EARTHQUAKE RESPONSE AND DAMAGE PREDICTION OF REINFORCED CONCRETE MASONRY MULTISTORY BUILDINGS
PART I: PROGRAM DEFINITION

by

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SYNOPSIS

This paper outlines portions of an extensive research program on reinforced concrete masonry. Sample results are discussed in Part II.

INTRODUCTION

Earthquake hazard mitigation through improved design and analysis is the subject of a large-scale experimental, analytical, and numerical research program described, in part, herein. Of primary interest is the development of a basis for a rational earthquake response and damage analysis of load-bearing reinforced concrete masonry multistory buildings. The experimental effort is intended to define structural-material rheology; the analytical phase involves the translation of observed experimental data into viable mathematical models; the numerical effort concerns the conversion of mathematical models into numerical form and the construction of digital computer codes to simulate building response and damage accumulation resulting from earthquake ground motion.

The approach selected to achieve the project objectives involves a sequence of increasingly complex levels of concurrent experimentation, analysis, and numerical simulation. This sequence begins with elementary experiments on the basic constituents of reinforced concrete masonry and their interactions; e.g., by fracture and slip across block-block interfaces. It proceeds to biaxial tests of panels (the first such tests) under both quasi-static and dynamic cyclic load histories. The above is complemented by tests on typical connections. The sequence culminates with experiments and studies on major structural elements. The ability to extrapolate from conceptually simple laboratory-scale experiments to a wide variety of structural configurations, including full-scale building simulations to earthquake ground motion, is one of the most significant and original aspects of the project.

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This research effort constitutes one of the largest earthquake engineering programs of the National Science Foundation. The research team is an integrated university-industrial consortium with unusual capability and facilities. Participants include the University of California, San Diego (host institution); San Diego State University; Agbabian Associates; Weidlinger Associates; Convair Division/General Dynamics Corporation; and a panel of practicing engineers specializing in masonry structures.

SMALL-SCALE TESTS

Modeling on the micro-scale—the most open-ended—commences at the constituent level and requires a knowledge of constituent, and constituent-interface behavior under various stress states. The latter is of prime interest in these studies. Joints or block-to-block interfaces in concrete masonry assemblages constitute both planes of weakness and a major source of damping. Failures frequently initiate in joints, and subsequent deformation and energy absorption occurs by relative slip across joint planes. Joint types selected for study include: 1) ungrouted bed joints; 2) grouted bed joints with and without steel; 3) head joints; 4) combination head and bed joints. Mortar geometry includes both full and face-shell bedding. Test specimens in this series consist primarily of triplets (three blocks, two interfaces). Joint planes are subjected to constant levels of normal stress and quasi-static monotonic, quasi-static cyclic, or dynamic cyclic shear-stress (the latter by driving the center block under displacement control). In each test the initial and post-fracture shear-stress vs. normal-stress envelopes, and deformation histories, are determined. The specific materials under study are described in the following section.

STATIC AND DYNAMIC BIAXIAL PANEL TESTS

Modeling on the continuum or macro-scale, and calibration of micro-models, is accomplished via biaxial panel tests of two basic stress-state types: homogeneous and inhomogeneous.

Globally Homogeneous Stress-States — These tests are unique in that the panels are laid in running bond, but are saw-cut such that the bonds run at oblique incidence or layup to the edges of the finished panel. The rationale: any combination of shear and normal stresses on the critical bed and head joint planes can be induced by an appropriate direct (principal) stress (tension or compression) to panel edges, and the selection of a proper layup angle. The ability to apply direct tensile stresses which exceed the tensile strength of the assemblage, and direct compressive stresses with negligible induced shear, follows from the use of a unique polysulfide bonding agent with a low shear modulus ($\simeq 150$ psi) between the specimen and the load-distribution fixtures. In the case of uniform load application to each panel edge, the resulting panel stress distribution is globally homogeneous, and hence statically determinate. Thus, in contrast to conventional test methods [2], rheology is not prejudiced by boundary constraints; further, in contrast to indirect methods [1], extraction of biaxial failure states does not necessitate a conjecture of isotropic, linear elastic material behavior prior to macrocracking.

