



ANALYSIS OF THE CYCLIC BEHAVIOR OF MASONRY-INFILLED RC FRAMES USING THE FINITE ELEMENT METHOD

I. Koutromanos¹, A. Stavridis¹ and P. B. Shing²

ABSTRACT

This paper presents two constitutive models that can be used to simulate the inelastic cyclic behavior of masonry-infilled reinforced concrete frames in a detailed manner. One is a smeared-crack model that is intended to capture diffuse cracks and crushing in concrete members and masonry units, and the other is a cohesive interface model developed to simulate crack opening and sliding in a discrete fashion. The interface model also incorporates Coulomb friction, shear dilatation, and the compaction of a mortar joint due to damage. The models have been implemented in a finite element program and used with an appropriate finite element discretization scheme to accurately reproduce the hysteretic behavior and failure mechanism of a masonry-infilled reinforced concrete frame subjected to in-plane quasi-static cyclic load reversals. The models have also been used to capture the damage progression and failure mechanism of a large-scale, three-story, infilled frame tested on a shake table.

Introduction

Unreinforced brick masonry panels are commonly used as infill walls in reinforced concrete (RC) frame construction for aesthetic, fire proofing, and sound proofing purposes. This type of buildings can be found not only in older construction in the Western United States, but also in modern construction in the Eastern United States and Southeast Europe, where it represents a significant portion of the built environment. Although brick infill panels are usually not considered as part of the load-resisting system in the design of these structures, the frequent absence of separation joints between the infill and the frame leads to the interaction of the two when the structure is subjected to lateral loads. This interaction may lead to a variety of possible failure mechanisms, including the crushing of the infill, sliding along mortar bed joints, and shear failure in the columns.

The analysis of infilled frames subjected to lateral loads can be performed by a number of different techniques, ranging from simplified diagonal strut models (Crisafulli and Carr 2007, Madan et al. 1995, Perera 2005) to advanced finite element models (Mehrabi and Shing 1994, Stavridis and Shing 2010). While simple strut models have limited predictive capabilities, refined computation models provide advanced capabilities to simulate various failure mechanisms that can

¹Graduate Research Assistant, Dept. of Structural Engineering, University of California at San Diego, 9500 Gilman Drive, Mail Code 0085, La Jolla, CA 92093-0085

²Professor, Dept. of Structural Engineering, University of California at San Diego, 9500 Gilman Drive, Mail Code 0085, La Jolla, CA 92093-0085

occur in an infilled frame. However, the latter can be computationally demanding.

Recently, a finite element modeling scheme and a combined smeared and discrete crack modeling approach have been successfully used to reproduce the inelastic behavior of masonry-infilled concrete frames subjected to monotonically increasing in-plane loads (Stavridis and Shing 2007, Stavridis and Shing 2010). The two constitutive models used in that study have been recently extended to simulate the inelastic cyclic behavior of concrete and masonry materials. One is a smeared-crack model that is intended to capture diffuse cracks and crushing in concrete members and masonry units, and the other is a cohesive interface model developed to simulate crack opening and sliding in a discrete fashion. The latter is crucial for capturing the brittle behavior of concrete members induced by diagonal shear cracks and the sliding shear behavior of mortar joints. This paper summarizes the constitutive models and the previously proposed finite element modeling scheme, and presents results of numerical studies to validate the models. The experimental results used for the model validation include those obtained from a quasi-static test conducted on a 2/3-scale, one-story, one-bay, frame at the University of Colorado at Boulder (CU), and the dynamic test of a three-story, two-bay, infilled frame conducted on the large outdoor shake table at the University of California at San Diego (UCSD). The tests were conducted as part of a collaborative research project investigating the seismic performance of nonductile infilled RC frames (Shing et al. 2009).

Constitutive Models

To model the inelastic behavior and failure mechanisms of masonry-infilled RC frames, two different constitutive models have been implemented in a finite element program: a smeared crack continuum model and an interface model.

