

# REINFORCED CONCRETE COLUMNS SUBJECTED TO UNIAXIAL AND BIAXIAL LOAD REVERSALS

Murat Saatcioglu (I)

## SUMMARY

The behavior of reinforced concrete columns, subjected to uniaxial and diagonal biaxial load reversals was investigated. Seven full scale column tests were conducted. The main variables were the axial load, amount of shear reinforcement and the type of cyclic loading. It was found that the presence of axial compression reduced ductility and accelerated strength and stiffness degradation. Increased shear reinforcement improved the hysteretic behavior of columns. Overall column behavior was not affected by reversing the lateral load cycles along a column diagonal.

## INTRODUCTION

Columns of a frame structure are largely responsible for overall strength and stability of the structure. Contrary to a local structural failure, consequence of a column failure, supporting a number of floors can be quite severe. Therefore, it is desirable to proportion members such that a significant portion of the earthquake induced energy can be dissipated by yielding in the beams, rather than the columns. However, at the base of a multistory building, it is practically impossible to prevent inelastic action under severe ground excitations. It is therefore necessary to investigate the behavior of reinforced concrete columns under reversed cyclic loading, well into the inelastic range.

Under a reversed cyclic loading, members exhibit either a "flexure dominant" or a "shear dominant" behavior depending on the relative magnitudes of shear and flexure. The presence of axial load also has a significant influence on column behavior and therefore deserves full attention.

The objective of this paper is to present the results of an experimental investigation on reinforced concrete columns. The experimental program currently underway at the Structures Laboratory of the University of Toronto involves full scale testing of concrete columns under uniaxial and diagonal biaxial load reversals with or without axial loads.

## EXPERIMENTAL PROGRAM

### Test Specimens

The test specimens used were reinforced concrete columns representing a portion of a first story column between the foundation and the inflection point. The columns had 350 mm by 350 mm cross-section and 1.0 m height (shear span). Figure 1 illustrates the dimensions of the test specimens. Two types of columns were constructed; one for uniaxial, and the other for diagonal

(I) Assistant Professor, Department of Civil Engineering, University of Toronto, Toronto, CANADA

biaxial loading. In the latter case, the columns were cast 45 degree rotated in the horizontal plane to facilitate the same loading arrangement as the uniaxial specimens. Specimens for uniaxial and diagonal testing were designated by "U" and "D" respectively. A detailed discussion of the experimental program is given in Ref. 1.

The longitudinal reinforcement arrangement was identical in all columns and consisted of eight 25 mm bars, equally spaced along the four faces. The transverse reinforcement consisted of 10 mm ties spaced at 150 mm, 75 mm, or 50 mm.

Top ends of the column specimens were constructed with special care to insure a proper load transfer. Shear keys and matching steel plates were used to transfer the load. The load was applied at the center region of the column section, which was then distributed to the specimen through a steel plate and the shear keys.

#### Test Procedure

The columns were subjected to slowly applied forced deformation cycles. The column footing was post-tensioned to the strong floor of the laboratory, to restrain the bottom end against rotation. Horizontal translations were applied at the column top end by means of two servo controlled 220 kN MTS hydraulic actuators. Three of the seven columns were deflected uniaxially, and the rest were deflected along a diagonal. Five columns were tested under constant axial load of 600 kN by means of a 2700 kN MTS hydraulic test frame. Figure 2 illustrates the test set-up.

The displacement history followed during the horizontal load reversals is shown in Fig. 3. The magnitude of deflection at each cycle was based on an increment of the yield deflection  $\Delta_y$ . The yield deflection corresponded to the deflection at which the critical column section yielded as a whole, rather than the level at which the first yielding of the extreme reinforcement took place.

#### Observed Behavior

All specimens developed flexural and shear cracks. First flexural cracks appeared near the column base. These cracks later developed along the column height, mostly at the tie levels, on faces perpendicular to the loading. First diagonal cracks appeared in the mid-height region, prior to yielding of the longitudinal steel. At the later stages of loading, diagonal cracks developed along the entire height, on faces parallel to the loading. Those specimens loaded along a diagonal showed diagonal cracks on all four faces. Typical crack patterns for uniaxial and biaxial specimens are shown in Figs. 4 and 5.

The load-deflection curves for the seven columns tested are shown in Fig. 6. The overall column behavior can be obtained by examining these curves. Among the seven specimens, only D4 showed predominantly flexural behavior, with very little or no pinching. The others showed predominantly shear behavior. The failure of D4 resulted from disintegration of the core concrete within the hinging region, near the base. The behavior was ductile,

and relatively high deflections could be developed with little or no strength loss. In all the other specimens wide diagonal cracks led to the spalling of concrete in the middle region of the specimens. Grinding of the core concrete, along the shear cracks followed the widening of the diagonal cracks prior to failure.