Figure 1 illustrates the basic concept of oblique layup testing. If the x_1, x_2-axes are principal stress directions, then the stress resultants N'_{11}, N'_{22}, N'_{12} associated with axes x'_1, x'_2 along bed and head joint directions are related to the principal stress resultants N_{11}, N_{22} through

$$N'_{11},\ N'_{22} = \frac{N_{11} + N_{22}}{2} \pm \left(\frac{N_{11} - N_{22}}{2}\right) \cos 2\theta\ , \quad N'_{12} = \left(\frac{N_{22} - N_{11}}{2}\right) \sin 2\theta\ . \qquad (1)$$

Equations (1) imply that any homogeneous stress-state $(N'_{11}, N'_{22}, N'_{12})$ in a panel with surfaces oriented parallel to the head and bed joints can be obtained by selecting an appropriate layup angle θ and direct stress resultants N_{11}, N_{22}. In particular, given a desired stress-state $(N'_{11}, N'_{22}, N'_{12})$, the combination (N_{11}, N_{22}, θ) is selected according to

$$N_{11},\ N_{22} = \frac{N'_{11} + N'_{22}}{2} \pm \left(\frac{N'_{11} - N'_{22}}{2}\right) \cos 2\theta \mp N'_{12} \sin 2\theta\ , \quad \tan 2\theta = -2N'_{12} / \left(N'_{11} - N'_{22}\right) . \qquad (2)$$

As an example, consider the initial yield or failure surface (onset of macrocracking)—a surface of primary interest. This surface will be closed and convex in the 3-dimensional stress space $(N'_{11}, N'_{22}, N'_{12})$. While the entire failure surface can be mapped by several procedures, the following is worth noting: In practice N'_{22} is due primarily to gravitational forces and vertical accelerations, while N'_{12} is the result of horizontal forces; generally one expects that $|N'_{11}| << |N'_{22}|, |N'_{12}|$. Hence the curve representing the intersection of the plane $N'_{11} = 0$ with the yield surface is of considerable importance. The case $N'_{11} = 0$ and equations (2) yield $N_{11} = -N_{22} \tan^2 \theta$. It is thus evident that the condition $N'_{11} = 0$ with fixed layup angle θ leads to proportional loading.

The test panels of 64-by-64 inches are precision cut from 8-by-8 foot fully grouted, unreinforced or reinforced concrete masonry walls constructed to current field practice. Cutting is accomplished by use of a dynamically balanced, 30-inch-diameter, diamond-edge saw on an air-driven turbine. The above panel size constitutes the smallest specimen deemed to be a "macroelement," i. e., such that the minimum panel dimension is one order of magnitude greater than the largest micro-element (block units). Two masonry types are under study: 1) "normal strength"—type N normal weight concrete block (ASTM C90), Type S mortar (ASTM C270), 2000 psi fine grout (ASTM C476); 2) "high strength"—light-weight block ($f_c' \geq 3750$ psi), type M mortar (ASTM C270), 3750 psi fine grout (ASTM C476).

A schematic of the biaxial test procedure is shown in Fig. 2. The actual setup is illustrated in Fig. 3. The load conditions include quasi-static monotonic, quasi-static cyclic, and dynamic cyclic (.05 to 5 Hz). The system is capable of load, displacement, or combined load-displacement control. This is accomplished with a mini-computer-controlled, closed-loop hydraulic servo system utilizing four active actuators on each panel side connected to load distribution fixtures. This test system is housed in a massive dual test frame, Fig. 4. A high-speed digital data acquisition system (14 bits absolute value plus sign, 300 samples/sec/channel), Fig. 5, monitors 40 channels of signals from load cells, linear variable differential transformers (LVDTs), and strain gages.