Smeared Crack Model

The 4-node isoparametric smeared crack element used here to capture diffuse cracks and crushing in concrete and masonry is based on the model originally proposed by Lotfi and Shing (1991). It has been extended here to simulate the cyclic load response in a robust and accurate manner. The uncracked material is assumed to be elasto-plastic with compressive yielding described by a von Mises loading surface combined with a Rankine tension cutoff as shown in Fig. 1a, in which f'_c and f_t denote the uniaxial compressive and tensile strengths of concrete or masonry. The evolution of the loading surface for compressive strain hardening and softening is governed by the effective stress-effective plastic strain relation shown in Fig. 1b. An associated flow rule is used to account for plastic deformation. When the tensile strength is exceeded by the maximum principal stress, a crack normal to the maximum principal stress direction forms. The material is then assumed to be orthotropic with the axes of orthotropy normal and parallel to the crack direction. Once a crack forms, its direction is assumed to be fixed.

After tensile fracture, the behavior along the orthotropic axes is described by the stress-strain curve presented in Fig. 2. For simplicity, the residual shear after fracture is assumed to be bounded by a strength that is equal to one-half of the tensile strength of the material. In the cracked material, the tensile stress is an exponentially decaying function of the tensile strain, and the tensile unloading and reloading follow a secant modulus. The compressive stress-strain law has a form that closely matches the compressive behavior of the uncracked material. In this way, a smooth transition is ensured from the uncracked to cracked state. Compressive unloading and reloading

follows the initial elastic modulus.

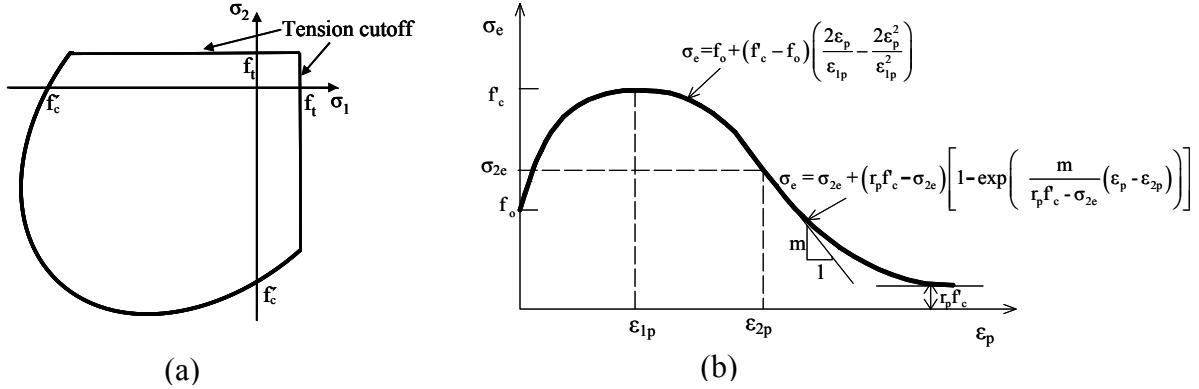


Figure 1. (a) von Mises yield surface with tension cutoff in principal stress space, and (b) compressive strain hardening and softening law for the smeared crack element.

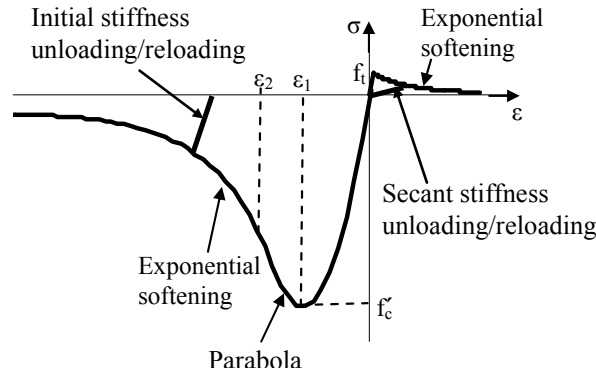


Figure 2. Normal stress-normal strain relation used in the orthotropic model for cracked material in the smeared crack element.