#### Effect of Axial Load

Columns U1 and D1 had no axial load. Both specimens initially showed little strength and stiffness degradation under the increased deformation cycles. The strength loss at  $2\Delta_y$  was approximately 16% in U1 and 1% in D1.

Two companion specimens, U2 and D2 were tested under 600 kN constant axial compression. This load level was approximately equal to 60% of the balanced section axial load. These two specimens showed excessive strength and stiffness degradation with increased deflections and increased number of load cycles. The strength loss resulted from the three cycles at  $2\Delta_y$  was approximately 48% in U2 and 42% in D2. At  $3\Delta_y$  both specimens deteriorated significantly, showing very little load resistance.

Two other specimens under 600 kN constant axial compression with twice the shear reinforcement as U2 and D2 were tested. These specimens (U3 and D3) also showed excessive stiffness and strength loss with increased deformations. The comparison between the columns with and without axial compression clearly indicated that the ductility was drastically reduced with axial compression.

#### Effect of Shear Reinforcement

Three different magnitudes of shear reinforcement were used in this phase of the investigation. The shear reinforcement consisted of 10 mm ties. Specimens U2 and D2 had 150 mm tie spacing. The load-deflection curves shown in Fig. 6 indicates that these specimens showed rapid strength and stiffness degradation under the increased deformation cycles. Wide diagonal shear cracks developed along the entire height of the specimens. Yielding of the tie reinforcement and subsequent grinding of core concrete along the diagonal cracks led to full disintegration of the specimens. The strength at the end of three cycles at  $2\Delta_y$  was approximately 52% of the peak strength in U2 and 58% in D2. The specimens failed prior to completing cycles at  $3\Delta_y$ .

Specimens U3 and D3 had 75 mm tie spacing. In spite of the fact that the shear reinforcement was increased by a factor of two, as compared to the previous two specimens, improvement in the overall behavior was very little. Similar observation was also made by other researchers (Ref. 2). The strength at the end of three cycles at  $2\Delta_y$  was approximately 70% of the peak strength in U3 and 62% in D3. This time however, the specimens could develop three more cycles at  $3\Delta_y$ , although the strength had dropped tremendously.

Specimen D4 had 50 mm tie spacing. With this level of shear reinforcement the behavior improved significantly. The specimen developed  $4\Delta_y$  and was subjected to 18 load cycles at various magnitudes and showed almost no strength loss. The hysteresis loops were stable showing a ductile behavior. At this load stage the axial load was removed because the lateral deflection capacity of the axial load frame was approached. The specimen was further

cycled without the axial load and developed high deflections with some strength and stiffness loss at very high deformation levels.

### Biaxial Load Effects

The column specimens were constructed in pairs, one for uniaxial and the other for biaxial displacement reversals. Only a special case of the biaxial loading, namely the diagonal biaxial loading was considered in this phase of the investigation.

Examination of the test results indicate that the yielding in each direction in a biaxial specimen occurs at a resistance lower than the yield resistance under uniaxial loading. This is expected mainly due to the biaxial interaction effects. The force-deflection curves given in Fig. 6, however, indicates that the overall behavior of uniaxial and biaxial specimens are similar. When ductility, stiffness, and strength characteristics of biaxial columns are examined it can be seen that they are similar to those of the uniaxial columns.

### CONCLUSIONS

The following conclusions can be made based on the test results:

- The effect of constant axial compression on the hysteretic behavior of reinforced concrete columns is to accelerate the strength and stiffness degradation under increased deformation cycles. The inelastic load and deformation capacity of columns is severely reduced by the presence of axial compression.
- There is a limit to the amount of shear reinforcement below which an increase in shear reinforcement does not produce appreciable improvement in column behavior. However, once this limit is exceeded, column behavior improves substantially and the dominant behavior mode changes from shear to flexure. The test specimens designed to satisfy the ACI 318-83 (Ref. 3) requirements for regions of high seismic risk performed poorly when tested under constant axial compression. A specimen with 50% more lateral steel than that of the ACI requirement performed satisfactorily, showing a ductile behavior.
- Biaxial load effect on columns is to reduce the yield capacity in each direction as compared to the uniaxial load capacity. However, the overall column behavior and the hysteretic behavior of uniaxial and biaxial columns are found to be similar.