Rheological aspects of singular interest include: 1) elastic properties; 2) degree of anisotropy of elastic properties; 3) damping or stress-strain hysteresis in the "elastic" regime; 4) strain-rate sensitivity of item 3, above, in the .05 to 5 Hz range; 5) initial "yield" or macro-fracture surface; 6) degree of anisotropy of item 5 above; 7) ultimate strength; 8) influence of load history on the degradation of stiffness and ultimate strength; 9) hysteresis in the highly nonlinear range; 10) role of reinforcing steel geometry and volume in the control of macrocracking.

Nonhomogeneous Stress-States—The system described above, with modification of the bonding agent, is capable of creating pure shear deformation (in contrast to pure shear-stress), simple shear deformation, simple shear deformation with superposed axial deformation, etc. Such tests, conducted on 0°-layup specimens only, mirror the behavior of shear walls and piers under varying degrees of end restraint. They are more complex than the previous tests, and they comprise an advanced step in the modeling process.

CONNECTION TESTS

Connections are a major concern to both designer and analyst. Little or no data relevant to concrete masonry shear-wall structures is presently available. Tests have therefore been included in this program to investigate the behavior of floor-to-wall and wall-to-wall connections. Floor types will include precast slabs, cast-in-place slabs, and prestressed concrete plank with topping. A number of steel layouts will be investigated. Only minor modifications of the biaxial test system described previously will be necessary to accommodate connection tests. Load histories ranging from quasi-static (.05 Hz) to dynamic (5 Hz) are anticipated.

ANALYTICAL MODELING AND NUMERICAL SIMULATIONS

Numerical simulations at the micro-level have been performed, using the finite element method, of joint tests and biaxial panel tests. Joint fracture and post-fracture behavior (slip) has been modeled by assuming a velocity-independent Coulomb-type friction law with a displacement-dependent friction coefficient. A variable modulus approach has been tentatively adopted to account for block cracking and crushing. Joint slip, separation, and recontact necessitated the development of a method for incorporating interface discontinuities in a finite element analysis. The method presently in use [3] eliminates the need for a finite element to represent an interface, thus avoiding the difficulties due to pseudo thickness and fictitious material properties. For computational purposes, the procedure has been implemented into the nonlinear structural analysis program NONSAP which has undergone extensive revision including extension to an "out-of-core" capability [4].

The above micro-level calculations are intended to serve as a guide in the construction of macro or continuum models which accurately reflect nonlinear material behavior. The latter will be used in the analysis of multistory buildings. Several variable modulus and plasticity-type models for this purpose are under study.

Good correlation with experimental results has been obtained to date for both load and/or displacement histories associated with the aforementioned experiments, and will be discussed in Part II.

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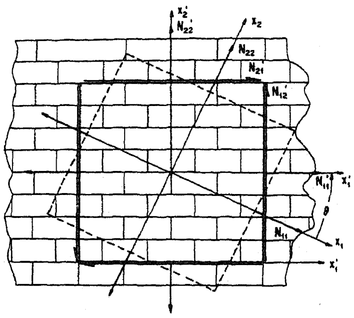

Fig. 1 Stress Transformation.

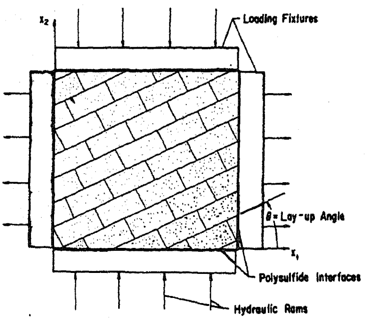

Fig. 2 Loading Schematic.