Interface Model

A 4-node isoparametric interface element is proposed to model cracks in a discrete fashion. This is to capture the fracture behavior of shear cracks in RC columns and that of mortar joints in masonry infill in a more accurate manner. It adopts an elasto-plastic formulation to simulate mode I, mode II, and mixed-mode fracture of quasi-brittle materials. The model accounts for Coulomb friction and shear dilatation that can develop along a crack interface.

The relative interface displacement vector \mathbf{d} has a normal component d_n and a shear component d_t along the interface's normal and tangential directions, respectively, as shown in Fig. 3a. It is decomposed into three parts to represent the different phenomena that can develop in a non-smooth crack interface. Eq. (1) shows this decomposition in a rate form.

$$\dot{\mathbf{d}} = \dot{\mathbf{d}}^e + \dot{\mathbf{d}}^p + \dot{\mathbf{d}}^g \quad (1)$$

where $\dot{\mathbf{d}}^e$ is the elastic (reversible) part, $\dot{\mathbf{d}}^p$ is the plastic (irreversible) part, intended to capture the effects of material damage and loss, and $\dot{\mathbf{d}}^g$ is the geometric part to describe the recoverable shear dilatation due to the wedging action of the asperities in a crack.

The yield surface used for the interface has a hyperbolic shape, which has been adopted in a number of different interface models (Gens et al. 1988, Lotfi and Shing 1994, Mehrabi et al. 1994, Carol et al. 1997). The particular formulation adopted here is based on the work of Lotfi and Shing (1994). The yield criterion is defined by the following expression:

$$F = \tau^2 - \mu^2 (\sigma - s)^2 + 2r(\sigma - s) = 0 \quad (2)$$

where μ is the slope of the asymptote of the hyperbola representing the frictional coefficient, r is the radius of the yield surface at its apex, and s is the tensile strength, as shown in Fig. 3b. The cohesive strength c_o of the material can be evaluated from the three parameters as shown in the figure.

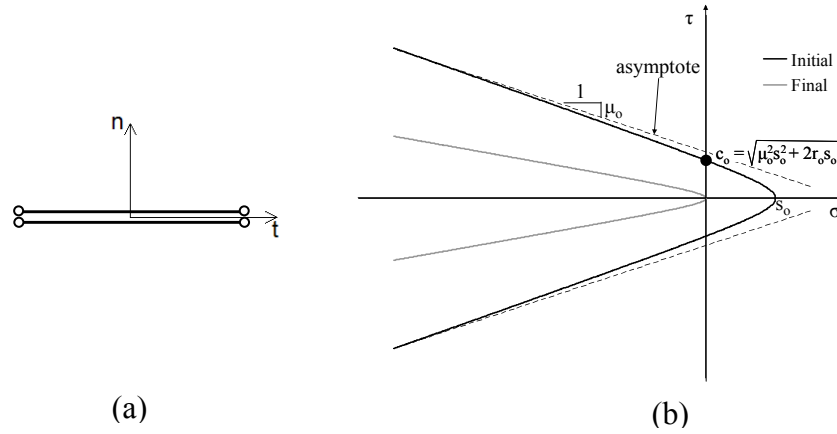


Figure 3. Interface model; (a) local coordinates, and (b) failure surface.

An elastic prediction-plastic correction approach (Ortiz and Popov, 1985, Ortiz and Simo, 1986) is employed to update the tractions based on the given interface displacement increment. The plastic (irreversible) displacement representing tensile crack opening, shear sliding, and material crushing is computed with a non-associated flow rule:

$$\dot{\mathbf{d}}^p = \dot{\lambda} \cdot \mathbf{m} \quad (3)$$

where $\dot{\lambda}$ is a plastic multiplier and \mathbf{m} is a vector representing the direction of plastic flow. In the current formulation, the calculation of \mathbf{m} depends on whether the normal stress is compressive or tensile, as shown in Fig. 4. For an interface under compression, $\mathbf{m} = \partial Q / \partial \boldsymbol{\sigma}$ where the plastic potential is an elliptical function as follows (Mehrabi and Shing 1994):