#### ACKNOWLEDGEMENTS

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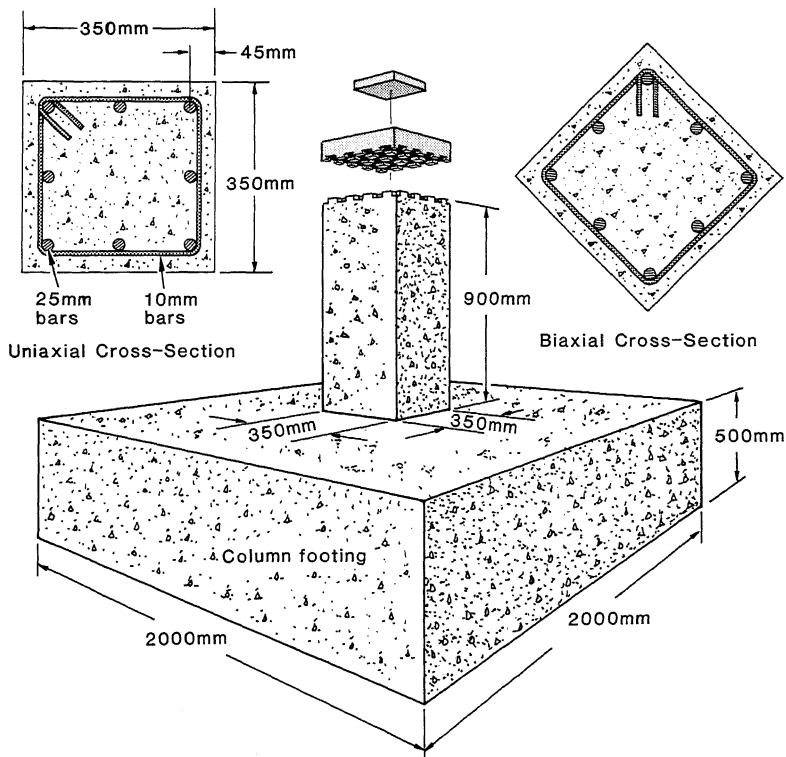


