Predictive and diagnostic analysis models for masonry buildings

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ABSTRACT: A three-dimensional, nonlinear finite element based analytical model for the analysis of reinforced concrete and masonry structural systems is described. Biaxial constitutive relationships are based on equivalent uniaxial stress-strain laws for either nonlinear elastic or nonlinear inelastic behavior, and smeared rotating crack theory is adopted. Comparison of the model with experimental results shows that the accuracy of the model is satisfactory for both monotonic and cyclic load histories, and that the model can be used both as a predictive and a diagnostic research tool to investigate the dominant nonlinear response phenomena in structural masonry systems.

1 INTRODUCTION

Past earthquakes have demonstrated that masonry structures can be particularly vulnerable to the severe cyclic loads and displacements induced by earthquakes; however, it has also been shown that properly detailed masonry structures can behave in a ductile manner under seismic loads [Priestley, 1981]. In order to design safe masonry structures while maintaining the economic viability of masonry construction in seismic zones, new design guidelines based on ductile structural system behavior and limit states design rules must be developed. The development of such guidelines has been undertaken as part of a comprehensive research effort on the behavior of masonry systems subjected to seismic loads, coordinated through TCCMAR (Technical Coordinating Committee for Masonry Research) in the United States and in Japan. The U.S.-TCCMAR program consists of parallel analytical and experimental research programs at the material, component, subassemblage, and prototype structure levels to provide a comprehensive research basis to expand the state-of-the-art in earthquake resistant masonry design. The experimental program will culminate with the testing of a full-scale 5-story reinforced masonry research building at UC San Diego (Figure 1). This test will provide the final validation of the TCCMAR design philosophy and analytical models.

The development of analytical models to predict the behavior of structural masonry and concrete systems forms a key part of the TCCMAR coordinated research effort, focusing on the complete representation of the nonlinear response of such systems subjected to fully-cyclic seismic loads. Models of varying complexity have been developed in
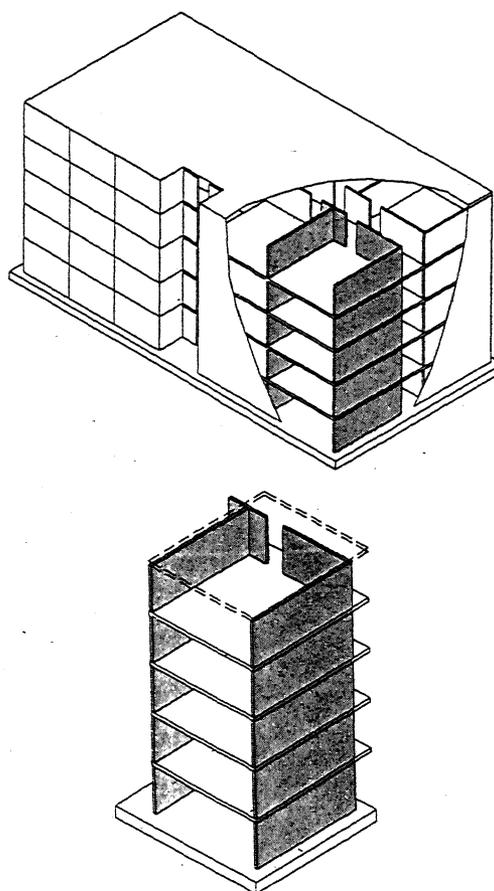

Figure 1. Five-story full-scale masonry research building: prototype structure and test specimen.

support of both design and research needs with the primary goal of capturing critical behavioral limit states of structural masonry systems. An analytical model developed at UCSD employs the finite element method to allow an accurate representation of geometric and constitutive properties of the structure, and serves as a predictive and diagnostic tool for full-scale structural systems testing.

