THE INFLUENCE OF LOAD HISTORY ON THE SHEAR BEHAVIOR OF SHORT RC COLUMNS

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SUMMARY

Virtually all previous experimental work on the behavior of columns has been concentrated on unidirectional lateral loads and constant axial loads (generally compressive). However, seismic motions can occur in any horizontal direction in a structure and may be accompanied by variable axial forces on the columns (tension or compression). As part of an extensive program at The University of Texas at Austin, a series of columns was tested to determine the influence of bidirectional lateral deformations and varying axial forces on the behavior of short reinforced concrete columns.

EXPERIMENTAL PROGRAM

In this paper the results of 18 specimens simulating a short column between stiff floors are reported. The columns had a cross section of 30×30 cm and a length of 91 cm. The test specimen is shown in Fig. 1. The longitudinal reinforcement consisted of eight 19 mm bars with 90° hooks anchored in the end blocks. Transverse reinforcement was fabricated from 6 mm deformed bars spaced at 65 mm and designed to produce a column that might not perform satisfactorily under the imposed loads, but which represented typical practice in column design. The nominal yield strength of the reinforcement was 420 MPa. The nominal strength of the concrete was 35 MPa with values ranging from 30 to 41 MPa. The geometry and reinforcement was kept constant throughout. The specimens were subjected to a number of load histories, as discussed below. In each case the lateral deformations were applied to a given level for three reversals and then the deformation was increased or the deformation path was changed. The following lateral deformation and axial load histories were considered.

1. No axial load with the following lateral deformation path:
   - (a) Unidirectional; 0-U (Fig. 3)
   - (b) Unidirectional with constant deflection in one direction; 0-U4, 0-U2 (Figs. 7, 8)
   - (c) Bidirectional, previous loading in orthogonal direction, 3 cycles to selected level; 0-B2, 0-B4 (Figs. 4, 5)
   - (d) Bidirectional, alternate directions; 0-BA (Fig. 6)
   - (e) Skewed along a 45° axis (uni- or bidirectional); 0-D, 0-DA (Figs. 9, 10)
   - (f) Z-pattern, quadrants 1 and 3; 0-Z (Fig. 13)
   - (g) Square; 0-S (Fig. 14)

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2. Constant compressive (1 level, 120^k or 530 kN) or constant tensile (3 levels, 50, 100, or 200^k; 220, 450, or 900 kN) axial loads with two lateral deformation paths:
   (a) Unidirectional; 120C-U, 50-T-U, 100T-U (Fig. 18), 200T-U
   (b) Bidirectional; 120C-B, 50T-BA

3. Alternating tensile and compressive axial loads:
   (a) Unidirectional; ATC-U
   (b) Bidirectional; ATC-BA (Figs. 21, 22)

The lateral loading was deformation-controlled and axial loading was load-controlled. Deflection levels were multiples of Δ_i, the deflection producing yield in the longitudinal reinforcement under loading 0-U. A schematic elevation view of the test setup is shown in Fig. 2 (similar arrangement in the orthogonal direction). The lateral loads are applied with 670 kN servo-controlled actuators and the vertical load with a 1330 kN servo-controlled actuator. Three paired positioning actuators are used to control the rotation of the top end in each plane. The loading frame and hydraulic loading system are anchored to the floor-wall reaction system. Details of the loading apparatus are described in Ref. 1.

TEST RESULTS--NO AXIAL LOAD

Shear lateral displacement curves for most of the specimens subjected to various lateral load histories are shown in Figs. 3-14. In each figure, a sketch showing the NS and EW lateral deformation history is shown. Loading history 0-U (Fig. 3) provides a base from which other loadings may be compared. In each figure a dashed line is shown to indicate the expected monotonic response. The monotonic response was determined from loading 0-B4 (Fig. 4) in which a large deformation was imposed during the first cycle. Note the large difference in response between 0-B4 and 0-B2 (Figs. 4 and 5). With the application of three cycles of load to a deflection level of $4\Delta_i$ in the EW direction, the NS response showed that the section had failed prior to NS loading. Loading in the EW direction to $2\Delta_i$ did not have nearly as large an effect as the subsequent NS response.