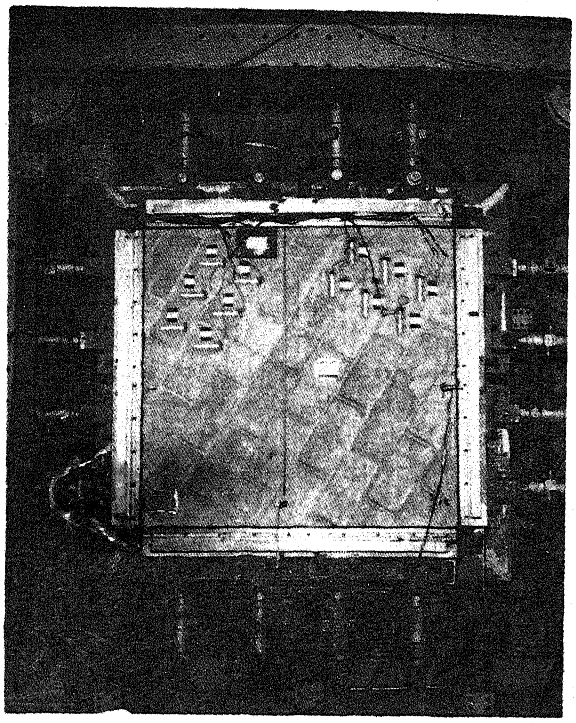

Fig. 3 Biaxial Fixture.

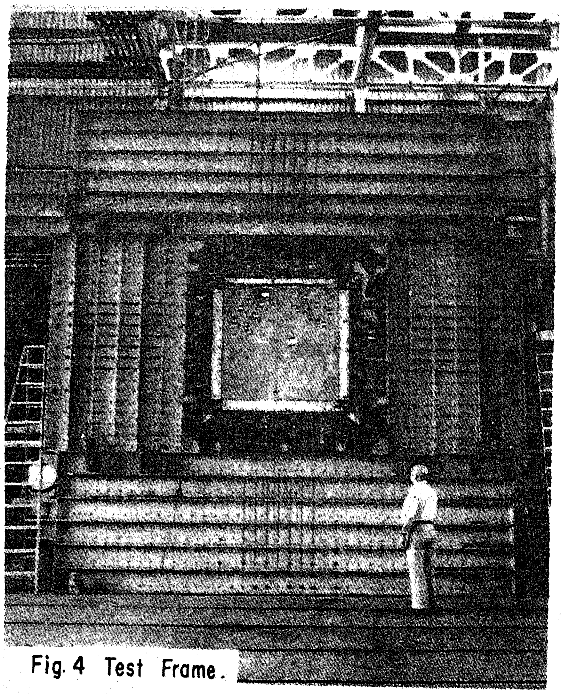

Fig. 4 Test Frame.

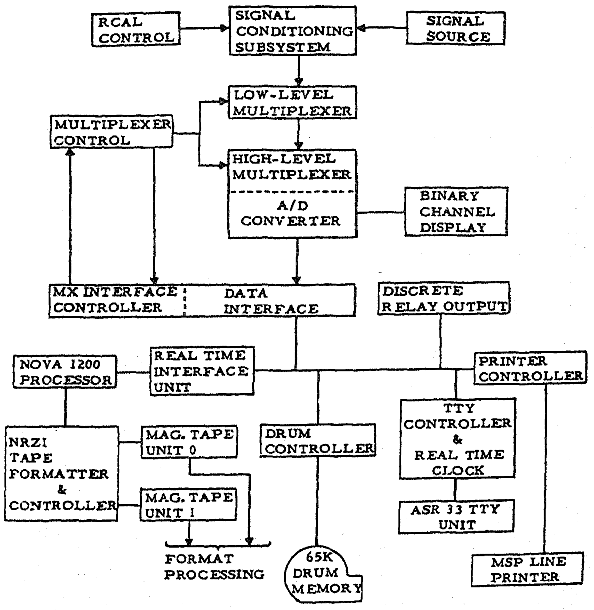

Fig. 5 Data Acquisition.