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Effect of bar slip on hysteretic behaviour of concrete columns

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ABSTRACT: The effect of reinforcing bar slip on nonlinear response of reinforced concrete columns is discussed. Tests of full scale column specimens under inelastic load reversals are described. Slippage of main column reinforcement embedded in column footing and its effect under cyclic loading is presented. Results indicate that additional rotation caused by reinforcement slip can form 40 to 60 % of total rotation. A very significant portion of total horizontal displacement in columns can be attributed to reinforcing bar slip.

1 INTRODUCTION

Performance of reinforced concrete structures during recent earthquakes has demonstrated that column hinging may occur in the critical regions of structures during a strong earthquake. Therefore, prediction of inelastic deformations and the associated hysteretic response of reinforced concrete columns is essential for aseismic design of structures.

Inelastic deformations in a frame member are generally produced by flexure. Shear forces may also produce appreciable inelasticity in a member depending on aspect ratio and relative strengths in flexure and shear. When hinging occurs adjacent to a connecting element, yielding of reinforcement generally penetrates into the adjoining member. Elongation of the embedded steel and the resulting deterioration of bond between concrete and steel produces additional deformations. These deformations concentrate at member ends in the form of rigid body rotations and are not accounted for in flexural and shear analyses. The contribution of reinforcement slip to total deformation can be very significant, and its neglect can lead to gross inaccuricies in estimating structural stiffness.

Ismail and Jirsa (1972) observed that yield penetration into the anchorage zone accounts for up to 60 % of total deflection. Other researchers (Bresler and Bertero 1968, Bertero and Popov 1977) also concluded that deformations due to bar slip can be very significant.

The effect of reinforcing bar slip on hysteretic response of first storey columns was investigated by the authors, as part of a comprehensive investigation on nonlinear response of columns (Saatcioglu, Ozcebe and Lee 1987). Full size column specimens were instrumented to measure the hysteretic deformations due to bar slip and were tested under reversed cyclic loading. The results are summarized in this paper.

2 EXPERIMENTAL PROGRAM

2.1 Test specimens

A portion of a first storey column, between the foundation and the inflection point was selected for testing. Details of a representative test specimen are illustrated in Fig. 1.

Four columns were instrumented to measure deformations due to bar slip. Longitudinal reinforcement, consisting of eight 25 mm diameter bars, were used in all specimens. Computed flexural capacity, based on specified concrete strength of 30 MPa and reinforcement yield strength of 400 MPa was 285 kN.m. Shear capacity, in excess of that corresponding to the flexural capacity, was provided in all columns. Details of the transverse reinforcement are shown in Fig.1. Type A transverse reinforcement arrangement was used in specimens U4 and B2. Types B and C were used in specimens U6 and U7 respectively. A summary of the material properties is given in Table 1.