Figure 6 shows the response under alternate loadings in the NS and EW directions. The response is nearly identical in both directions and compares closely with that of 0-B2. This is summarized in Fig. 12 which shows the normalized peak values of shear in the first cycle to each deflection level. Shear was normalized with respect to the core area and $\sqrt{f'}$ to reduce differences produced by material strengths. In general, when the previous loading in either direction produced deflections in excess of that at which peak capacity was reached under unidirectional loading (about $2\Delta_i$) stiffness and strength degraded rapidly.

Two specimens (Figs. 7 and 8) were cycled unidirectionally NS but with a constant deformation in the EW direction. As before, with a large deflection in the EW direction, considerable loss of capacity in the NS direction is noted. Two specimens were subjected to loads along the diagonals. For test 0-D (Fig. 9), the NS and EW response is nearly identical but is considerably below the monotonic curve. If, however, the resultant shear and deformation are computed by combining the NS and EW components, the response compares favorably with unidirectional or monotonic. This is shown in

Figs. 11a and 11b. Figure 10 shows the response under diagonal loading in alternate directions. The top plot in Fig. 10 is for the NS direction under loading in the NE-SW diagonal and the bottom plot is for the EW direction under loading along the NW-SE diagonal. Four plots are needed to fully present the data; however, only two are shown here to give the response in the first and last cycles at a given deflection level. If resultant values are computed, the response compares favorably with unidirectional or diagonal loading (one diagonal only).

More complex paths were applied, as indicated in Figs. 13 and 14. In each case the deformation is applied first in one direction, held while the second (orthogonal) deflection is applied, and then the first deformation is reversed while the second is held. The resulting loading patterns are denoted by the general shape of the path, "Z" (0-Z) and square (0-S). Note that the curves for 0-Z show vertical (shear) discontinuities near the origin while those for 0-S show large changes in shear with little change in deflection at peak deflections. The changes in shear are produced when the load required to hold a given deflection in the NS direction, for example, reduces as the EW deflection is increased or decreased. Figure 15 shows that loading 0-S and 0-Z were the most severe in terms of the loss of capacity at large deflection levels and with increase in number of cycles. In general, the most severe degradation of shear capacity and stiffness occurred in those loadings in which orthogonal directions were loaded simultaneously (0-U2, 0-U4, 0-Z, 0-S).

Figure 16 compares the shear-displacement curves from different loading histories between two given deflections (points 1 and 2) in the first and third quadrants. Note that the response is nearly the same in all cases with the curves falling in a fairly narrow band.

TEST RESULTS--AXIAL LOAD

Axial load variations were selected with the intention of developing basic information. Because no data have been reported regarding cyclic lateral loads in combination with axial tension, three levels of axial tension were included and only one of compression. The upper limit for tension axial force (200T) is represented by the force required to produce yield in the vertical reinforcing bars. The level of axial compression used produced an average stress (based on the core area) of 8.4 MPa. Tests ATC-U and ATC-BA are included to simulate loads induced by an earthquake on an exterior column in which tension alternating with compression occurs. Test ATC-BA is intended to simulate loads induced by an earthquake on an exterior column of a slender R/C building in which tension alternating with compression occurs for deformations in one direction, and only compression for deformations in the orthogonal direction. The sequence of application of axial force in relation to lateral loads is shown in Fig. 21.