Fig. 1 Test Specimen

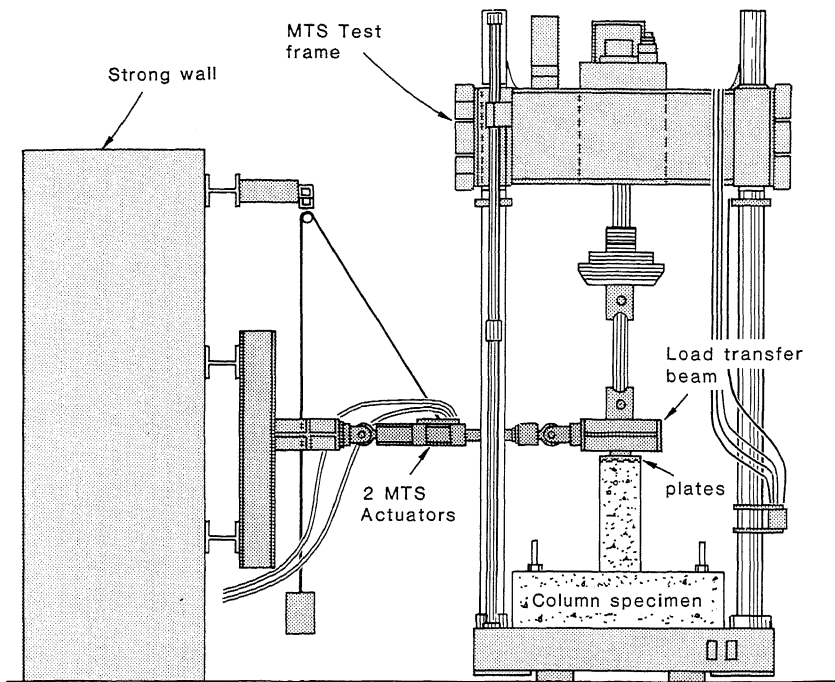


Fig. 2 Test Set-Up

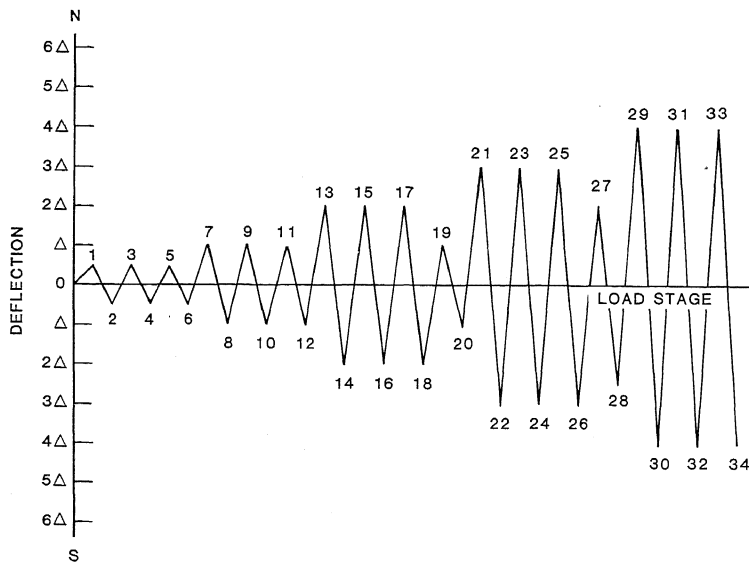


Fig. 3 Deflection Cycles

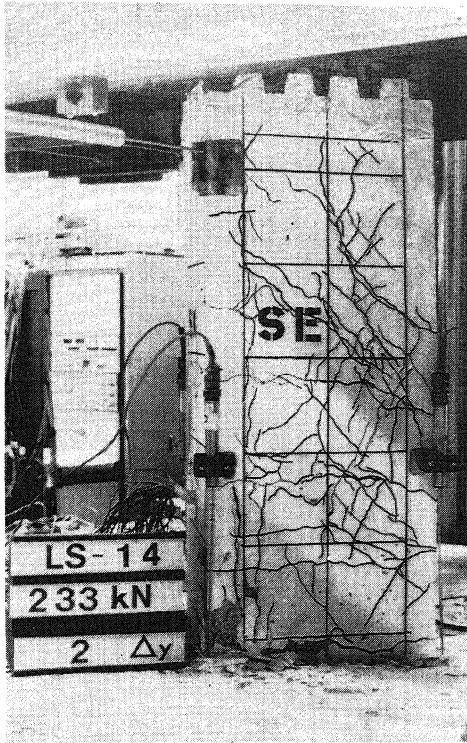


Fig. 4 Crack Pattern of Specimen D2

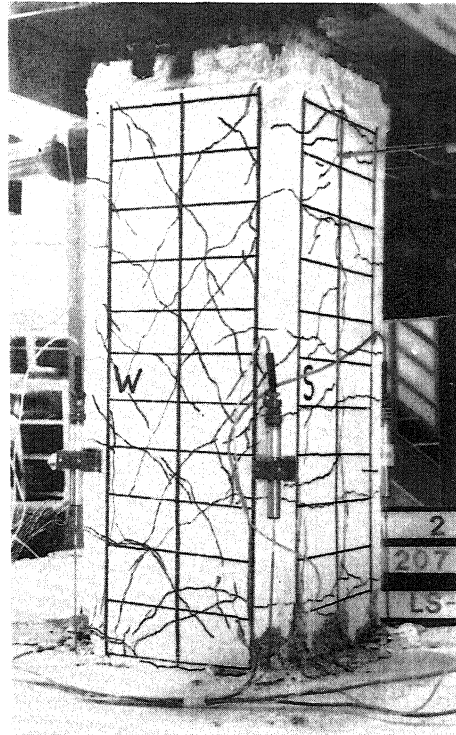


Fig. 5 Crack Pattern of Specimen U3

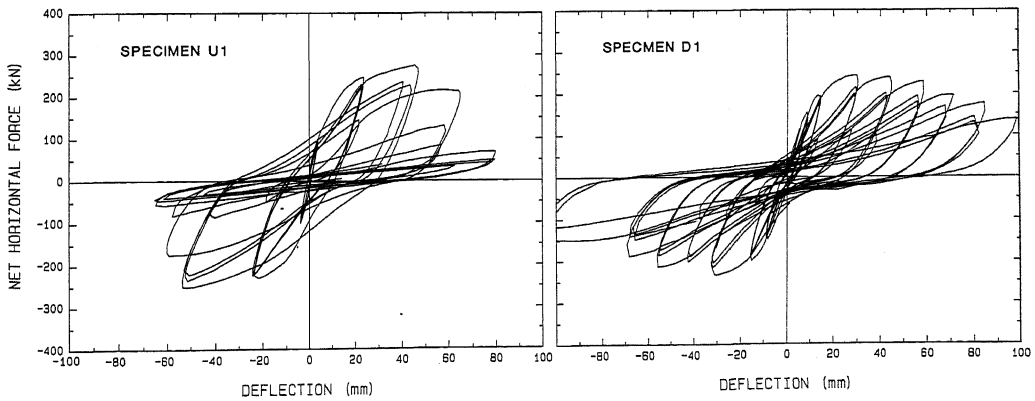


Fig. 6 Horizontal Load Versus Top Deflection Curves.  
(Loads and deflections for "D" type columns  
are along the diagonal)