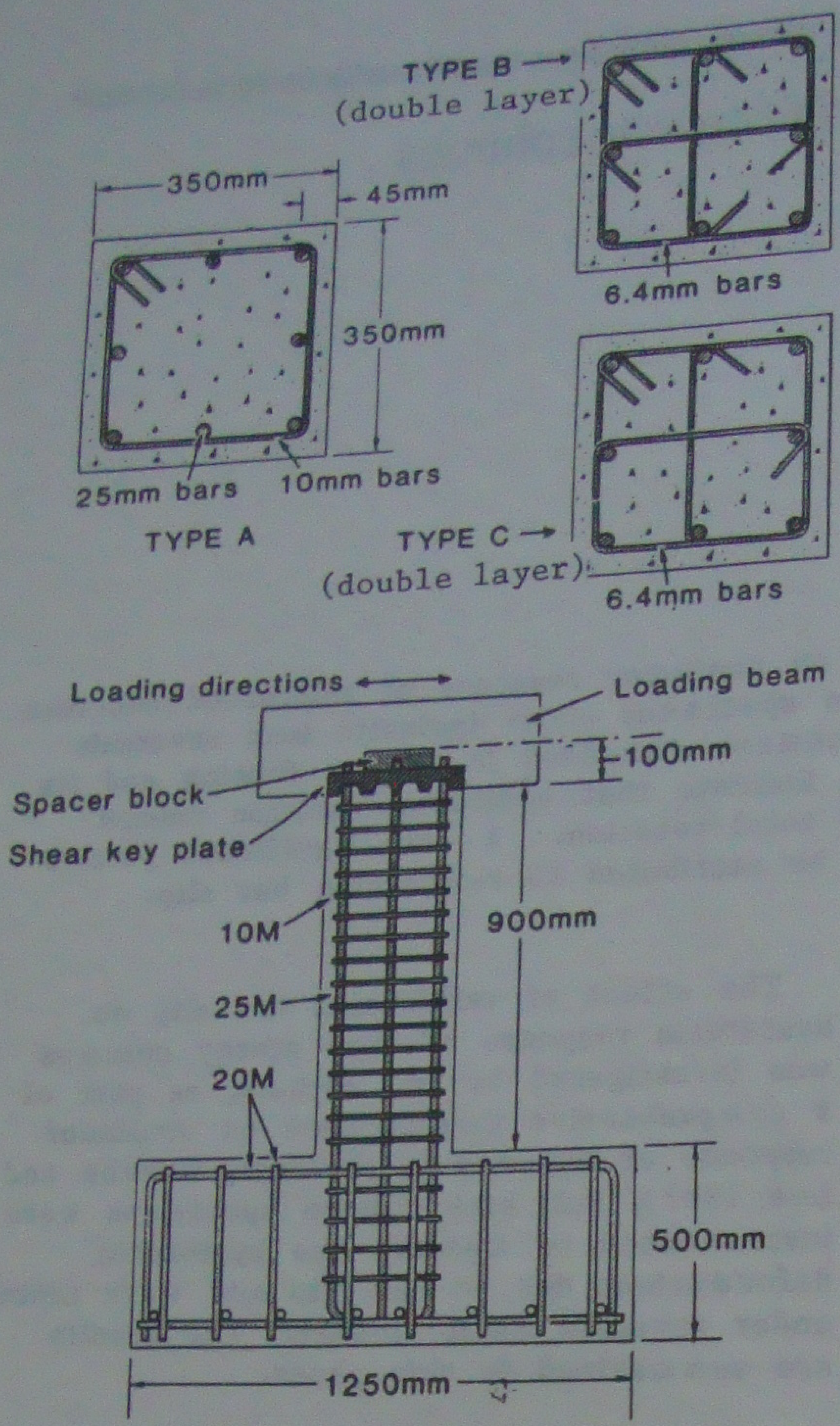

Figure 1. Details of test specimens

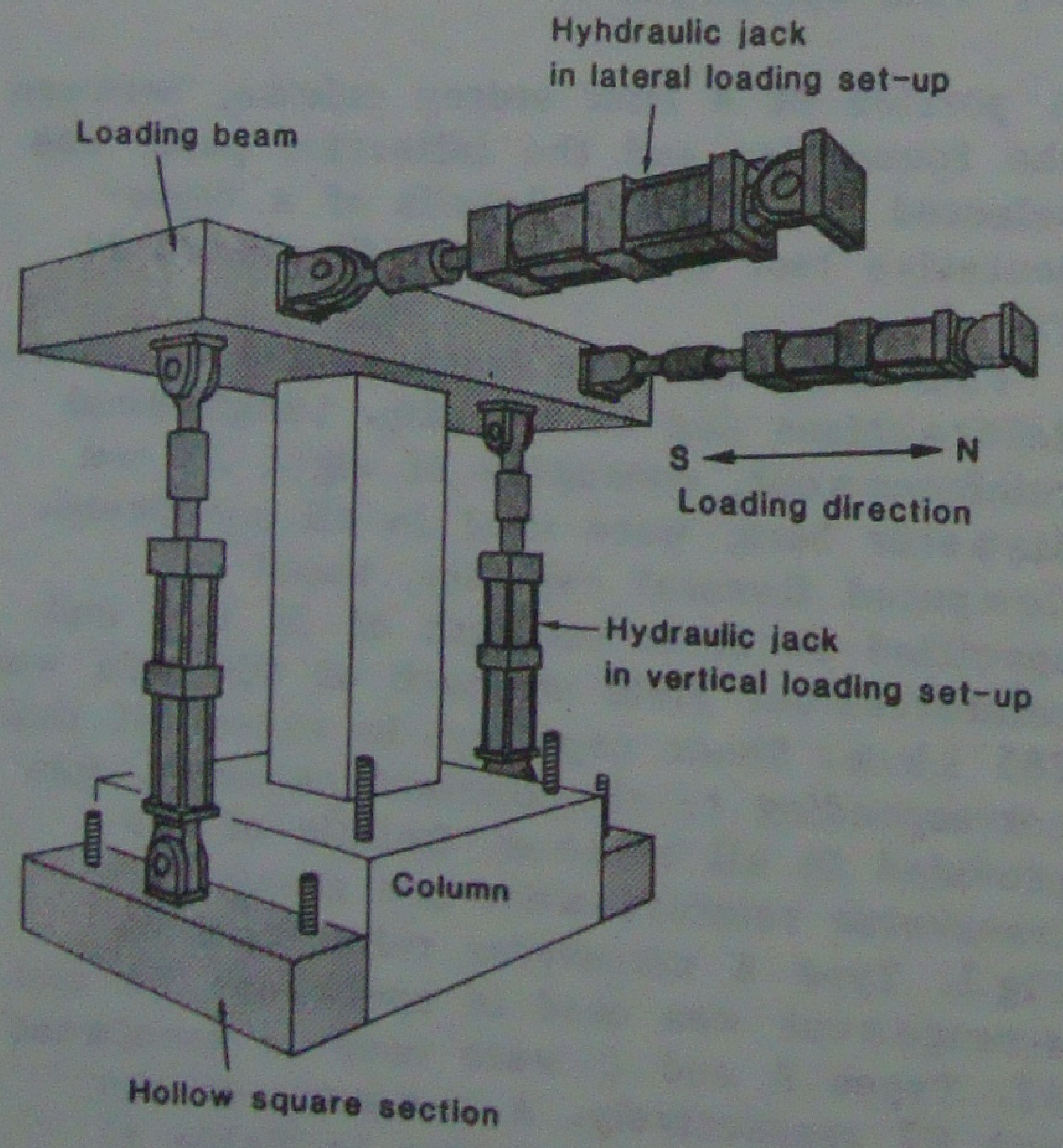

Figure 2. Test set-up

Table 1. Material Properties

test specimen	concrete strength (MPa)	long.steel strength (MPa)	trans.steel strength (MPa)
U4	32.0	438	470
U6	37.3	437	425
U7	39.0	437	425
B2	32.0	430	470

Specimens U4, U6, and U7 were subjected to uni-directional displacement cycles. Specimen B2 was subjected to bi-directional deformation cycles, following an elliptical path.

2.2 Test setup

The test setup is illustrated in Fig.2. Column footing was post tensioned to the laboratory strong floor to achieve full fixity. The lateral load was applied by means of two servo controlled 250 kN capacity MTS actuators. A special load transfer assembly was used to transfer the load on to the columns. An additional hydraulic jack was attached to the load transfer assembly in the transverse direction for bi-directional loading.

All columns were tested under 600 kN of constant axial compression. Two 500 kN capacity hydraulic jacks were used to apply the axial load. The applied level of axial load corresponded to approximately 12 % of the nominal column capacity, or 20 % of the column design strength.

2.3 Loading program

The specimens were subjected to displacement controlled lateral load reversals, following the displacement history shown in Fig. 3. Horizontal displacement cycles were progressively increased as increments of yield displacement Δ_y . The yield displacement was determined during the test. When the rate of increase in deflection was beginning to be high at a relatively constant level of load, the displacement was recorded to be the yield displacement. This level of displacement was observed to be slightly higher than the level at which the first yielding of extreme reinforcement was recorded.

Specimen B2 was simultaneously subjected to deformations in both principal directions. An elliptical deformation path, shown in Fig. 4, was used to simulate the response of a structure subjected to major deformation cycles in one direction, while