In Fig. 17, the peak normalized shear for the first and last peaks at each deflection level in the north direction are compared for tests 00-U, 00-B, 120C-U, and 120C-BA. The monotonic curve is also shown for comparison. In 120C-U and 120C-BA, applied shear first increases for levels of deformation up to $2\Delta_i$ and after that a high rate of shear deterioration is exhibited. The effect of lateral alternate deformations in the orthogonal direction is reflected by a more drastic shear deterioration after the $2\Delta_i$ level. In Fig. 18, the shear-deformation response is shown for a specimen with constant tension at half of yield (100T). Envelopes of first and last peaks of normalized shear for tests with constant tension are presented in Fig. 20. The required shear to attain given deformation decreases as the level of tension increases but less shear deterioration is observed. In Fig. 19, the progressive strain in a tie for tests 00-U, 120C-U, and 200T-U is shown. In 00-U, the tie remains below yield, while a similar tie in 120C-U reaches yield at $2\Delta_i$ level. The tie in 200T-U remains low throughout.

Figure 23 shows the envelopes in the NS direction of loading for test ATC-BA as compared with 50T-BA. Peaks to the north show similar behavior but lower strength in relation to 50T-BA (same level of tension applied to different sequence). This is due to the mode of application of tension and the presence of compression in the orthogonal direction in ATC-BA. For peaks to the south, test ATC-BA shows similar behavior to 120C-BA but less shear deterioration is noted. A more complete description of tests with axial load is given in Ref. 2.

CONCLUSIONS

Based on the tests, the following general conclusions may be made:

(1) The load history influences the rate of stiffness and strength degradation. Bidirectional lateral histories in which the deformations were applied alternatively in each direction produced a slightly more rapid degradation than unidirectional loadings. Response under loading along a skew (NE-SW or NW-SE) axis was nearly the same as when deformations were applied along a major (NS or EW) axis of the specimen.

(2) Square deformation paths or those in which a constant deformation was applied and held while cycles were applied in an orthogonal direction produced very rapid deterioration of the columns.

(3) Constant compressive axial loads appeared to accelerate shear deterioration. Constant tension decreased shear deterioration but substantially reduced the shear capacity and the stiffness. Alternating tension and compression produced results quite similar to that of constant compression except at the peak deformations where tension was imposed on the column.

ACKNOWLEDGMENT

The support of the National Science Foundation through Grants ENV75-00192 and ENV77-20816 for this work is gratefully acknowledged. The opinions, findings, and conclusions are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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2. Ramirez, H., and Jirsa, J. O., "The Influence of Axial Load on the Response of Columns under Bidirectional Loadings," CEB Seismic Symposium, Rome, June 1979.

