage and separation that occurs between the mortar and unit.

The analytical approaches mentioned above are used in the context of force-based methods mainly to find the final strength (capacity) of a structure. This has been investigated by different researchers and the formulations proposed are all based on different modes of failure observed during their specific experimental tests. A variety of equations have been proposed using limit-state analysis by considering appropriate/relative failure modes. A comparison between these equations can be found in Al-Chaar (1998), Mehrabi (1994) and Shing and Mehrabi (2002). However, these methods are based on the assumption that the infill will fail under pure in-plane loads, whereas under earthquake loads they may collapse as the result of out-of-plane loads before they reach to their ultimate in-plane capacity.

Out-of-plane behaviour of infill-frames

The out-of-plane behaviour of infill-frames has been investigated since the 1950s. As reported by Shing and Mehrabi (2002), many studies (Angel 1994, Mander et al. 1993; Bashandy et al. 1995; and Flanagan 1999) on out-of-plane behaviour of infill-frames indicate that infill panels restrained by frames can develop significant out-of-plane resistance as a result of arching effect. The out-of-plane strength of a masonry infill is mainly dependent on its slenderness. If an “x” pattern of cracks develops under both in-plane and out-of-plane loading, this implies that there may be some substantial deterioration in either in or out-of plane strength under the loading in the opposite direction (Angel 1994). It is shown by Angel (1994) that the out-of-plane strength deterioration may reach as much as 50% for infill panels with high slenderness ratio where they have already been cracked under lateral in-plane loading. Based on the results of tests conducted by (Angel, 1994), the following behaviour can be expected due to different values of slenderness ratio:

- a) Crushing along the edges for low h_m/t (where h_m and t are the height and thickness of the infill panel, respectively);
- b) Snap-through (small effect of arching) for high h_m/t i.e. approximately between 20 and 30 (this limit depends on the crushing strain of the masonry which usually varies between 0.002 and 0.005).

Regarding the out-of-plane behaviour of masonry (bare) walls, it has been shown that they exhibit substantial out-of-plane displacement capacity and hence more ductile behaviour than is conventionally accepted (Griffith et al. 2007). A comprehensive study on the damping of masonry walls in out-of-plane (on-way) flexure can also be found in Lam et al. (2003).

The displacement-based method of design has been used by Magenes et al. (1997) to study the in-plane behaviour of masonry walls. The displacement-based method has also been used for the analysis/assessment of out-of-plane behaviour and stability of masonry walls and validated by experimental results (Doherty et al. 2002). A similar approach, considering the effect of amplification of the acceleration at different levels and the P- Δ effect is proposed by Priestley et al. (2007). However, the simultaneous effects of in- and out-of-plane behaviour were ignored. The results from these studies are not directly

applicable for an infill panel for which the boundary conditions are different from a bare wall as the result of the interaction between the masonry panel and frame.

Preliminary study in masonry FE modelling

Previous research has mainly focused on the ultimate strength of the infill-frames and usually ignores the simultaneous effect of in- and out-of-plane behaviour. A PhD research project is currently being undertaken at the University of Melbourne to further investigate the behaviour of the infill-frame at different levels of loading. This will be more in the context of displacement-based methods considering the simultaneous effect of in- and out-of-plane loads. In this respect, Finite-Element modelling has been performed using ANSYS 11.0. The main goal of the analyses explained here is to provide evidence on whether different types of contact elements available in this programme are capable of predicting the behaviour of the interface between bricks and mortar in masonry structures. Experimental results (Heath et al. 2008) of “Triplet” (Figure 4) and “Prism” (Figure 5) tests have been used to validate preliminary FE models.

Material properties required for these analyses are: mortar and brick modulus of elasticity, their Poisson’s ratio, friction coefficient at the interface between them and the cohesion of the interface. It should be noted that it is assumed that the material is not loaded beyond its proportional limit. The modulus of elasticity of the mortar has been found experimentally by Heath et al. (2008) and is taken as 1,900 MPa. The modulus of elasticity of the brick units is assumed to be equal to 19,000 MPa which is ten times that of the mortar. The friction coefficient and cohesion (μ_0 and C_0 in coulomb friction model: $\tau = C_0 + \mu_0 P$) from the experimental results are also adopted in this FE study. For the triplet test it was found that μ_0 and C_0 are equal to 0.85 and 0.39, whereas for the prism tests they are equal to 0.7 and 0.89, respectively.