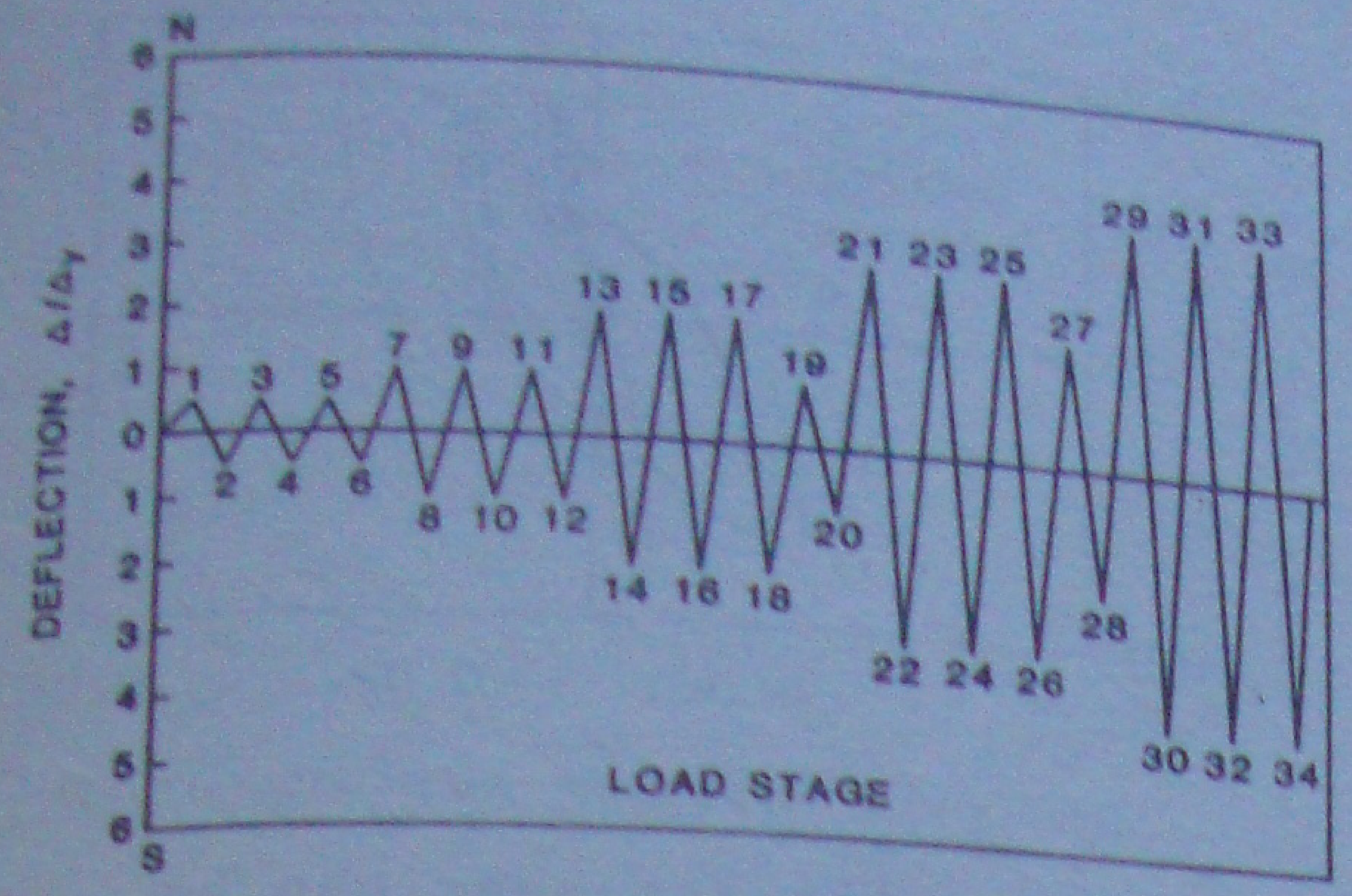

Figure 3. Uni-directional loading

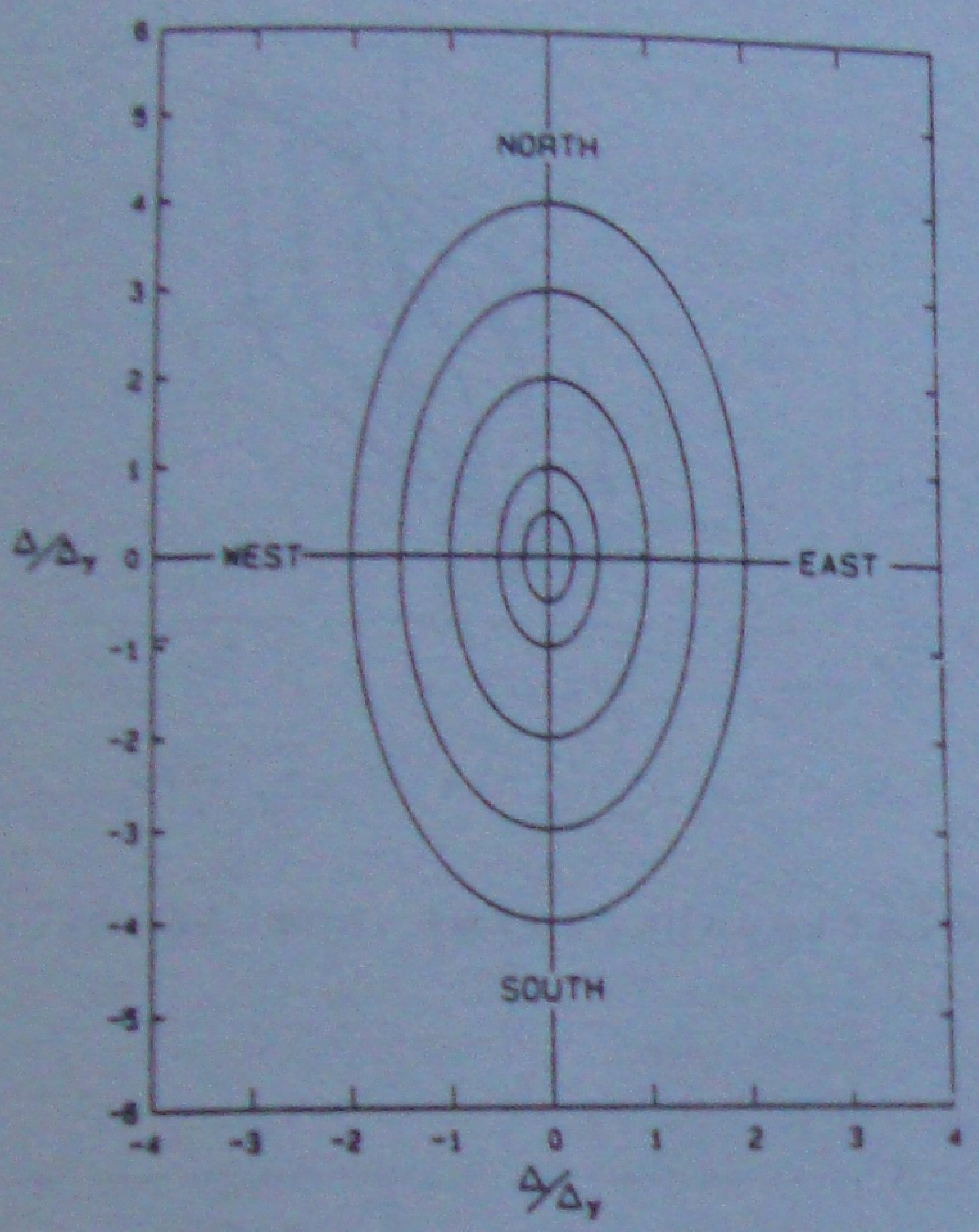

Figure 4. Bi-directional loading

simultaneously subjected to minor cycles in the orthogonal direction. The aspect ratio of the ellipses was 1/2.

2.4 Instrumentation

The specimens were instrumented with DC operated Linear Variable Differential Transformers (LVDT). Horizontal displacements were measured at three different locations along the column height. Four LVDT's were placed in the hinging region in an upright position to record the rotations relative to the column critical section. Additional LVDT,s were placed in the same region to measure the total rotation of the hinging region relative to the column footing. This reading included the rotation due to bar slip. The difference between the two readings gave the base rotation due to bar slip alone.

Both the horizontal and vertical reinforcements were instrumented with electric resistance strain gauges. A Hewlett Packard (HP) 3052A automatic data acquisition system was used to record the data.

2.5 Test procedure

Each test was started by applying the axial load. This load was kept constant at 600 kN during the test. The horizontal load was applied slowly and controlled by deformations. The loading program shown in Figs. 3 and 4 were followed. The horizontal load was increased in increments of the yield displacement until strength degradation was excessive, and the specimens resisted very little load. In the case of bi-directional loading, the specimen was first deformed in the major direction to the desired level of displacement. The elliptical path was then followed until the next displacement level was reached.

