# MODELING OF REINFORCED CONCRETE MEMBERS AT SMALL SCALES

by

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## SYNOPSIS

A three-part experimental program investigating response of small-scale reinforced concrete structural components is described. The series of test specimens consisted of replicate portions of multistory model structures subjected to simulated earthquake motions: (a) beams used to couple structural walls, (b) structural walls, and (c) beam-column assemblies. Characteristics of behavior are discussed in terms of measured load-deflection relationships to demonstrate the applicability of substituting hysteretic response of small-scale units for that of units constructed at larger scales.

## INTRODUCTION

Because costs of testing buildings within the nonlinear range of response are generally prohibitive, experimental investigations of the behavior of multistory structures subjected to strong ground motions are limited usually to studies using small-scale models secured to platforms of earthquake simulators. Congruent load-deflection relationships for components of small-scale models and actual buildings are essential for valid extrapolations of conclusions made from simulated earthquake tests. The object of this paper is to demonstrate the applicability of using small-scale (approximately one-twelfth scale) construction to represent hysteretic response of large-scale construction.

The three-part investigation consisted of tests of (a) beams used to couple structural walls, (b) structural walls, and (c) interior and exterior beam-column joints. Specimen design, fabrication procedures, test apparti, and experimental procedures are described followed by a presentation of observed response of each specimen type and a brief comparison with response of large-scale specimens.

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## SPECIMEN DESCRIPTION AND FABRICATION

Geometry and reinforcement for each specimen was selected to replicate portions of model structures [3,4] subjected to simulated earthquake motions.

Beams used to couple structural walls (Fig. 1) were 25 x 38 mm deep and 102 mm long. Longitudinal reinforcement consisted of No. 8 gaged knurled wire which was varied from two to one bars top and bottom.

Structural walls (Fig. 2) were 38 x 203 mm deep and loaded at a height above the base which varied from 458 mm to 787 mm. Walls were either lightly reinforced with four No. 2 gage knurled wires or heavily reinforced with sixteen No. 2 gage knurled wires.

Beam-column assemblies (Fig. 3 and 4) consisted of columns 38 x 52 mm deep and beams 38 x 38 mm deep. Load and support points shown in the figure were established to represent idealized locations of contraflexure of multistory frames: midspan of bays and midheights of stories. Longitudinal reinforcement in beams and columns consisted of No. 13 gage wire which was varied from two to three bars top and bottom in beams. In addition, circular spiral reinforcement was provided within the joint regions.

Transverse reinforcement in all specimens consisted of No. 16 gage wire which was provided at small spacings so that effects attributable to diagonal tension would not be significant. Further details of each specimen type are presented in [1,2,3].

Specimens were fabricated of mortar and annealed wire with stress-strain properties similar to full-scale concrete and reinforcing steel. Model concrete was mixed from cement, fine sand and coarse sand in the ratio of 10:0.9:3.6 by dry weight with a water-cement ratio of 0.8. Nominal compressive strength was 32 MPa with a splitting strength equal to 3.5 MPa. Bright-basic wire was annealed and redrawn slightly to attain a precise value of yield stress nominally equal to 350 MPa. A previous investigation indicated that the yield stress of the wire was not sensitive to strain rates on the order of 0.005 per second which corresponded to the range of strain rates attributable to fundamental frequencies of the model structures.

## EXPERIMENTAL PROGRAM

A total of eighteen specimens were subjected to a series of slowly applied loading reversals. Loads were applied through a controlled history containing cycles of progressively increasing displacement so that characteristics of strength and stiffness deterioration could be examined. Alternately for the beam-column specimens, loads were programmed to represent measured interstory displacement histories of multistory frame structures.

The apparatus used to test the coupling-beam specimens simulated the bending provided by a pair of ideally symmetrical walls. Moments were applied to the ends of the test beams, resulting in tension on opposite fibers at each end. A system of ball bearings and steel members described in [1] were used to apply loads and anchor the specimens according to this behavior. Three displacement transducers were used to measure rotation at each end of the beam which eliminated vertical and horizontal movements attributable to connection slip from the observation.

Structural walls were fixed against translation and rotation at base by prestressing base anchorages to a nearly rigid test floor. Readings from dial gages during loading indicated negligible movement of specimens at base. Measurements consisted of lateral displacements of wall and rotations at base.

The apparatus used to test beam-column assemblies was arranged so that loadings could be applied in accordance with equivalent story displacements or joint rotations. Horizontal loads representing story shears of frames were transferred across column members that were restrained partially against rotation by beam members. Hardware included ball-bearing connections that simulated roller supports at ends of beams and a pin support at base of the column member.