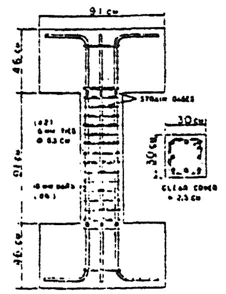


Fig. 1 Test specimen

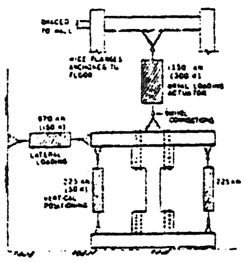


Fig. 2 Elevation of Test Setup

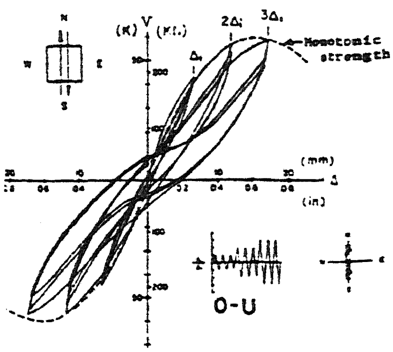


Fig. 3 Load History 0-U

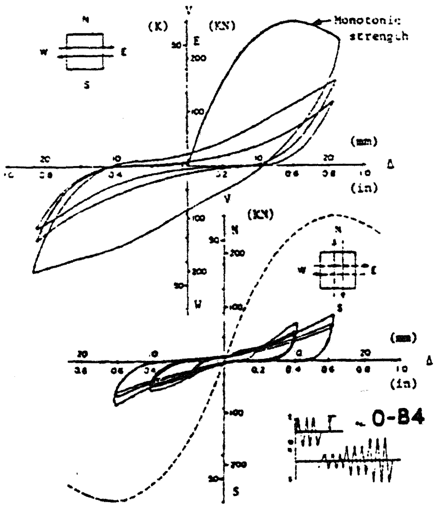


Fig. 4 Load History 0-B4

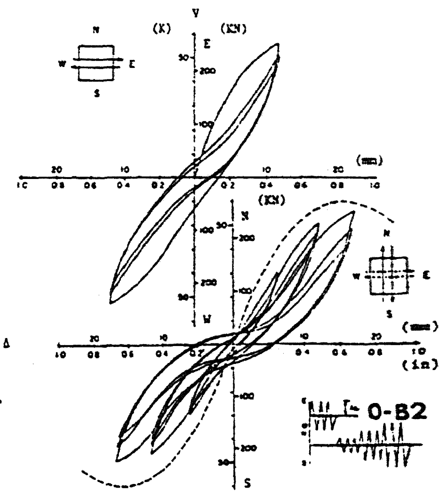


Fig. 5 Load History 0-B2