3 SUMMARY OF RESULTS

All specimens developed flexural and shear cracks. Flexural cracks first appeared near the column base, during the initial three cycles prior to yielding. One of the first flexural cracks took place at the column footing interface. New flexural cracks formed during the subsequent three cycles at yield displacement. Widening of the crack at the column footing interface was observed during the post yield cycles. This was an indication of bar slip within the column footing. As the deformations were increased, further widening of the existing cracks were observed. Very few new cracks formed during the subsequent cycles. At $2\Delta_y$, the crack at the column footing interface became very wide, indicating a significant concentration of rotation due to bar slip at column base.

Shear cracks formed on faces parallel to the direction of loading. The first diagonal shear crack appeared shortly before yielding. Unlike the flexural cracks, new diagonal cracks formed whenever the magnitude of load exceeded the previous maximum.

Figs. 5 through 8 illustrate the moment-rotation hysteretic relationships recorded during the tests. The total rotation of hinging region includes rotations due to flexure and bar slip. Examination of the hysteresis curves indicates that a significant portion of column rotation is caused by bar slip. This rotation starts as early as elastic response, and increases with

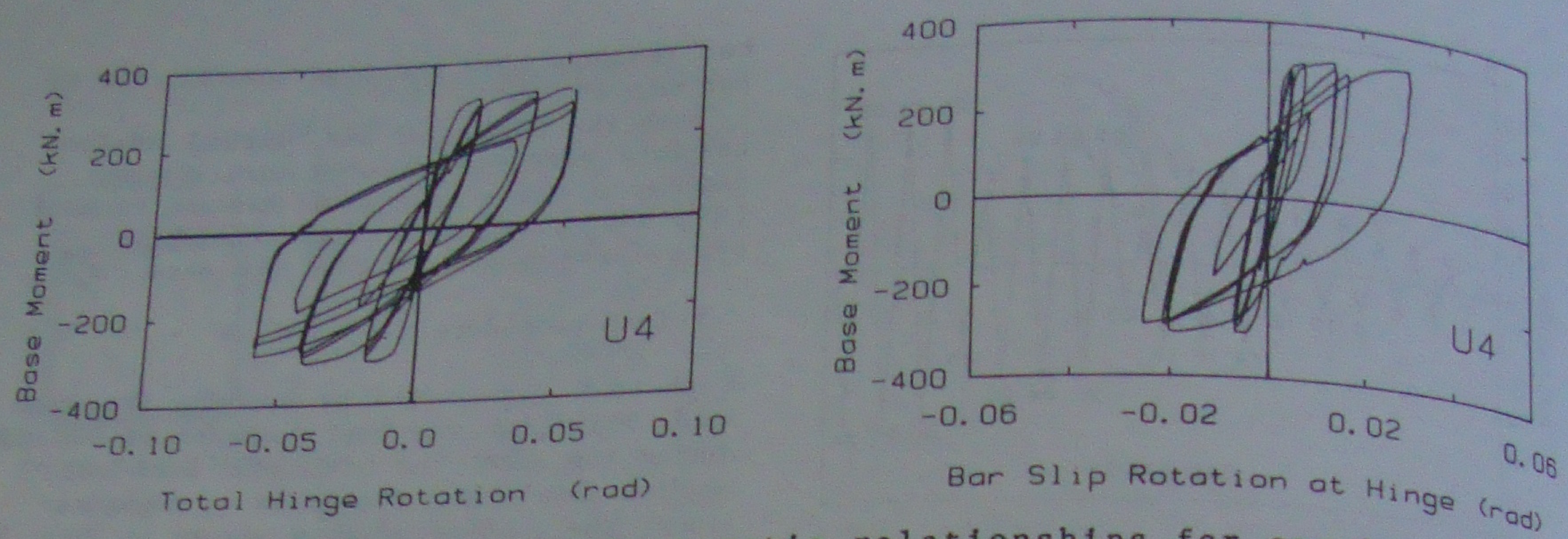

Figure 5. Moment-rotation hysteretic relationships for specimen U4 (Hinge length : 260 mm)

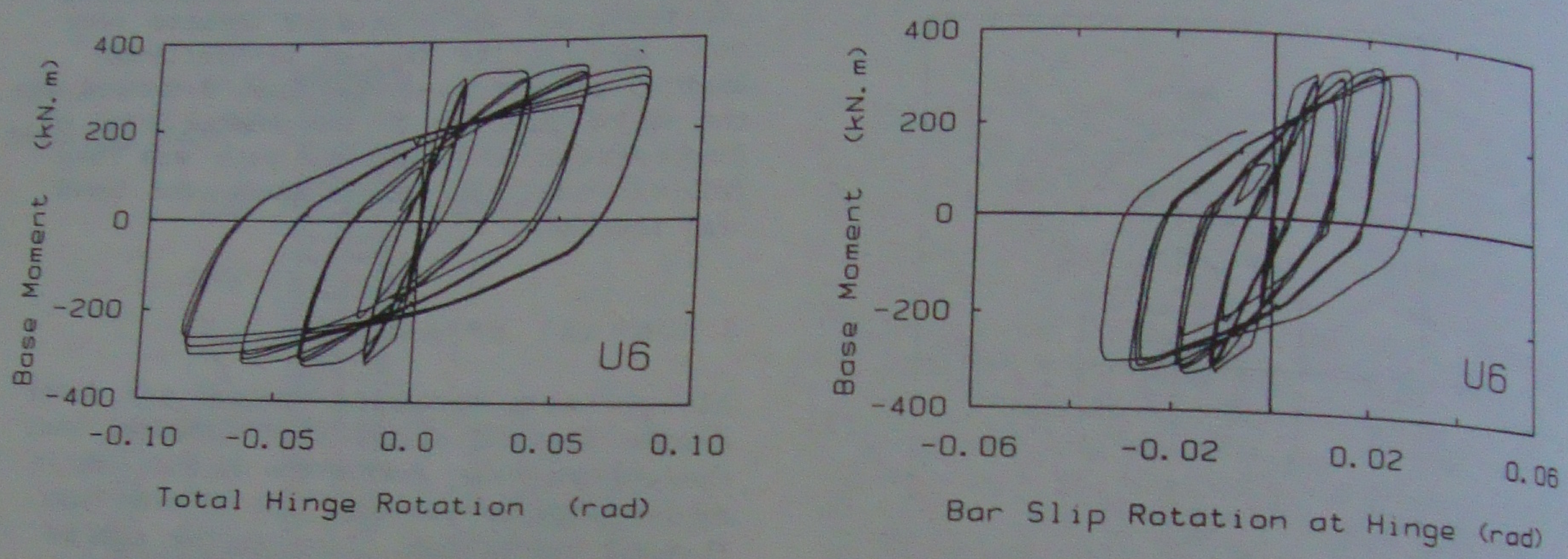

Figure 6. Moment-rotation hysteretic relationships for specimen U6 (Hinge length : 270 mm)