$$Q = \frac{1}{2} \eta \tau^2 + \frac{1}{2} (\sigma + \alpha)^2 \quad (4)$$

When subjected to a tensile normal stress, the direction of the plastic displacement rate is assumed to be collinear with the trial elastic stress vector, $[\sigma^{tr}, \tau^{tr}]^T$, as shown in Fig. 4. This is to ensure the robustness of the interface model in numerical computation, and to distinguish the kinematics of a crack interface in the compression and tension regimes.

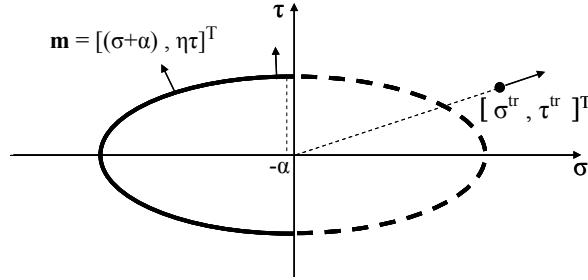


Figure 4. Plastic potential and plastic flow directions for different stress states.

The geometric part of the displacement increment is given by Eq. (5):

$$\dot{\mathbf{d}}^g = \begin{Bmatrix} \dot{d}_n^g \\ \dot{d}_t^g \end{Bmatrix} = \begin{Bmatrix} \zeta_{dil} \text{sign}(d_t^p) \dot{d}_t^p \\ 0 \end{Bmatrix} \quad (5)$$

where \dot{d}_t^p is the plastic shear displacement rate and ζ_{dil} is a dilatation coefficient that varies with the plastic shear displacement as given by Eq. (6):

$$\zeta_{dil} = (\zeta_{dil,o} - \zeta_{dil,r}) \exp\left(-\frac{|d_t^p|}{d_o}\right) + \zeta_{dil,r} \quad (6)$$

where $\zeta_{dil,o}$, $\zeta_{dil,r}$, and d_o are material parameters.

After an interface has opened in mode-I fracture, compressive stress can develop only upon full crack closure as shown by the unloading-reloading behavior in Fig. 5.

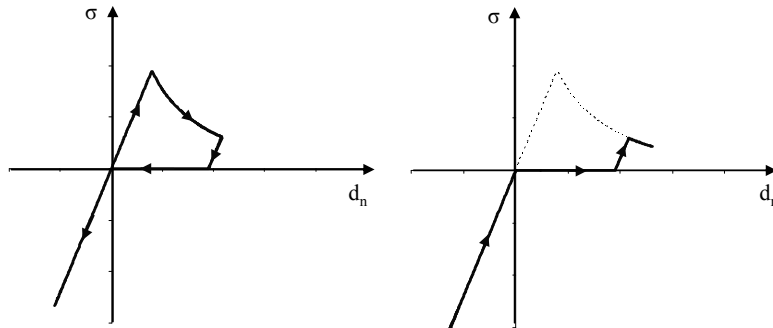


Figure 5. Interface behavior for normal loading/unloading (left) and reloading (right).

A single interface element has been subjected to a constant normal compression of 70 psi and cyclic shear reversals to reproduce the response of a mortar joint test conducted by Amadei et al. (1989). As shown in Fig. 6, the analysis satisfactorily reproduces the initial and residual joint strength, as well as the effect of shear dilatation. However, the model over-estimates the joint compaction induced by damage.