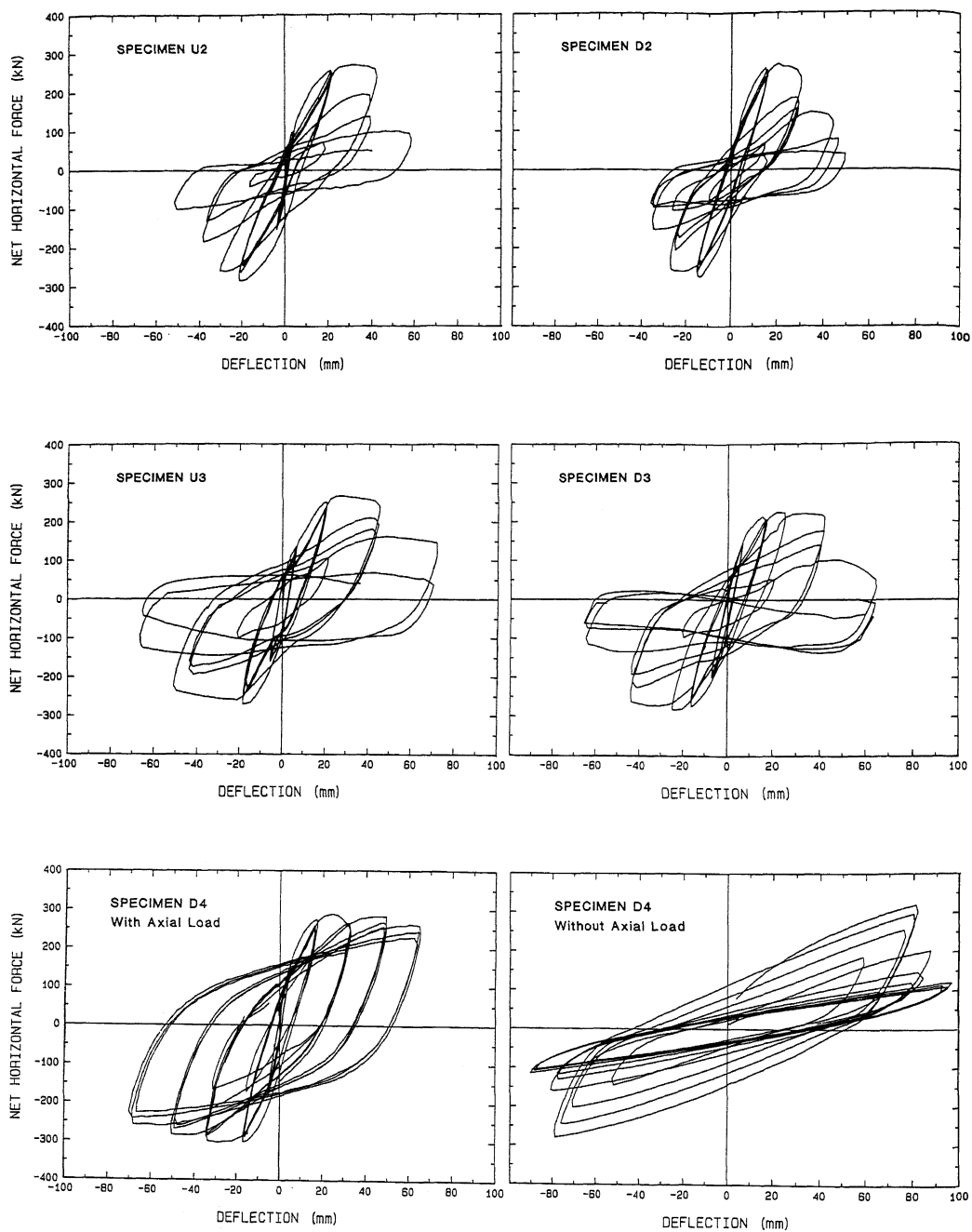


Fig. 6 (Cont'd) Horizontal Load Versus Top Deflection Curves  
(Loads and deflections for "D" type columns  
are along the diagonal)