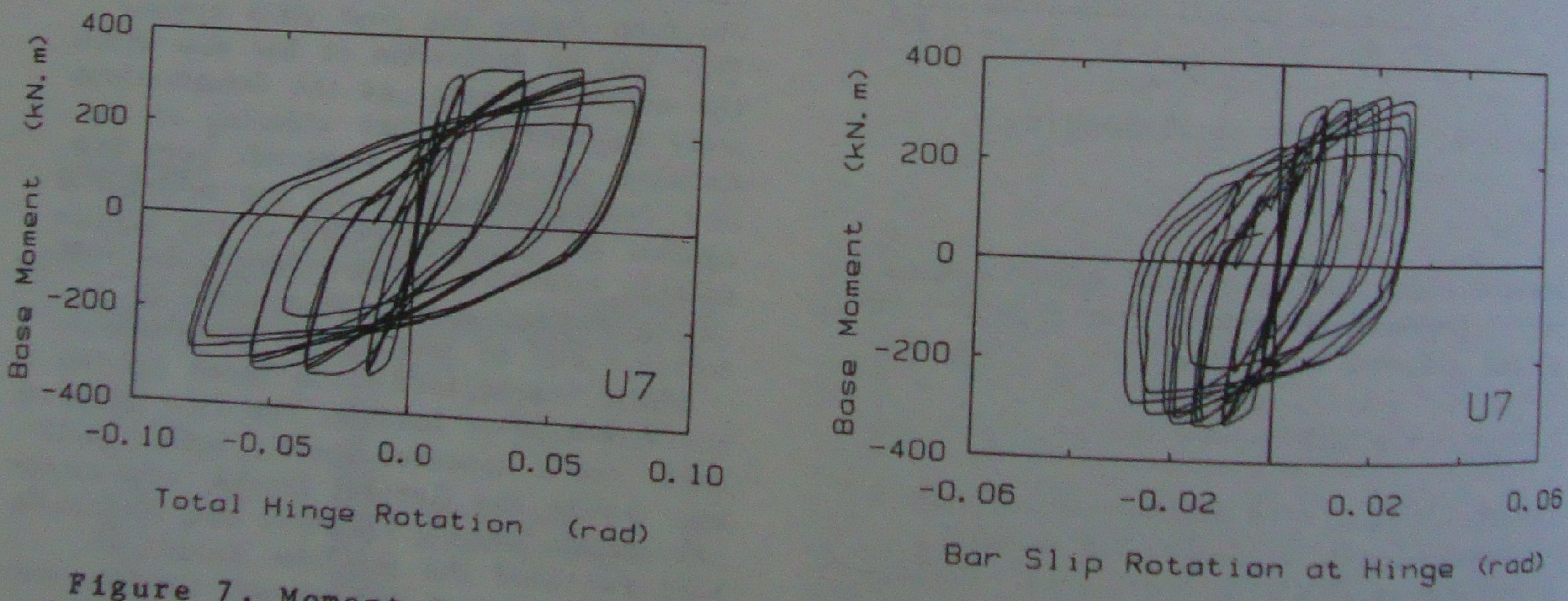

Figure 7. Moment-rotation hysteretic relationships for specimen U7 (Hinge length : 270 mm)

deformations. At yield, the magnitude of bar slip rotation forms approximately 50 % of the total rotation. With yielding progressing, bar slip rotations increase in proportion to flexural rotations.

In specimens U4 and B2, bar slip data could only be recorded up to $2\Delta_y$. Beyond this load stage, the LVDT's were removed because of the damaged concrete surface. However, in specimens U6 and U7 the LVDT's

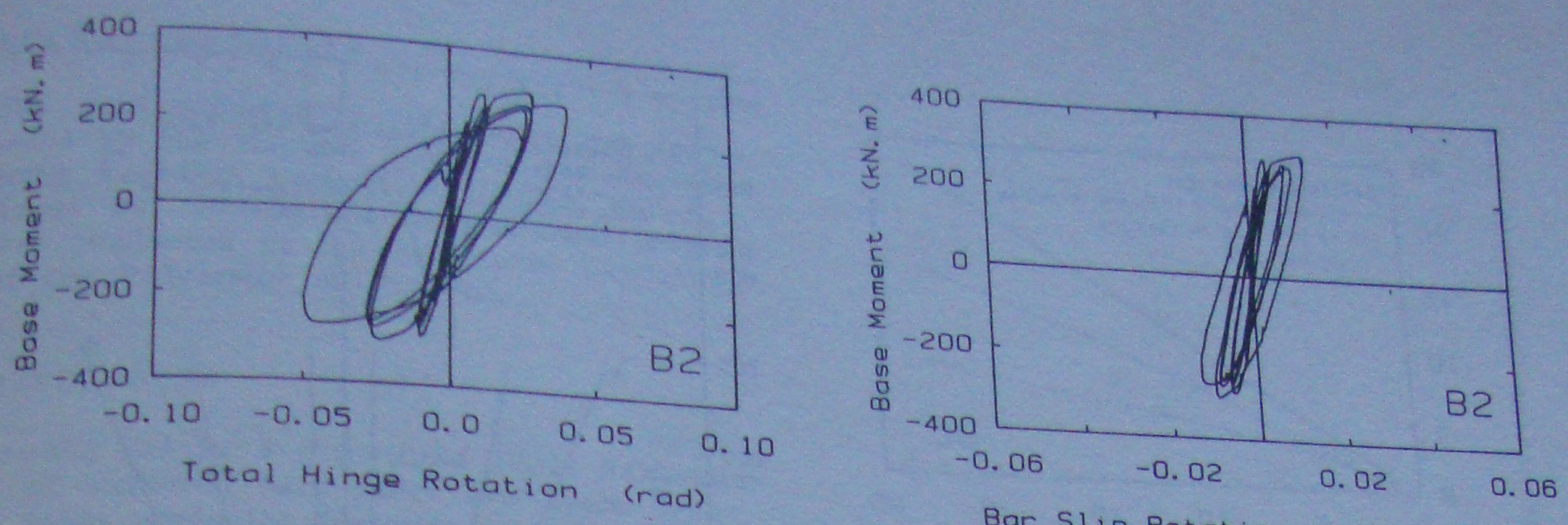

Figure 8. Moment-rotation hysteretic relationships for specimen B2 in the major direction (Hinge length : 275 mm)

were supported by steel pieces which were anchored into the core concrete. This technique permitted data recording during the later stages of testing.

Reversing of load undoubtedly increases deterioration of bond between steel and concrete. However, the effect of cycling the load at a constant deformation level appears to be negligible. The hysteresis curves follow a similar pattern during the three cycles of deformation at a constant amplitude.

Column specimens were designed to have the same flexural strength and two different shear strengths. Table 2 contains code (ACI 1983) predicted and observed capacities of the specimens. The material strengths and the confinement patterns varied between the specimens. Therefore the column behaviour shown in Figs. 5 through 8 is different for each specimen.