2 MODELING OBJECTIVES

The primary objective of the analytical model developed at UCSD is the analysis of the 5-story full-scale masonry research building test. Figure 1 shows the proposed research building as part of a prototype masonry building and also as an isolated full-scale test specimen. The test structure consists of two cantilever shear walls of unequal length, each with a long flange perpendicular to the plane of loading, coupled by topped precast pre-tensioned hollow-core concrete plank floor slabs. In the shorter shear wall, the flange is located in the center of the wall, while in the longer shear wall, the flange is located at the end of the wall. The presence of wall flanges and the continuously varying axial load in the walls imposed by coupling effects combine to create a structure with distinctly different strength and stiffness characteristics in the two loading directions.

The analysis requirements for the research building include predictive analysis in support of the structural design and test development, and post-test diagnostic analysis to maximize the utility of the test results and refine the analytical model. Of particular interest for both predictive and diagnostic analyses is the modeling of the coupling behavior in coupled shear wall systems, and the associated changing axial load effects in the walls. The effective width of the structural concrete slabs connecting the shear walls will have a significant effect on the level of coupling, and thus on the overall stiffness and strength of the system. Unlike a linear elastic system, however, the stiffness of the coupling slabs may degrade considerably under fully reversed cyclic loads [Seible et. al. 1991], so the effective width may change with increasing load and displacement levels. The effective width of wall flanges at various structural limit states will also affect the system response. To capture these aspects of the behavior of wall structures, a full 3-D, nonlinear representation of the structure is essential.

On a component level, the dominant phenomenological aspects of structural masonry or concrete behavior should be included in the model, namely:

1. Cracking of concrete or masonry.
2. Yielding and strain-hardening of reinforcing steel.
3. Nonlinear steel stress-strain behavior including the Bauschinger effect.

4. Crushing or strength degradation in concrete or masonry (softening).
5. Tension stiffening behavior of reinforced concrete following cracking.
6. Material anisotropy due to orientation of mortar joints (masonry).
7. Stress-induced anisotropy.

On the structural systems level the model must include the critical aspects of system behavior:

1. 3-D finite element domain.
2. Shear lag effects in wall flanges
3. Shear lag and coupling effect in floor slabs
4. Precast prestressed hollow core plank response characteristics.
5. Interaction of all of the above

In order to capture the critical behavior limit states of the system components while still allowing efficient modeling of complete, full-scale structural systems, a finite element formulation is employed which uses relatively simple constitutive models, and a 2-D in-plane representation of wall elements to approximate the interaction of components in the full 3-D system. In-plane behavior of shear walls and the associated shear lag effects in the wall flanges may be modeled effectively by ignoring out-of-plane wall response, and enforcing displacement compatibility only in the vertical degrees of freedom at the wall intersections. Floor slab elements, on the other hand, must include both out-of-plane bending response and membrane action to capture the complex behavior of coupling slabs and diaphragm action. Further refinements to the slab element are necessary to represent the orthotropic, voided cross-section of the precast planks. In the following section, the development of the in-plane wall element is described. The slab element is discussed in section 5.