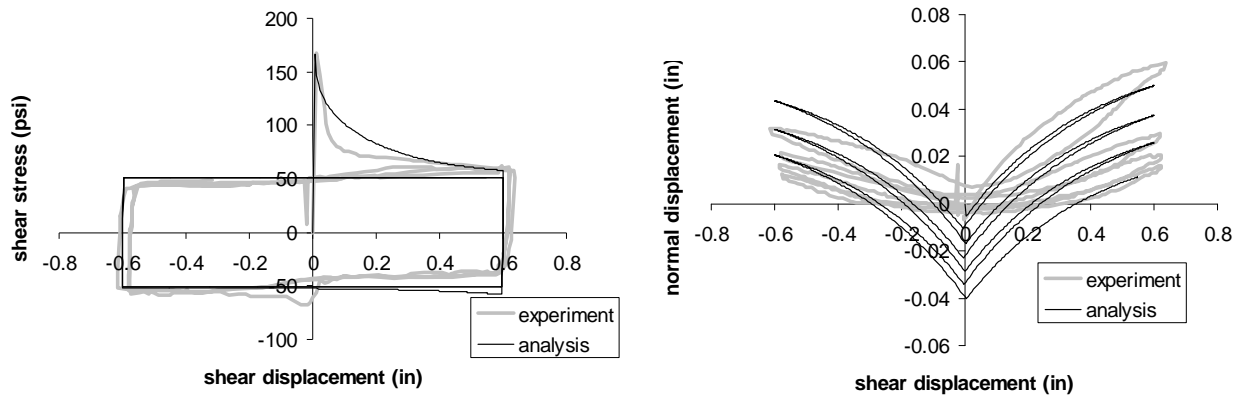


Figure 6. Validation of interface model with experimental data for a cyclic shear test on brick masonry mortar joint under a constant compressive stress of 70 psi (Amadei et al 1989).

Meshing Approach for Infilled RC Frames

To capture the failure behavior of an infilled frame in an accurate manner, an appropriate meshing scheme must be employed. The meshing approach suggested by Stavridis and Shing (Stavridis and Shing 2007, Stavridis and Shing 2010) is used. For concrete columns, triangular smeared crack elements are combined with interface elements as shown in Fig. 7. The use of interface elements to model cracks in a discrete fashion is to circumvent the deficiency of smeared crack elements in capturing the brittle shear behavior of RC columns. According to the mesh geometry in Fig. 7, discrete cracks can develop at specific orientations of 0° , $\pm 45^\circ$ and 90° with respect to the horizontal.

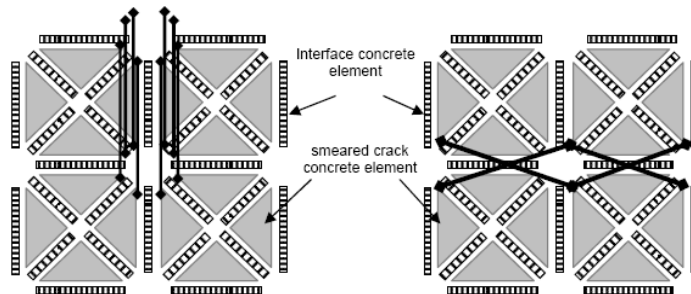


Figure 7. Meshing scheme used for reinforced concrete columns and description of longitudinal (left) and shear (right) reinforcement (Stavridis and Shing 2007).

Truss elements are used to model the reinforcing steel, with the area of each longitudinal bar divided into multiple bars and the area of each stirrup divided into two bar elements. For the infill panel, quadrilateral smeared crack elements are used to model the brick units, as shown in Fig. 8. Each brick is represented by two quadrilateral smeared crack elements, with a vertical interface element in-between to allow the formation of a splitting vertical crack through a brick unit. Interface elements are employed to describe the fracture of mortar head and bed joints, which normally occurs at a brick-mortar interface.

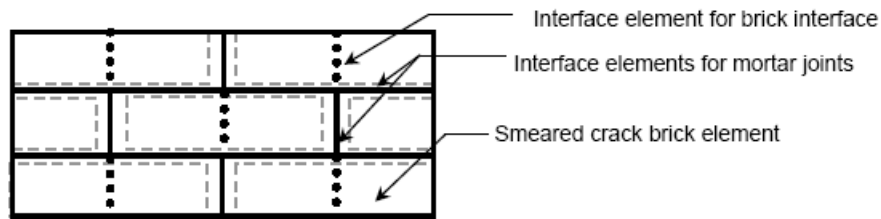


Figure 8. Meshing scheme used for masonry infill panels (Stavridis and Shing 2007).