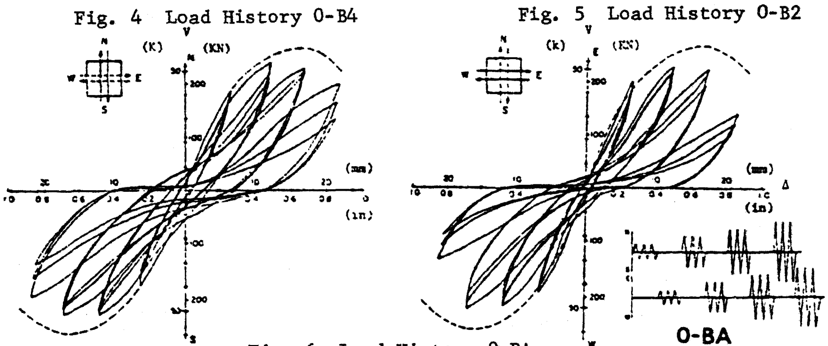


Fig. 6 Load History 0-BA

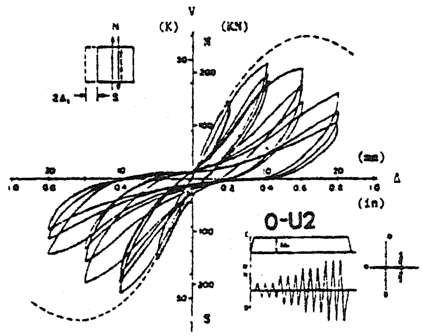


Fig. 7 Load History 0-U2

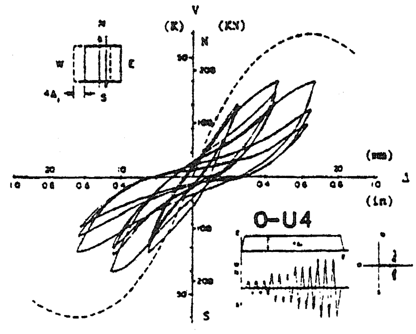


Fig. 8 Load History 0-U4

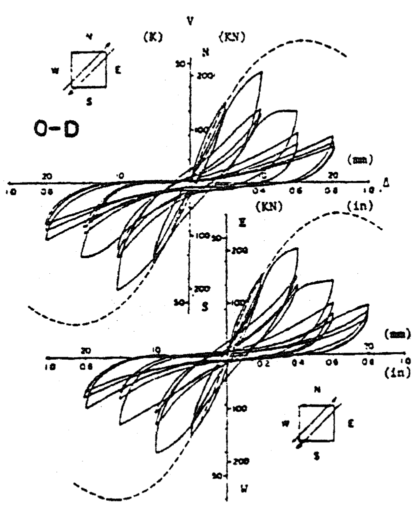


Fig. 9 Load History 0-D

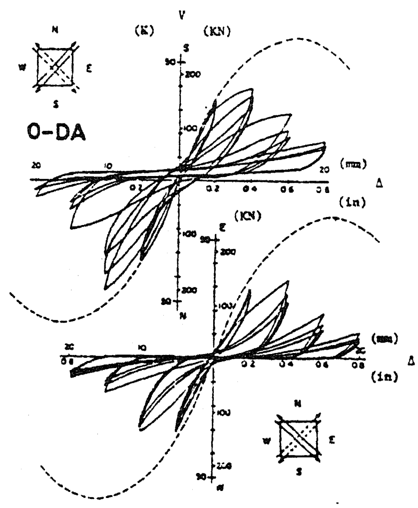
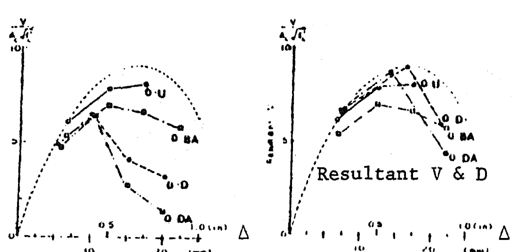