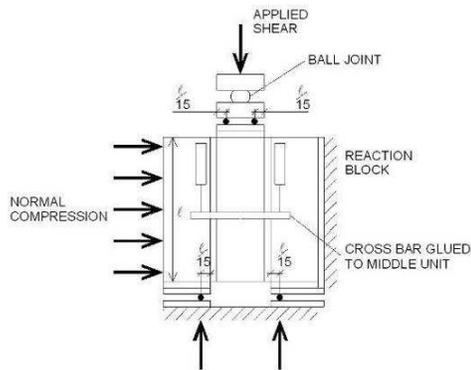


Figure 4: Triple test set-up diagram (Heath et al. 2008). As shown, the specimen includes three masonry units attached to each other by mortar in between.

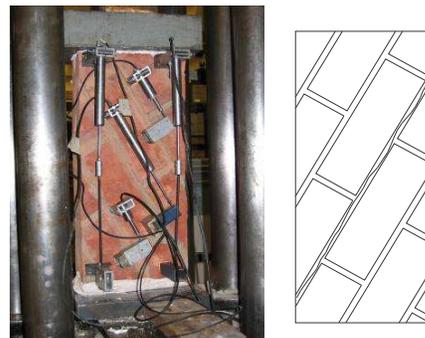


Figure 5: Prism test set-up and a sample of the crack pattern for the tests with the angle of 60 degree (Heath et al. 2008).

Triplet tests were conducted at different levels of normal compression stress ranging from 0.00-1.50 MPa. A total of 44 tests were conducted for which the average of the maximum vertical force resisted by the specimens at different levels of normal pressure is compared with the force obtained from the 2-D and 3-D FE models in Figures 6 and 7. The main difference between the 2-D and 3-D models is in the type of contact elements used; either node-to-node or surface-to-surface, respectively. The contact elements simulate the behaviour of the interface between mortar and brick units. The main drawback of the node-to-node contact elements is that the cohesion between the two nodes which define a

contact element cannot be modelled. The bricks and mortar were modelled using 4-node plane and 8-node solid elements in 2-D and 3-D analyses, respectively.

It can be argued that the shear force related to cohesion should be constant for all sets of tests performed, as it is not a function of the normal stress induced on a surface. The shear force relating to the test with 0.00MPa horizontal pressure is developed merely as the result of such cohesion between two surfaces ($\tau = C_0 + \mu_0 * 0.0 = C_0$). By deducting this value (the maximum shear force during a test with zero horizontal pressure) from the maximum shear force developed in other tests, the remainder would be the shear force caused by the normal force on the interface of the two surfaces ($\tau = C_0 + (\mu_0 * P) - C_0 = \mu_0 * P$). The experimental force-displacement curves vary considerably especially at low levels of normal pressure. Therefore, the force-displacement curves for normal pressure of 1.00 and 1.25MPa are compared herein with the FE results as shown in Figure 8.

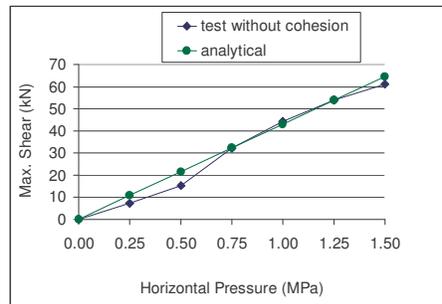


Figure 6: Comparison between the averages of maximum shear forces due to friction measured during the tests and calculated by 2-D FE models.

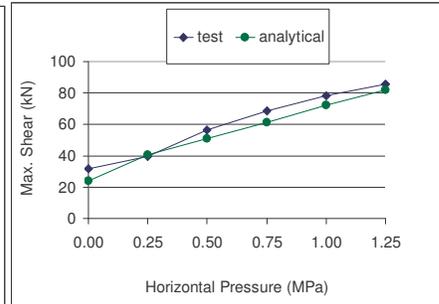


Figure 7: Comparison between the averages of maximum shear forces measured during the tests and calculated by 3-D FE models.

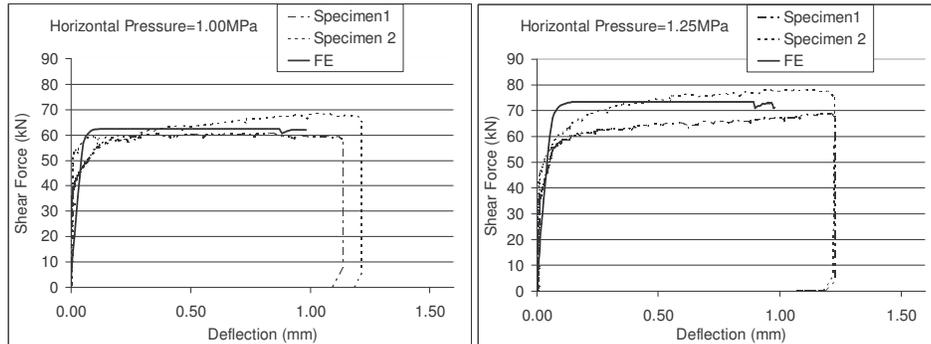


Figure 8: Comparison between the experimental results and 3-D FE models for triplet tests.