Verification

For the validation of the finite element models, results of a quasi-static test conducted on an infilled frame tested at the University of Colorado at Boulder (Shing et al. 2009) are used. The test specimen is presented in Fig. 9.

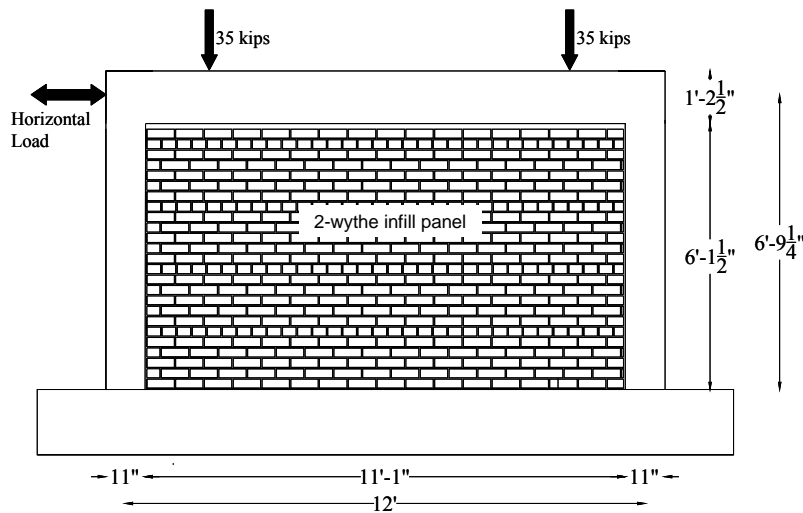


Figure 9. Dimensions and setup of a single-story, single-bay, infilled RC frame specimen tested at CU Boulder.

The force-displacement curves obtained in the test and analysis are compared in Fig. 10. The peak lateral load obtained in the test was 153 kips, which occurred at a drift ratio of 0.25%. A significant load drop occurred at a drift ratio of about 0.4%, due to the formation of diagonal shear cracks in the concrete columns. The specimen retained a residual strength of 80 kips in the positive direction and 75 kips in the negative direction after the peak. As shown in Fig. 10, the

analysis reproduces the cyclic response, including the strength and stiffness degradation, reasonably well, but it underestimates the peak load by 15%. Figure 11 compares the cracking pattern obtained in the analysis with the experimentally observed failure mechanism. As shown, the finite element model captures the cracking pattern observed, which is a combination of diagonal and horizontal sliding shear cracks in the infill panel and shear cracks in the concrete columns.

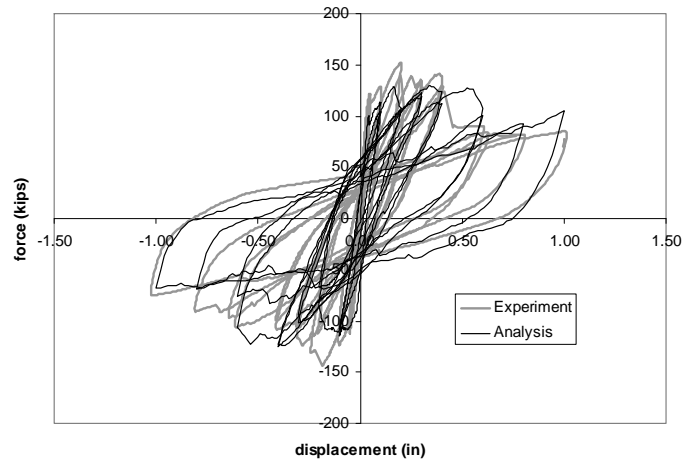


Figure 10. Comparison of experimentally recorded and numerically calculated load-displacement curves for the infilled RC frame specimen tested at CU Boulder.