3 IN-PLANE WALL ELEMENT DEVELOPMENT

The finite element model utilizes rectangular plane-stress elements with 4 to 8 nodes to represent walls under in-plane loads, and a 9-node lagrangian layered plate element including membrane forces to model floor slabs under out-of-plane bending and in-plane diaphragm action. The biaxial constitutive equations for reinforced grouted masonry and concrete are based on Darwin and Pecknold's orhogonally anisotropic model [Darwin and Pecknold,1977] and on Collins and Vecchio's Modified Compression Field Theory [Vecchio and Collins,1986]. Cracks in masonry or concrete are represented using smeared crack approximations. Masonry and steel reinforcement are treated as overlaid elements in which the constitutive laws for each are formulated separately while assuming that both materials are subjected to identical strain fields. Equivalent uniaxial stress-strain laws are adopted for concrete and masonry in the principal
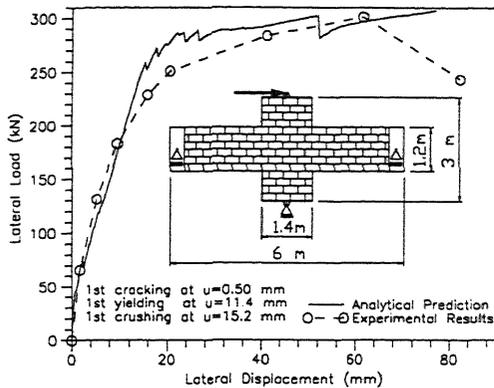
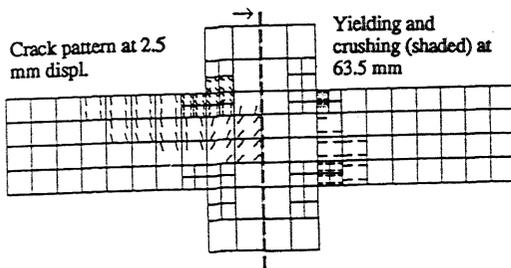(a) Lateral load-displacement response of a point at the top of the column section

Figure 2. Prediction of Masonry Wall Frame Joint Response.

directions, with coupling between the principal directions provided by a damage parameter. Initial anisotropy associated with the presence of mortar joints in masonry is treated by introducing a variable relationship between the cracking stress and the principal tensile stress orientation. A complete description of the wall element development is presented in [LaRovere, 1990].

4 FINITE ELEMENT MODEL APPLICATIONS

The analytical model has been successfully applied in both predictive and diagnostic capacities for TCCMAR and related research tasks. In the following sections, three applications of the model will be described. In the first two -- a masonry wall frame joint and a two-story perforated wall -- the model is used as a true predictive tool in pre-test analyses of reinforced masonry test specimens. In the third application, a flanged masonry wall specimen is investigated as part of a post-test diagnostic analysis of a full-scale experiment.

Masonry Wall Frame

The application of the analytical model to a masonry frame structure is depicted in Figure 2. A reinforced concrete masonry beam-column connection with joint shear reinforcement was tested at UCSD to substantiate planned changes in the U.S. Uniform Building Code (UBC). A true force deformation prediction estimating key design limit states was made prior to the test. Subsequent comparison of the prediction and the experimental results showed good agreement, as depicted in Figure 2(a). The predicted yield and crushing locations shown in Figure 2(b) clearly reflect the formation of flexural plastic hinges in the beam at the column face, which corresponds to the design objective and the full-scale test results.
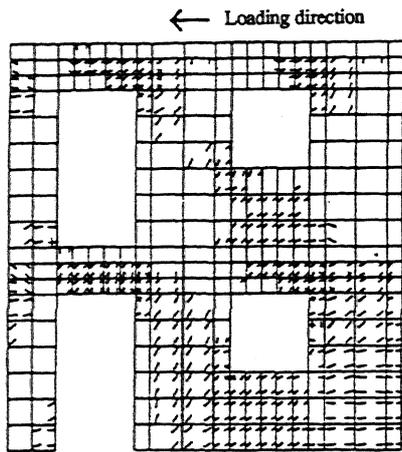
Two-story Perforated Shear Wall

Two-story reinforced concrete shear walls were tested under the TCCMAR program by Klingner [Klingner, 1990] at the University of Texas, Austin. The two-story shear wall tests included coupled wall specimens and perforated walls with door and window openings. A true pre-test prediction of the behavior of a perforated wall test was made using the developed nonlinear finite element model (Figure 3(a)). Predicted cracking, yielding and crushing patterns are shown in Figures 3(b) and 3(c). Figure 3(b) shows the cracking pattern at a lateral displacement of -5mm, and Figure 3(c) shows predicted locations of steel yielding (line segments) and masonry crushing (shaded) at a lateral displacement of 50 mm. The depicted distress patterns for the structure subjected to two horizontal floor loads of equal magnitude to the left indicate that the wall will respond with hinging in the left column member and compression toe failure of the main wall next to the door opening. No yield penetration into the upper story was predicted. Subsequent test results confirmed these findings. The lateral load-deformation envelopes for this perforated wall are depicted in Figure 3(a) for both a true pre-test prediction and the experiment. Close agreement between prediction and test can be observed. The prediction also included assessment of critical design limit states such as first cracking, first yielding, and onset of crushing as illustrated in Figure 3(a).Masonry Flanged Wall