Testing of all specimens was monitored with an x-y plotter that displayed an observed relationship of load and deflection. Data was recorded at a sufficient number of points to represent a smooth curve, stored on a punched tape, reduced, and plotted using a digital computer. Displacement and rotation data measured with electronic transducers was confirmed with readings from mechanical dial gages.

## OBSERVED RESPONSE

Measured hysteretic relationships for each specimen type (Fig. 1 through 4) illustrate general characteristics common to all specimens tested and common to most large-scale reinforced concrete components subjected to loading reversals within the nonlinear range of response. Two distinctive trends were observed of all specimens: (1) an extreme variation in stiffness at different load levels within a particular cycle of loading, including a marked reduction in stiffness upon reversal of load, and (2) a reduction in stiffness at a particular load-level for successive cycles of progressively increasing deflection. It should also be noted that, except for coupling-beam specimens, reductions in flexural strengths were not significant. However, with sizeable reductions in stiffness for later cycles of loading, deflections necessary for strengths to be developed may be excessive for a particular type of structure.

Within a particular cycle of loading the following characteristics of the load deflection curve were common for all specimens tested:

(1) Slope of the curve in the loading portion of the first

cycle was appreciably larger than in loading portions of subsequent cycles. Furthermore, slopes calculated using curvature distributions based on stress-strain relationships of reinforcement and concrete were consistently larger (by as much as a factor of three for coupling-beam specimens) than measured slopes. Differences in calculated and measured values may be attributable to slip of longitudinal reinforcement which varied with specimen type.

(2) Slope of the curve near maximum loads reduced substantially which may be attributable to yield of longitudinal reinforcement or deterioration of bond strength.

(3) Slope of the curve in unloading portions of a cycle was larger than the slope in the previous loading portion. Initial unloading slopes were nearly vertical.

(4) Slope of the curve reduced suddenly in load-reversal regions of a cycle indicating a closing of flexural cracks and slip of reinforcement. This observation was most perceptible for coupling-beam (Fig. 1) and interior-joint specimens (Fig. 4).

(5) Slope of the loading portion in the low-load regions increased gradually in every cycle except the first.

Subsequent loading cycles following cycles of increased maximum deflections revealed reduced slopes in loading and unloading regions of the curves. Moreover, the stiffness transition in low-load regions occurred over a wider range of deflection than for cycles of smaller amplitude.

Observed patterns of damage supported the tendencies inferred from the measurements. Crack development for the coupling-beam specimens consisted of flexural cracks at opposite corners of each beam, and diagonal-tension cracks. Flexural cracks opened to approximately 0.2 mm at maximum loads suggesting that the observed nonlinear behavior was attributable to more than strain in the reinforcement. Reversing the load resulted in a closing of the flexural cracks at a load approximately equal to one-fourth of maximum. As the load reached maximum, faint splitting cracks on the tension face were observed with minor crushing of the concrete on the opposite face.

Cracks observed at base of structural walls indicated that reinforcement had yielded and extended within the anchorage. The stable load-deflection relationship upon reversal of the load suggested that the extension of anchored reinforcement had occurred elastically. At large-amplitude cycles, walls with heavy reinforcement cracked extensively in diagonal directions and crushed at extreme compression fibers. Plastic elongation of reinforcement was clearly noticeable, particularly for lightly reinforced walls during later cycles of loading.

Cracks attributable to flexure of beams in beam-column assemblies (as large as 0.6 mm) suggested strongly that slip of longitudinal beam reinforcement within the column had a controlling influence on the behavior of the assembly. Upon reversal of the loading, these cracks immediately closed further corroborating the occurrence of slip. This tendency was observed to be much more perceptible for interior-joint specimens than exterior-joint specimens as demonstrated by salient differences in the slope of the load-rotation curve in load-reversal regions (Fig. 3 and 4). Failure of the specimens resulted from fracture of the reinforcement or crushing of the concrete at an excessively large displacement (approximately nine percent of story height).

## COMPARISON WITH LARGE-SCALE SPECIMENS

Numerous investigators [5,6,7] have reported tests of large-scale reinforced concrete structural elements subjected to loading reversals. General tendencies associated with shapes of hysteresis loops of the small-scale specimens as discussed previously were also observed with specimens constructed at large scales: suggesting that the mechanisms of energy dissipation in reinforced concrete structures can be modeled correctly at small scales. However, sensitivities of overall structural response to differences in load-deflection behavior for small-and large-scale construction need to be examined to evaluate quantitatively the distortion involved with scaling nonlinear dynamic response of multistory structures. Parameters of overall response such as apparent natural frequencies, maximum displacements, displaced shapes, inertial loads and interaction between lateral-load resisting components should be calculated based on hysteretic behavior of both small and large-scale specimens for comparison of these sensitivities.