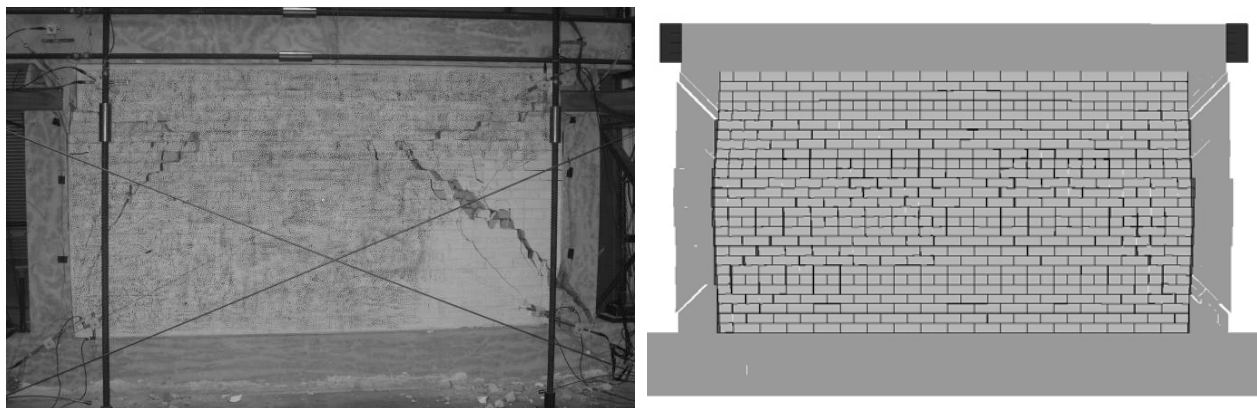


Figure 11. Comparison of experimentally (left) and numerically (right) obtained cracking patterns and failure mechanisms of infilled RC frame specimen.

To simulate the failure behavior of a multi-story frame under earthquake loading, results of a shake-table test (Shing et al 2009) performed at the UCSD NEES facility are used. The 2/3-scale, 3-story, 2-bay, frame specimen shown in Fig. 12 was subjected to a sequence of ground motions with increasing intensity, which were derived by scaling the Gilroy 3 record obtained during the 1989 Loma Prieta Earthquake in time and acceleration. A gradual increase of the base motion intensity induced diagonal and sliding cracks in the infill panels and shear cracks in the columns. A preliminary analysis has been performed, aiming to reproduce the failure mechanism

of the specimen. The computational model representing the shake-table specimen was subjected to a sinusoidal motion of gradually increasing amplitude. The failure mechanism of the finite element model closely matches the experimental observation, as shown in Fig. 13.



Figure 12. Three-story, two-bay, infilled RC frame specimen tested at UCSD.

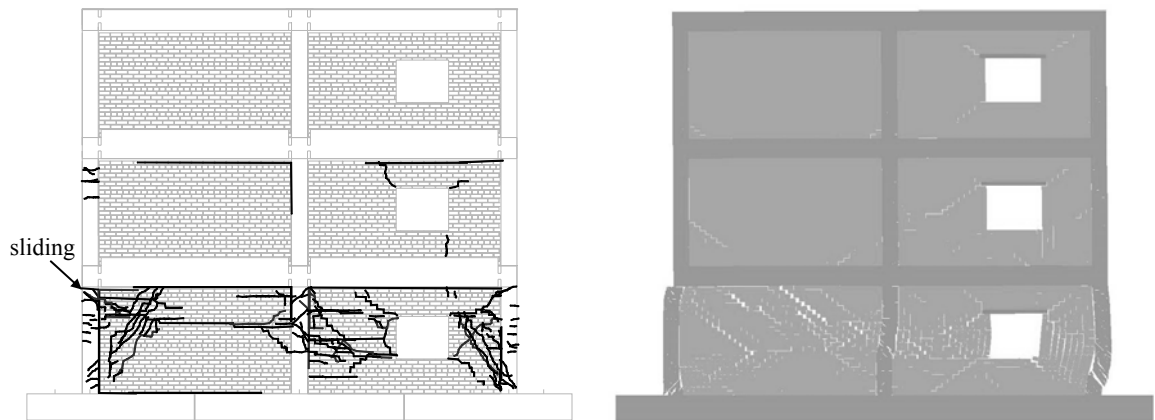


Figure 13. Comparison of experimentally (left) and numerically (right) obtained cracking patterns and failure mechanisms of infilled RC frame specimen tested at UCSD.