In order to asses the ability of the analytical model to represent the behavior of flanged wall systems typical of masonry wall structures and the 5-story research building, the model was applied, both as a predictive and diagnostic tool, to simulate the single-story flanged wall tests conducted at the University of California, San Diego [Priestley and Lemin, 1990].
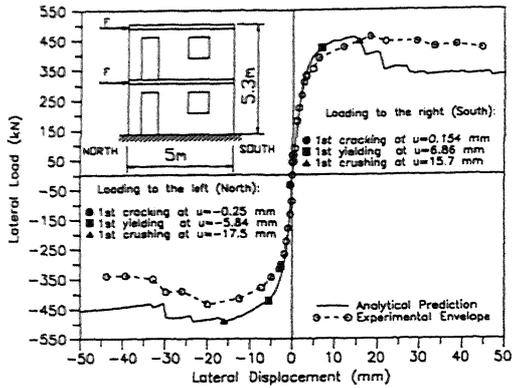
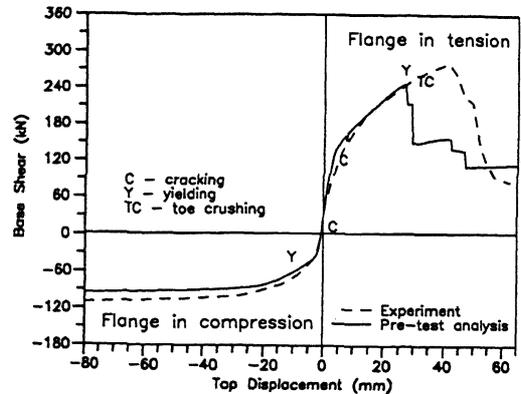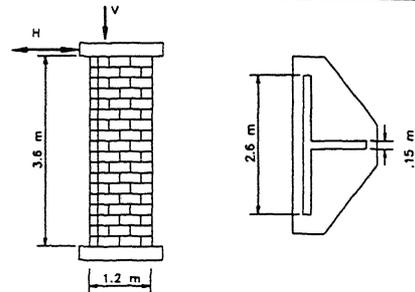(a) Lateral load-displacement response of a point at the center of the top slab.

← Loading direction

(b) Predicted crack patterns at lateral displacement of 5 mm

← Loading direction
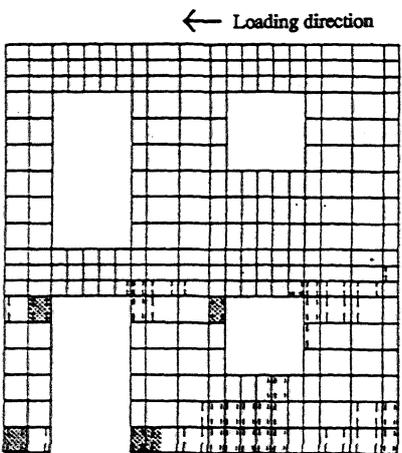
(c) Predicted locations of yielding steel (line segments) and crushing masonry (shaded) at a lateral displacement of 50 mm.

Figure 3. Two-story Perforated Masonry Shear Wall Analysis.