Table 2. Flexure and shear capacities

test specimen	ACI 318-83 shear (kN)	ACI 318-83 moment (kN.m)	applied shear (kN)	applied moment (kN.m)
U4	572	271	326	326
U6	420	286	343	343
U7	422	319	343	343
B2	386	265	306	306

Specimen B2 was subjected to bi-directional loading. Fig. 8 illustrates the response of B2 in the major direction of bending. The reinforcement slip characteristics of B2 was essentially the same as those of the uni-directional specimens.

Displacement componenets are further examined to asses the significance of each deformation component. Figures 9 through 12 show the make up of horizontal displacements at the top of the assumed hinging region. The results confirm the previous findings. All three components, namely; shear, flexure, and bar slip produce approximately the same magnitude of displacements. However, in many cases, displacements due to bar slip and flexure becomes more significant with increasing inelasticity.

While the displacement components are in the same order of magnitude in the hinging region, this behaviour changes with column height. Unlike shear deformations, rotations are magnified with height. Therefore the contributions of bar slip and flexure to column top displacement are larger than shear . This is shown in Fig. 13 for specimen U4.

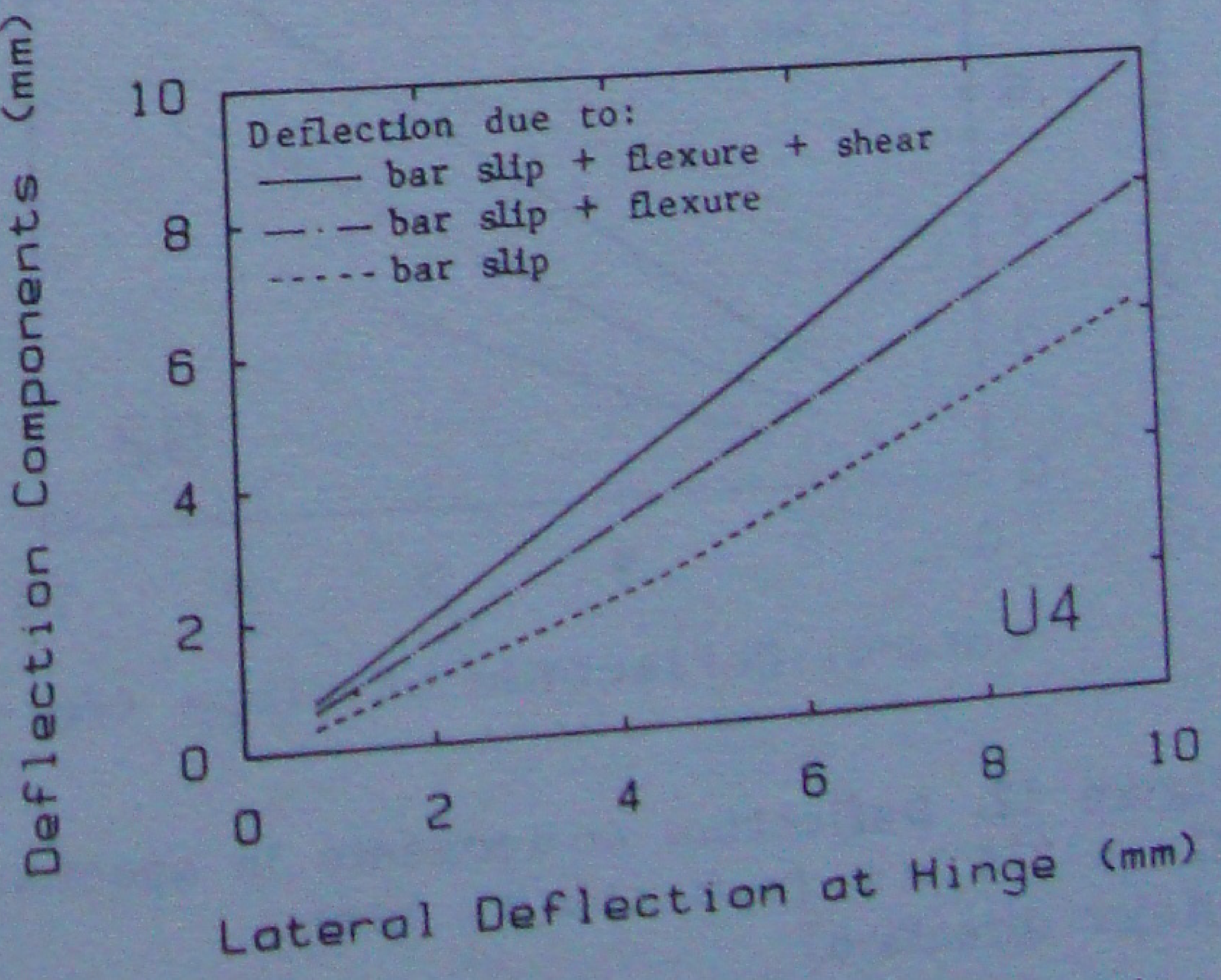

Figure 9. Deflection components in specimen U4 at 260 mm from column base

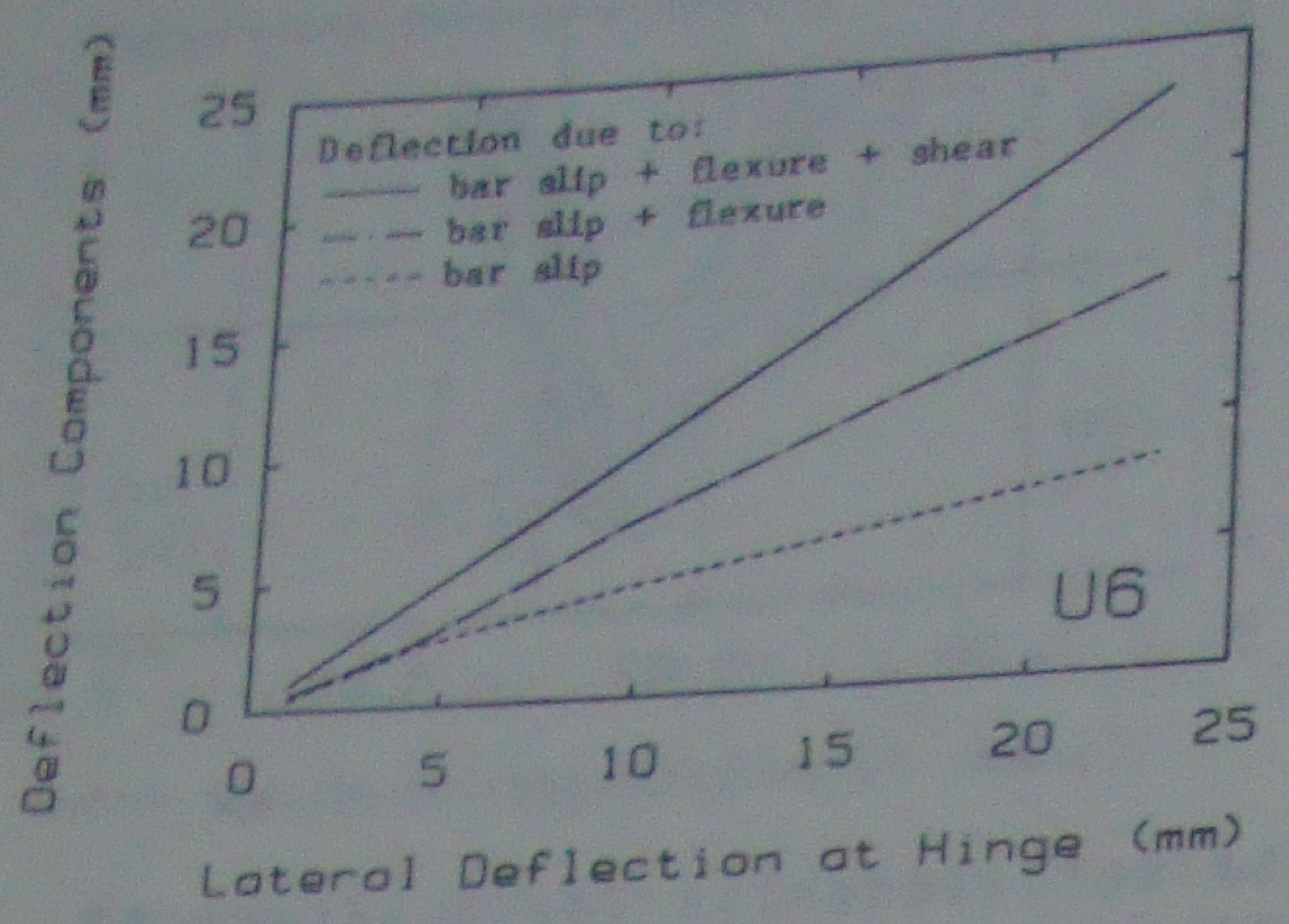

Figure 10. Deflection components in specimen U6 at 270 mm from column base

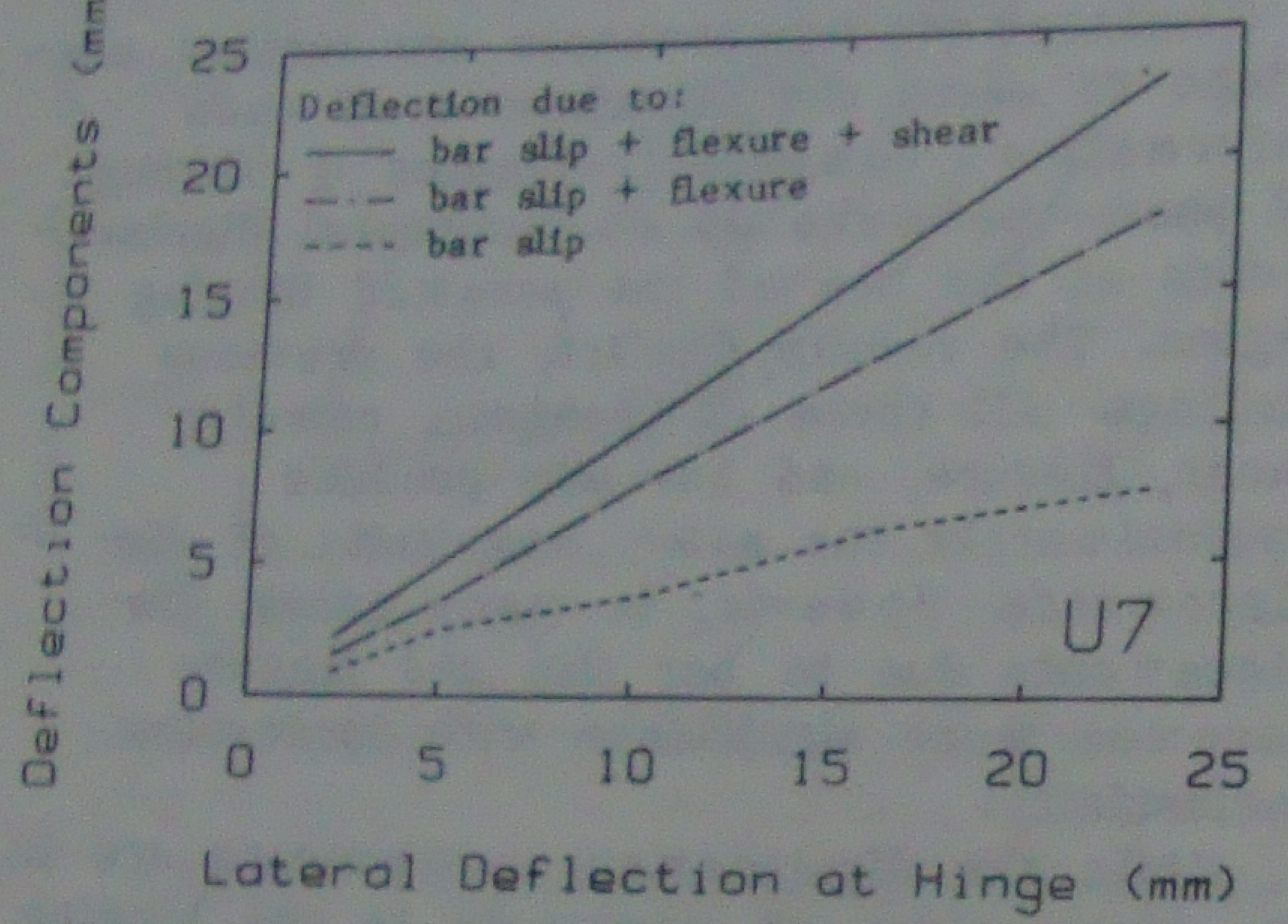

Figure 11. Deflection components in specimen U7 at 270 mm from column base

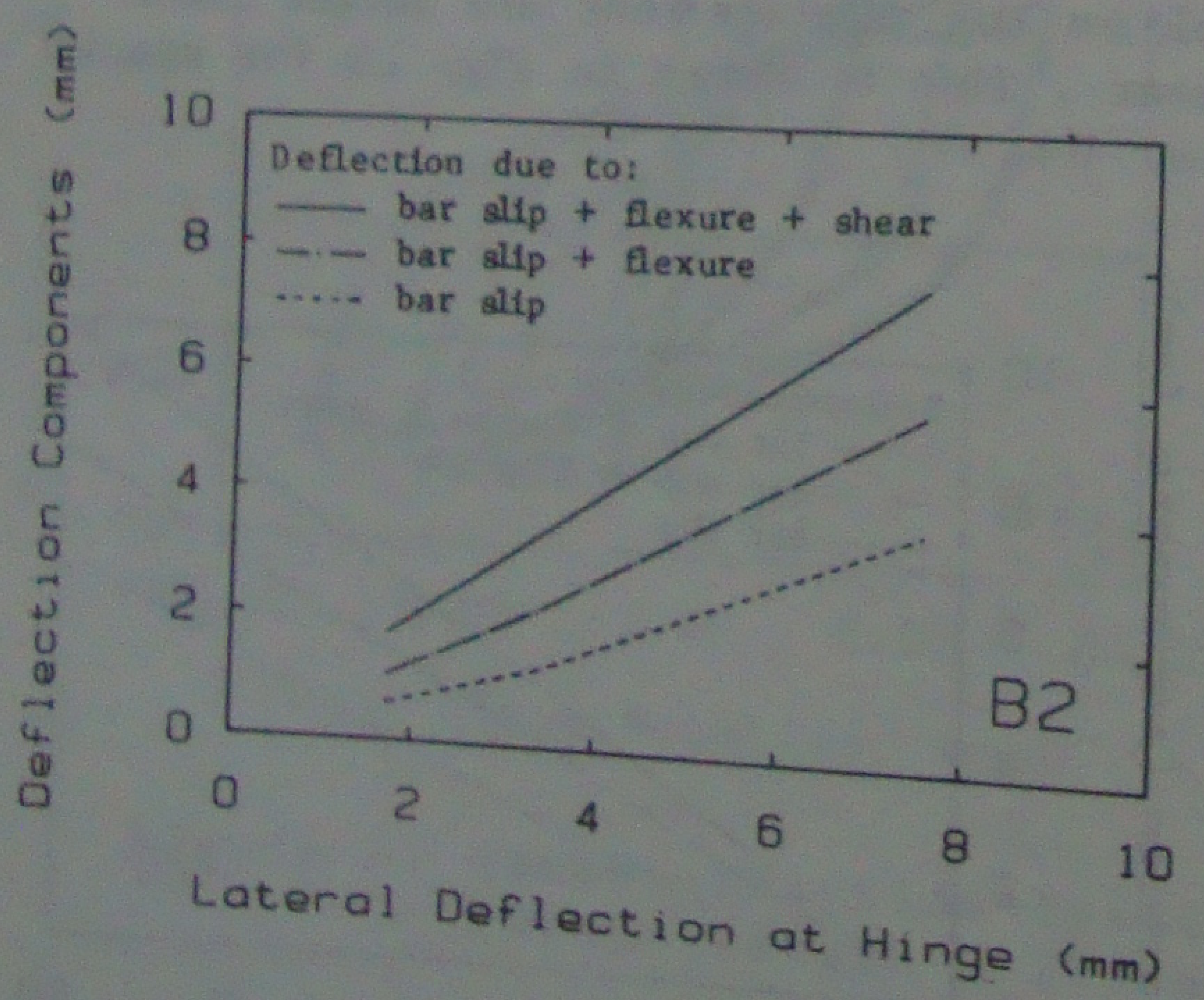

Figure 12. Deflection components in specimen B2 at 275 mm from column base (Major direction)

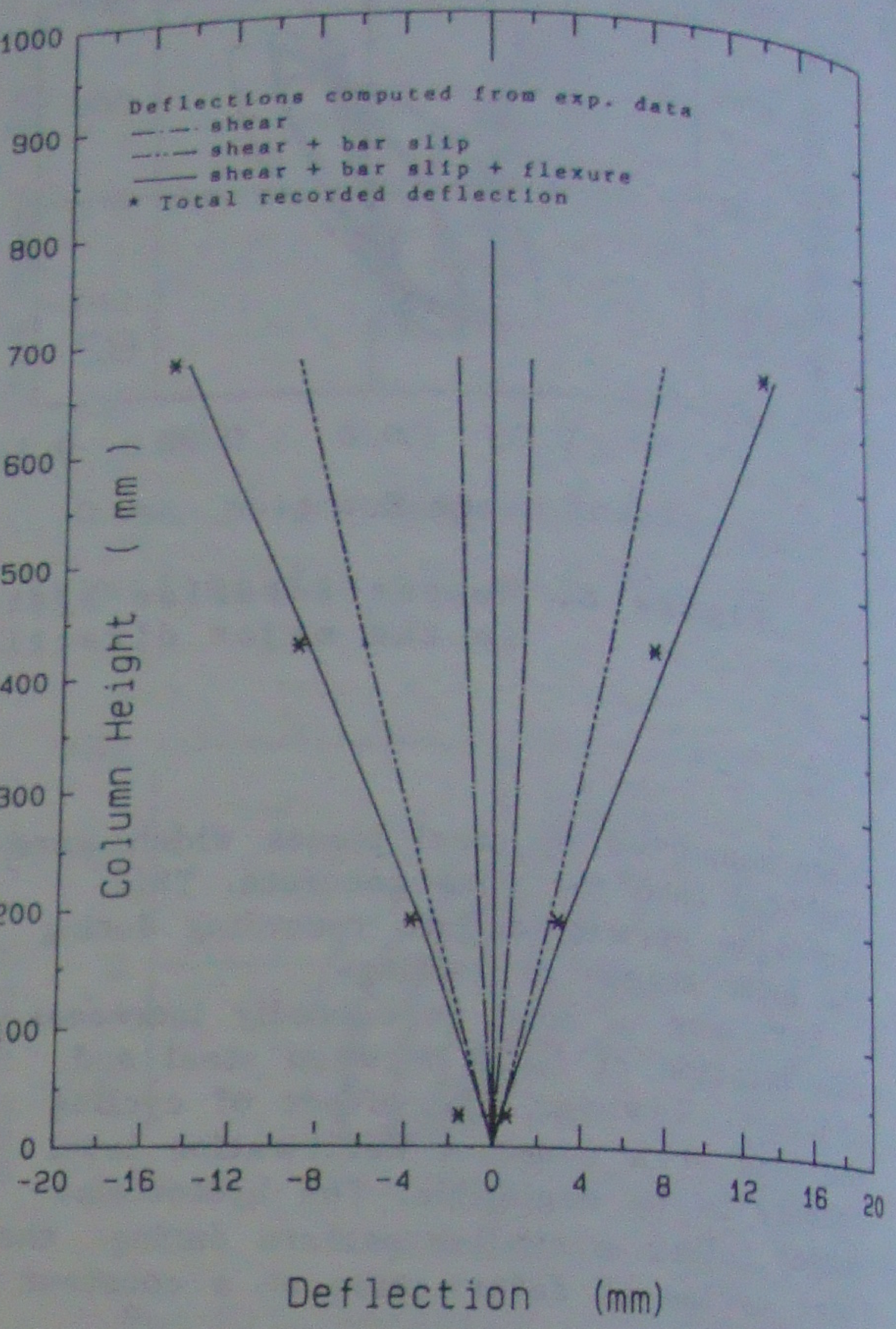

Figure 13. Deflection profiles for specimen U4 at yield deflection

4 CONCLUSIONS

The following conclusions can be made from the experimental investigation reported in this paper:

1. Reinforced concrete columns subjected to inelastic deformation cycles develop significant rotations due to the slip of main column reinforcement in the adjoining member. These rotations can form 40 to 60 % of total hinge rotation.

2. Lateral column displacement due to reinforcement slip increases proportionately with the total column displacement. Cycling the load at a constant level of displacement does not increase the deformation due to bar slip. The effect of bar slip on lateral displacement is magnified with column height.

3. Omission of bar slip effect produces gross inaccuracies in predicting structural stiffness and consequently the response to earthquake loading.

ACKNOWLEDGMENTS

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