Conclusions

The newly developed constitutive models for concrete and masonry when employed in a previously proposed finite element discretization scheme can well reproduce the cyclic response of the masonry-infilled reinforced concrete frames considered here. Although the strength of an infilled frame is slightly underestimated in one example, the residual strength, hysteretic loop shape, and cracking pattern satisfactorily match the experimental observations. Furthermore, satisfactory results are obtained from a preliminary dynamic analysis of a three-story frame tested on a shake table. However, in spite of the promising results, further validation is needed for frames with different configurations, design, and loading conditions, including infill walls with openings and frames subjected to earthquake ground motions.

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References

- Amadei, B., Sture, S., and S. Saeb, 1989. An evaluation of masonry joint shear strength in existing buildings, *Report to NSF Vol I*, University of Colorado at Boulder.
- Carol, I., Prat, P.C., and C.M. Lopez, 1997. Normal/shear cracking model: application to discrete crack analysis, *ASCE Journal of Engineering Mechanics*, 123 (8), 765-773.
- Crisafulli, F., and A.J. Carr, 2007. Proposed macro-model for the analysis of infilled frame structures, *Bulletin of the New Zealand Society for Earthquake Engineering*, 40 (2), 69-77.
- Gens A., Carol, I., and E.E. Alonso, 1988. An interface element formulation for the analysis of soil-reinforcement interaction, *Computers and Geotechnics* 7 (1-2), 133-151.
- Lotfi, H.R., and P.B. Shing, 1991. An appraisal of smeared crack models for masonry shear wall analysis, *Computers and Structures*, 41 (3), 413-425.
- Lotfi, H.R., and P.B. Shing, 1994. Interface model applied to fracture of masonry structures, *ASCE Journal of Structural Engineering*, 120 (1), 63-80.
- Mehrabi, A.B., Shing, P.B., Schuller, M.P., and J.L. Noland, 1994. Performance of masonry-infilled R/C frames under in-plane lateral loads, *Report CU/SR-94/6*, University of Colorado at Boulder.
- Ortiz, M., and E.P. Popov, 1985. Accuracy and stability of integration algorithms for elastoplastic constitutive relations, *International Journal for Numerical Methods in Engineering*, 21, 1561-1576.
- Ortiz, M., and J.C. Simo, 1986. An analysis of a new class of integration algorithms for elastoplastic constitutive relations, *International Journal for Numerical Methods in Engineering*, 23, 353-366.
- Perera, R., 2005. Performance evaluation of masonry-infilled RC frames under cyclic loading based on damage mechanics, *Engineering Structures*, 27, 1278-1288.
- Madan, A., Reinhorn, A.M., Mander, J.B., and R.E. Valles, 1995. Modeling of Masonry Infill Panels for Structural Analysis, *ASCE Journal of Structural Engineering*, 123 (10), 1295-1302.
- Shing, P.B., Stavridis, A. Koutromanos, I Willam, K. Blackard, B. Kyriakides, M.A. Billington, S.A., and S. Arnold, 2009. Seismic Performance of Non-Ductile RC Frames with Brick Infill. *ATC & SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures*, San Francisco, California.
- Stavridis, A., and P.B. Shing, 2007. Modeling of masonry-infilled RC frames with discrete and smeared crack elements, *ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Rethymno, Greece.
- Stavridis, A., and P.B. Shing, 2010. Finite element modelling of nonlinear behaviour of masonry-infilled RC frames, *ASCE Journal of Structural Engineering*, Article in Press.