Analysis	Unconfined Masonry		Confined Masonry				Masonry in Tension	
	f'_m (MPa)	ε_o	f'_{mc} (MPa)	ε_{oc}	D	E	f'_{cr} (MPa)	Model
Pre-test	20.0	0.0026	—	—	—	—	0.7	Masonry Referred α=0.03
Post-test	16.2	0.0026	23.8	0.0034	0.1	0.9	2.1	Masonry Referred α=0.03
Modified Post-test	19.8	0.0030	23.8	0.0036	0.1	0.9	2.1	Steel-Referred

(b) Monotonic lateral load-displacement response: analytical and experimental results.
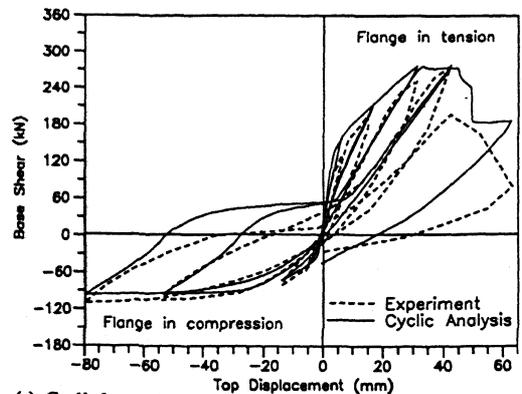
(c) Cyclic lateral load-displacement response: analytical and experimental results

Figure 4. Flanged Wall Model and Analysis Results

The flanged wall properties and dimensions are shown in Figure 4(a). Symmetry considerations allowed only half of the structure to be analyzed. Since the analytical model considers only in-plane degrees-of-freedom for shear wall elements, geometric compatibility between the flange and the web was enforced only in the vertical degrees of freedom of the nodes along the wall-to-wall intersection. Prescribed displacements were then applied in the plane of the web at the top of the wall. While this approach neglects the out-of-plane response of the flanges, the significant components of the flanged wall response can be captured without adding unnecessary complexity to the analysis.

The pre-test monotonic lateral load vs. displacement response envelope is shown in Figure 4(b). The asymmetrical behavior recorded in the experiment was clearly reflected in the analytical model response: when the flange is in compression the wall exhibits highly ductile response with low strength, whereas when the web is in compression the wall behaves like a highly over-reinforced section with high strength and a brittle failure mode. Agreement between the predicted and experimental response is quite good when the flange is in compression. When the web is in compression, the initial stiffness and failure mode are captured well, but the peak strength and displacement are poorly predicted (Figure 4(b)). These discrepancies were corrected in a post-test diagnostic analysis described below.

During the experiment, abrupt cracking across the width of the flange at clearly defined load levels allowed the accurate measurement of the experimental masonry cracking stresses [Priestley and Lemin, 1990]. The measured values were found to be three times greater than the values assumed in the pre-test analysis. A post-test monotonic analysis, shown in Figure 5(a), incorporated the increased cracking stress, but large discrepancies were then noted between the analytical and experimental peak load and displacement values. The over estimation of maximum load in the post-test analysis was due to residual tensile stresses in masonry following cracking associated with the masonry referred tension stiffening model [Seible and Kingsley, 1991]. In planar shear wall structures, such a tension stiffening model may be appropriate. However, the flanged wall has a very large area of masonry in tension, and small errors in the post-cracking tensile stresses resulted in a large overestimation of the moment capacity. To alleviate the problem, a steel-referred tension stiffening model [Seible and Kingsley, 1991] was employed in the modified post-test analysis described in Table 1 of Figure 4(a). Furthermore, very large measured compressive strains at the wall toe during the experiment indicated that the adjacent rigid foundation block was providing considerable lateral confinement to the bottom course of masonry. When these effects were incorporated in the modified post-test analysis, the agreement between the experimental and analytical curves was excellent. Through these diagnostic parameter studies, the analytical model