Tests of small-scale components have also suggested that correlation with response of large-scale components was dependent on the form of lateral-load transfer of the particular type of structural unit. Small-scale walls (Fig. 2) and exterior beam-column assemblies (Fig. 4) responded with stable hysteresis loops similar to those of large-scale specimens. Coupling beams (Fig. 1) and interior-joint assemblies (Fig. 4) responded with a more discernable softening in load-reversal regions and were more sensitive to stiffness deterioration than specimens constructed at large scales. Differences in behavior because of scaling may be attributed to differences in bonding of reinforcement to concrete which was crucial on behavior of both coupling beams and interior-joint assemblies because of the reversal of bar force from compression to tension over a relatively short distance (span length of coupling beam or width of column).

## SUMMARY AND CONCLUSION

A test series consisting of eighteen (approximately one-twelfth scale) specimens constructed of mortar and wire were subjected to slowly applied loading reversals to examine modeling of reinforced concrete members at small-scales. Structural units tested consisted of beams used to couple structural walls, structural walls, and beam-column assemblies.

Test results suggested that mechanisms of energy dissipation in full-scale reinforced concrete structures may be modeled correctly at small scales. General tendencies associated with strength and stiffness deterioration with loading cycles of successively larger amplitude, and shapes of hysteresis loops correlated with those for large-scale specimens tested by other investigators.

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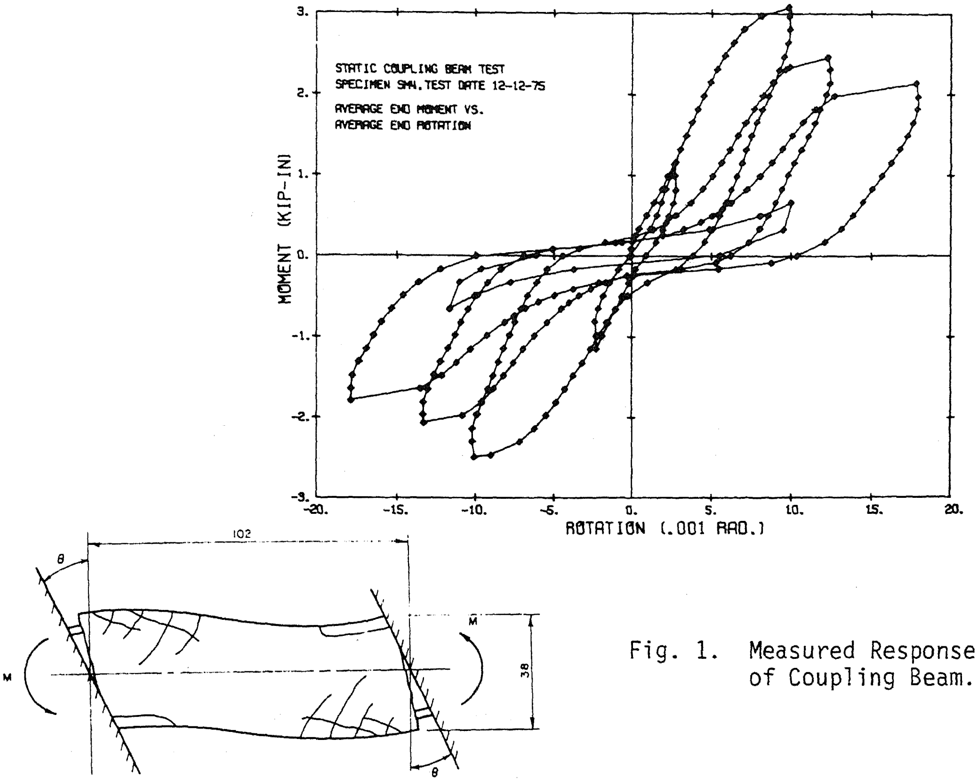

Fig. 1. Measured Response of Coupling Beam.