The experimental data for prism tests with 60 degree inclination of the bed joints (Heath et al. 2008) show that the maximum vertical loads ranged between 74.2kN and 85.9kN with an average of 79.7kN. Figure 9 shows the results of the 3-D FE model compared with the experimental results. The difference between the maximum vertical forces is expected to be as the result of the discontinuity between the head and bed joints in the model which has resulted in a lower maximum load and more flexible response. However, there is a good agreement between the location of cracks between the test and FE model. Deflected shapes of FE models of triplet and prism tests are shown in Figure 10. It should be noted that there is a variety of parameters controlling the

behaviour of contact elements which can be manually tuned. This is specifically critical to achieve the appropriate initial stiffness in the force-displacement curves.

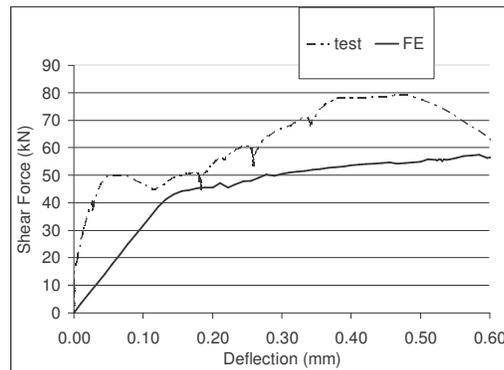


Figure 9: Comparison between the test results and FE model for prism test.

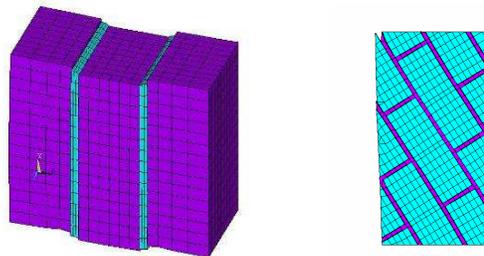


Figure 10: Deflected shape of the FE models for triplet and prism tests.

Conclusions

The structural interaction between the masonry infill panels and frames has been studied since the 1950s and a variety of FE models have been proposed to simulate the behaviour of infill-frames.

One of the most challenging aspects of infill-frame analysis is modelling the behaviour of the interface between the mortar and masonry units. Based on the preliminary studies on modelling the masonry material using ANSYS it is shown that the node-to-node and surface-to-surface contact elements can be successfully applied to simulate the cracks that initiate at the interface between the mortar and masonry units (specifically the shear or shear-compression cracks). Two and three dimensional models were developed to simulate triplet and prism tests conducted previously at the University of Melbourne.

The results of the masonry modelling are to be used in an overall FE model of a single bay RC frame with masonry infill. The in-plane load versus displacement behaviour and the damage levels at different levels of displacement will be compared with those recorded in experiments conducted by other researchers. The eventual aim will be to include the simultaneous effect of in-plane and out-of-plane behaviour in the model.

The stiffness of the infill-frame at different levels of displacement will be used in the context of displacement-based methods for analysis of such structural systems under the simultaneous effect of in- and out-of-plane loading. By relating the deterioration patterns of the infill-frame to different structural performance levels, performance-based analysis can be further applied for the assessment of the existing infill-frame structures or the design of new buildings.