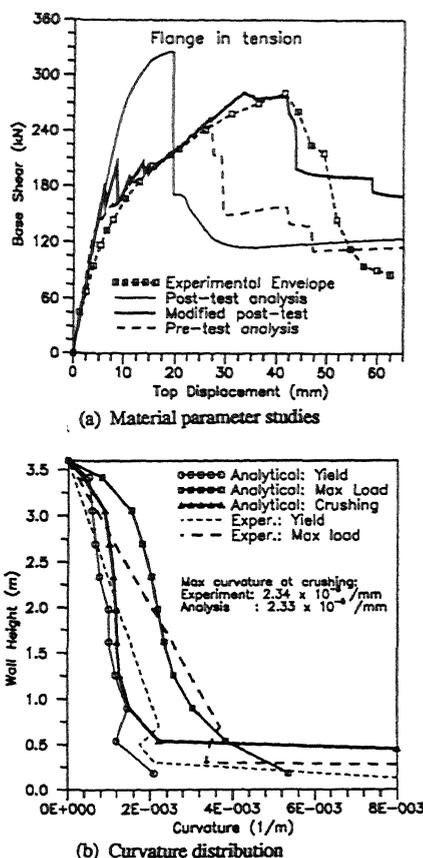(a) Material parameter studies

(b) Curvature distribution

Figure 5. Diagnostic Analysis of Flanged Wall

contributed greatly to the quantitative understanding of tension stiffening mechanisms in masonry and the confinement of masonry by adjacent stiff members. Finally, the now calibrated analytical model was used to compare analytical and experimental curvature distributions along the height of the flanged wall. The results, depicted in Figure 5(b), indicate close correlation between the two models, provide continued confidence in the developed analytical tool. This diagnostic analysis also confirmed that the 2-D in-plane representation of the structure was satisfactory, and that sufficient phenomenalogical parameters have been incorporated into the analytical model to accurately trace full scale laboratory tests all the way to failure.

The same flanged wall was analyzed under cyclic loading. While the experimental load history included repeated fully reversed cycles at prescribed load or displacement levels, only the first cycle at each level was modeled analytically. Results of the analysis are presented in Figure 4(c) with the experimental response. The envelope of the cyclic analytical response agrees well with the experimental envelope in both loading directions. A discrepancy exists on the unloading/reloading curves when the web is in

compression. This can be attributed to the simplified linear unloading law adopted for masonry in compression, where a nonlinear curve might be more accurate. A second discrepancy exists in the unloading curve when the flange is in compression, and the analytical model overpredicts the restoring force. This may be attributed to the oversimplified description of the Bauschinger effect in the cyclic law of the reinforcing steel.

5 FINITE ELEMENT EXTENSIONS

To analyze complete building systems the analytical model was extended to the full 3-D domain in a simplified special purpose application to minimize computational requirements for fully cyclic nonlinear analysis. In the 3-D building systems model, the above discussed structural components can be arranged in the three Cartesian planes connected only by translational compatibility requirements. Thus, component interaction is accounted for through the dominant shear lag effect while out-of-plane bending in the wall element is ignored. This concept was validated by the modeling of the flanged wall tests as shown above.

The precast pretensioned topped hollow core planks used as the floor system in the 5-story research building test requires the development of special floor elements which exhibit orthotropic flexural and shear characteristics from the unidirectional voids and post-tensioning, while conforming to the adopted rotating crack model. For simplicity a shear flexible semi empirical model for cellular decks, based on Hambley [Hambley,1976], was adopted in conjunction with a 9-node Lagrangian isoparametric layered Reissner-Mindlin plate element. Model verification and calibration with full scale floor and wall coupling tests performed at UCSD. [Seible et. al. 1991] are currently in progress.

This extended model will be used to predict the expected test performance and to investigate observed behavior characteristics in conjunction with the 5-story full scale TCCMAR research building test.

6 CONCLUSIONS

A finite element based analytical model for the analysis of structural concrete and masonry systems subjected to simulated seismic loads has been presented. Comparison of the model with numerous experimental results has shown that the accuracy of the model is satisfactory for both monotonic and cyclic load histories, and that the model can be used both as a predictive and a diagnostic research tool to investigate dominant nonlinear response phenomena. Further extensions of the model to allow for modeling of precast, prestressed hollow-core plank floor systems have been implemented.

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