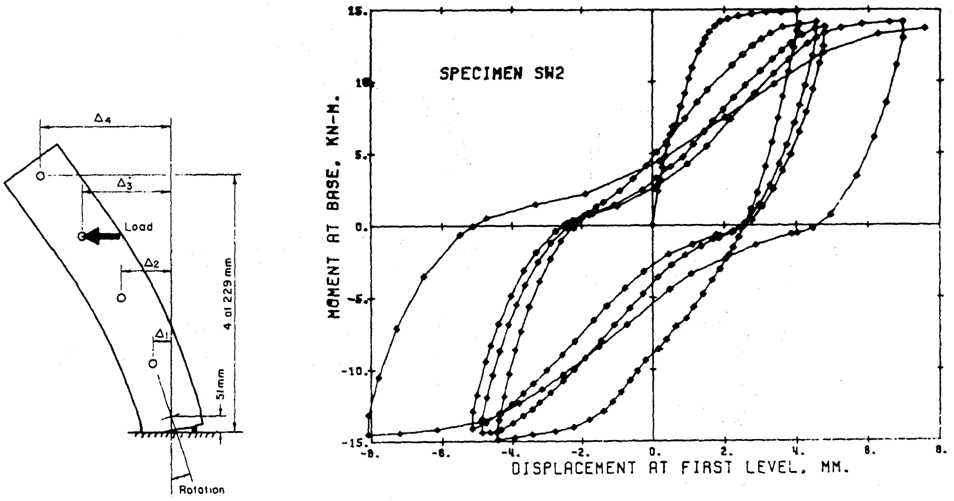

Fig. 2. Measured Response of Structural Wall.

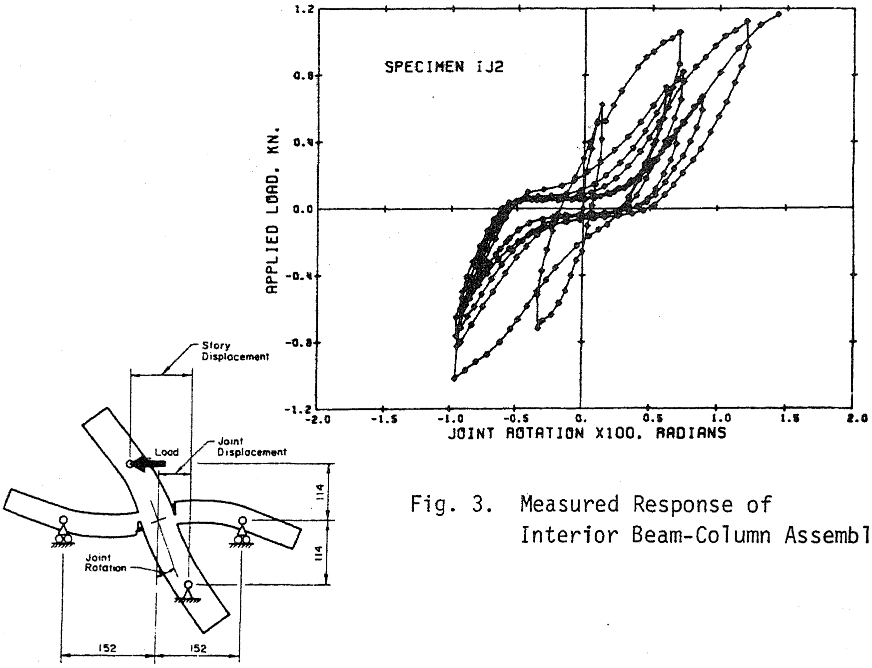

Fig. 3. Measured Response of Interior Beam-Column Assembly.

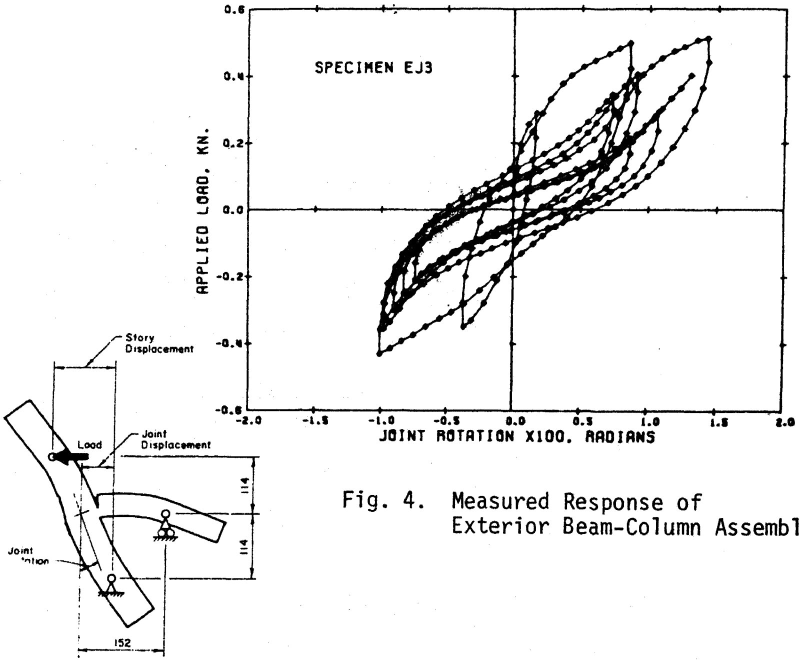

Fig. 4. Measured Response of Exterior Beam-Column Assembly.