References

- Al-Chaar, G. (1998). "Non-Ductile Behaviour of Reinforced Concrete Frames with Masonry Infill Panels Subjected to In-Plane Loading ", University of Illinois at Chicago, Chicago.
- Angel, R. E. (1994). "Behavior of reinforced concrete frames with masonry infill walls," University Illinois at Urbana-Champaign, Illinois.
- Bashandy, T., Rubiano, N. R., and Klingner, R. E. (1995). "Evaluation and analytical verification of infilled frame test data." Department of Civil Engineering, University of Texas, Austin, Texas.
- Crisafulli, F. J. (1997). "Seismic behaviour of reinforced concrete structures with masonry infills," University of Canterbury.
- Crisafulli, F. J., and Carr, A. J. (2007). "Proposed Macro-Model for the Analysis of Infilled Frame Structures." *Bulletin of the New Zealand Society for Earthquake Engineering*, 40(2), 69-77.
- Crisafulli, F. J., Carr, A. J., and Park, R. (2000). "Analytical Modelling of Infilled Frame Structures-A General Review." *Bulletin of the New Zealand Society for Earthquake Engineering*, 33(1), 30-47.
- Dawe, J. L., and Seah, C. K. (1989). "Behavior of Masonry Infilled Steel Frames." *Canadian Journal of Civil Engineering*, 16.
- Decanini, L. D., and Fantin, G. E. (1986). "Modelos simplificados de la mamposteria incluida en porticos. Caracteristicas de rigidez y resistencia lateral en estado limite." *Jornadas Argentinas de Ingenieria Estructural, Buenos Aires, Argentina*, 2, 817-836.
- Doherty, K., Griffith, M. C., Lam, N., and Wilson, J. (2002). "Displacement-based seismic analysis for out-of-plane bending of unreinforced masonry walls." *Earthquake Engineering & Structural Dynamics*, 31(4), 833-850.
- Durrani, A. J., and Luo, Y. H. (1994). "Seismic Retrofit of Flat-Slab Buildings with Masonry Infills." *NCEER Workshop on Seismic Response of Masonry Walls*, 1-3 to 1-8.
- FEMA306. (1998). "Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings."
- FEMA356. (2000). "Prestandard and Commentary for the Seismic Rehabilitation of Buildings."
- Flanagan, R. D., and Bennett, R. M. (1999). "Bidirectional behaviour of structural clay tile infilled frames." *Journal of Structural Engineering (ASCE)*, 125(3), 236-244.
- Griffith, M. C., Vaculik, J., Lam, N. T. K., Wilson, J., and Lumantarna, L. (2007). "Cyclic testing of unreinforced masonry walls in two-way bending." *Earthquake Engineering & Structural Dynamics*, 36(6), 801-821.
- Heath, D. J., Gad, E. F., and Wilson, J. L. (2008). "Damage Thresholds in Unreinforced Masonry." *Australian Journal of Structural Engineering*, 8(2), 145-157.
- Hemant, B. K., Durgesh, C. R., and Sudhir, K. J. (2006). "Code Approaches to Seismic Design of Masonry-Infilled Reinforced Concrete Frames: A State-of-the-Art Review." *Earthquake Spectra*, 22(4), 961-983.
- Lam, N. T. K., Griffith, M., Wilson, J., and Doherty, K. (2003). "Time-history analysis of URM walls in out-of-plane flexure." *Engineering Structures*, 25(6), 743-754.
- Liau, T. C., and Kwan, K. H. (1984). "Non-linear Behaviour of Non-Integral Infilled Frames." *Computers and Structures*, 18(3), 551-560.
- Lourenco, P. B. (1996). *Computational Strategies for Masonry Structures*, Delf University Press.
- Magenes, G., and Calvi, G. M. (1997). "In-plane seismic response of brick masonry walls." *Earthquake Engineering & Structural Dynamics*, 26(11), 1091-1112.
- Mallick, D. V., and Severn, R. T. (1967). "The Behaviour of Infilled Frames under Static Loading." *Proceedings of the Institution of Civil Engineers*, 639-656.
- Mander, J. B., Nair, B., Wojtkowski, K., and Ma, J. (1993). "An experimental study on the seismic performance of brick-infilled steel frames with and without retrofit." National Center for Earthquake Engineering Research, State University of New York, Buffalo, New York.
- Mehrabi, A. B. (1994). "Behavior of Masonry-Infilled Reinforced Concrete Frames Subjected to Lateral Loadings," University of Colorado, Boulder.
- Mehrabi, A. B., and Shing, P. B. (1997). "Finite Element Modeling of Masonry-Infilled RC Frames." *Journal of Structural Engineering*, 123(5), 604-613.
- Paulay, T., and Priestley, M. J. N. (1992). *Seismic Design of Reinforced Concrete and Masonry Buildings*, John Wiley & Sons.
- Polyakov, S. V. (1956). "On the Interaction Between masonry Filler Walls and Enclosing frame when Loaded in the Plane of the Wall." Earthquake Engineering Research Institute, Moscow.
- Priestley, M. J. N., Calvi, G. M., and Kowalsky, M. J. (2007). *Displacement-based seismic design of structures*, IUSS Press : Fondazione Eucentre, Pavia.
- Shing, P. B., and Mehrabi, A. B. (2002). "Behaviour and analysis of masonry-infilled frames." *Progress in Structural Engineering and Materials*, 4(3), 320-331.
- Stafford Smith, B. (1962). "Lateral Stiffness of Infilled Frames." *Journal of Structural Division*, 88(No. ST6).