Fig. 10 Load History 0-DA



a) NS axis b) Diagonal axis

Fig. 11 Influence of Load Path

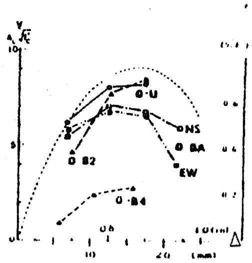


Fig. 12 Influence of Previous Loading

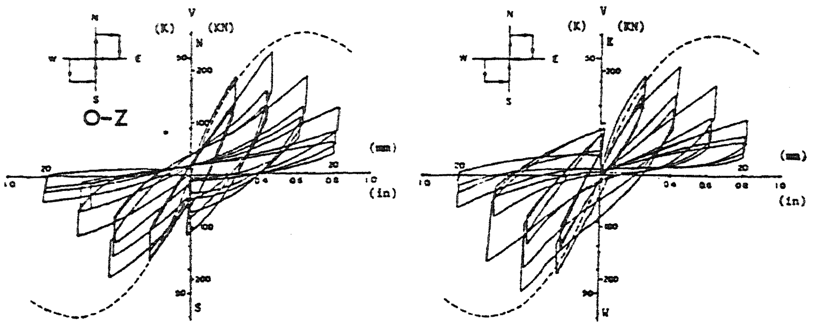


Fig. 13 Loading History 0-Z

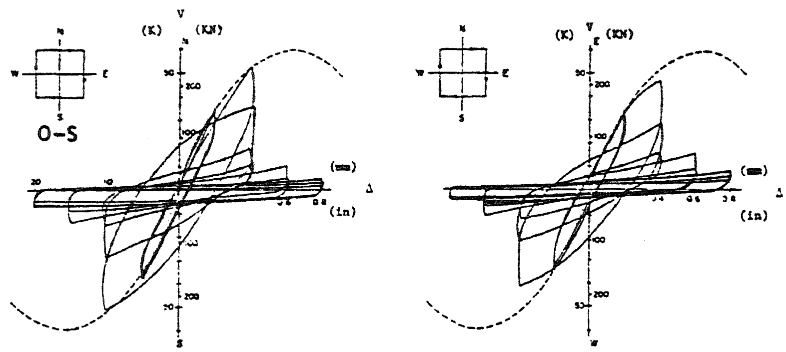


Fig. 14 Loading History 0-S

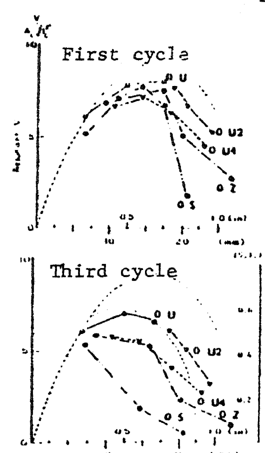


Fig. 15 Influence of Load Path

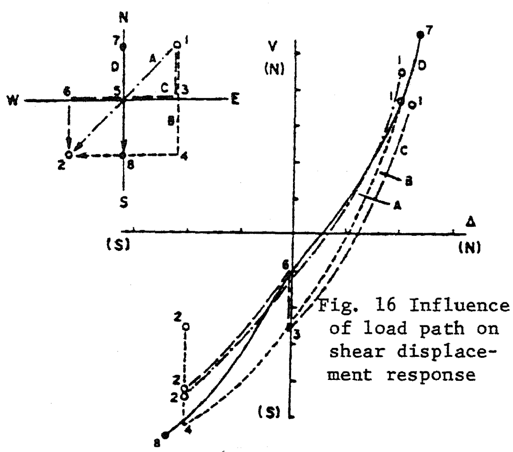


Fig. 16 Influence of load path on shear displacement response

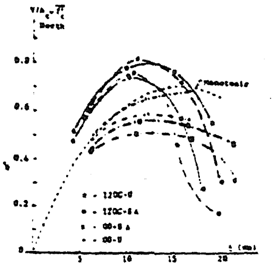


Fig. 17 Effect of Axial Load

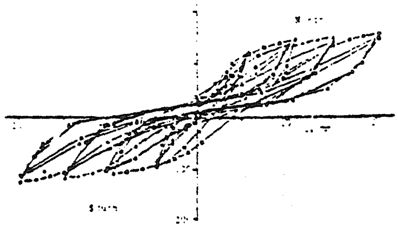


Fig. 18 Loading History 100T-U

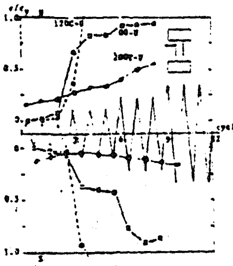


Fig. 19 Tie Strains

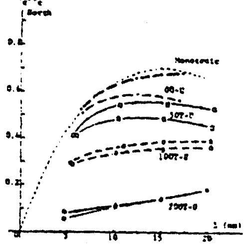


Fig. 20 Effect of Tension Load

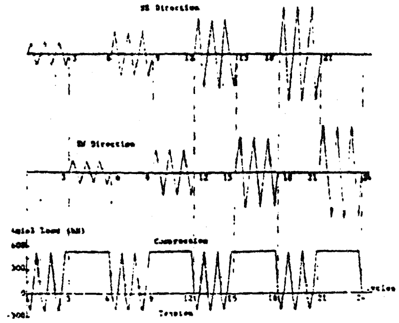


Fig. 21 Load Path, ATC-BA

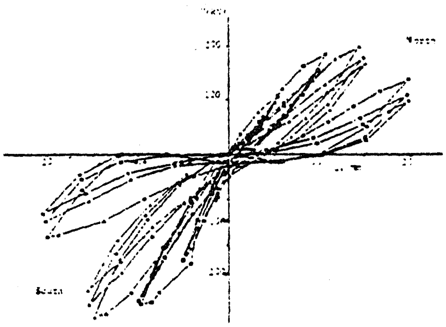


Fig. 22 Loading History ATC-BA

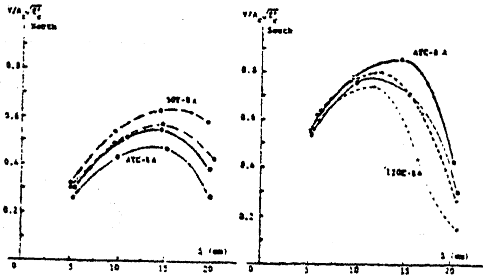


Fig. 23 Effect of ATC Loading