Moment-Reducing Hinge Details for the Bases of Bridge Columns

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16. ABSTRACT

Bridge foundations in seismic regions are usually designed to withstand the plastic hinge moments that develop at the bases of the columns. Various hinge details have been proposed to reduce or even eliminate the moments transferred to the foundations, and thereby reduce the sizes and costs of the foundations.

This study experimentally investigated the behavior of column specimens incorporating different moment-reducing hinge details. Tests were performed on reinforced concrete column specimens subjected to increasing inelastic lateral displacements under constant axial load. The study investigated effects on hinge performance of several parameters, including vertical discontinuity in the hinge detail, level of axial load, low-cycle fatigue characteristics, column aspect ratio, and different amounts of longitudinal and transverse reinforcement.

The test results of this investigation showed that hinge details can be incorporated into columns to significantly reduce the moment capacity at the bases of the columns. However, the moments are not negligible, as is sometimes assumed for design with the moment-reducing hinge details. Providing vertical discontinuity in the hinge resulted in reduced distress in the longitudinal reinforcement and improved the performance of the hinge. Preliminary design recommendations were proposed for the comprehensive design of moment-reducing hinge details at the bases of the bridge columns.

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Final Report

Research Project GC 8287, Task 5
Plastic Hinge Details

MOMENT-REDUCING HINGE DETAILS FOR THE BASES OF BRIDGE COLUMNS

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DISCLAIMER

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SUMMARY

Bridge foundations in seismic regions are usually designed to withstand the plastic hinge moments that develop at the bases of the columns. Various hinge details have been proposed to reduce or even eliminate the plastic moments transferred to the foundations, and thereby reduce the sizes and costs of the foundations. However, no code specifications for these moment-reducing hinge details currently exist.

This study experimentally investigated the behavior of column specimens incorporating different moment-reducing hinge details. Tests were performed on reinforced concrete column specimens subjected to increasing levels of cycled inelastic displacements under constant axial load. The tests looked at the effects on hinge performance of several parameters, including vertical discontinuity in the hinge detail, level of axial load, low-cycle fatigue characteristics, column aspect ratio, and different amounts of longitudinal and transverse reinforcement.

The test results of this investigation showed that hinge details can be incorporated into columns to significantly reduce the moment capacity at the bases of the columns. However, the moments are not negligible, as is sometimes assumed for design with the moment-reducing hinge details. Providing vertical discontinuity in the moment-reducing hinge detail reduced distress in the longitudinal reinforcement and improved the performance of the hinge. Preliminary design recommendations were proposed for the comprehensive design of moment-reducing hinge details at the bases of bridge columns.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

On the basis of the results of the experimental investigation, the following conclusions are made:

1. Columns with the moment-reducing hinge details of this study exhibited stable hinging behavior similar to that of a conventional column with the same dimensions and reinforcement as that of the hinge.
2. Substantial enhancement of the measured flexural strength over that predicted by current design approaches was observed for all columns. An average enhancement value of 1.17 was obtained for the conventional columns For columns incorporating moment-reducing hinge details that provided both horizontal and vertical discontinuity, the average enhancement value was 1.35, and for columns incorporating moment-reducing hinge details that provided only horizontal discontinuity, it was 1.52.
3. In comparison to the other hinge details of this study, the hinge detail with only horizontal discontinuity displayed greater distress in the longitudinal bars and reduced energy dissipation effectiveness.
4. Flexure controlled the behavior of all of the columns, including those with an aspect ratio of 1.25. However, greater strength degradation occurred in columns with higher aspect ratios.
5. Higher axial load levels had only a minor effect on the performance of columns with the moment-reducing hinge details. This lack of

effect was attributed to the confinement around the hinge provided by the outer column.

6. Columns tested with small horizontal discontinuity joint thicknesses experienced prying action due to contact of the column edges with the footing. This prying action increased the hinge moments and reinforcement strains.

7. In the columns with the moment-reducing hinge details, the concrete of the outer column provided significant lateral confinement around the hinge region. However, adequate confining reinforcement was still required in order to obtain stable plastic hinging behavior and satisfactory energy dissipation in the column.

8. Columns with circular, spirally-reinforced hinge details exhibited better performance than did columns with square hinge details with tie reinforcement.

RECOMMENDATIONS

The following preliminary recommendations are based on the results of this study and a survey of the literature.

1. Both vertical and horizontal discontinuity should be provided in the moment-reducing hinge detail. The thickness of the discontinuity joint should be selected to accommodate the anticipated rotation requirements of the column base.

2. The design of the column and the moment-reducing hinge detail should be based on the actual moment capacity of the hinge detail. Procedures based on known principles of performance should be used in the design.

3. Circular hinge sections should be used in the moment-reducing hinge, and spiral reinforcement should be provided over the full length of the hinge detail.

4. The hinge section at the base of the column should be designed for a value lower than the maximum allowable axial load capacity to ensure ductility when the column is subjected to seismic loadings.

5. Conservative evaluations were used for several parameters not investigated in this study, including the anchorage requirements of the reinforcing bars, very high axial load levels, shear strength, and the effect of clustering the longitudinal bars. Further research is needed to precisely define the influence of these parameters on the behavior of the moment-reducing hinge details. The current information should also be supplemented by tests of multiple column bents that incorporate moment-reducing hinge details at the bases of the columns.

INTRODUCTION

RESEARCH OBJECTIVES

The objectives of this study were as follows:

1. to evaluate current design practices for incorporating moment-reducing hinge details at the bases of oversized bridge columns;
2. to experimentally investigate the seismic performance of columns incorporating such details;
3. to identify any symptomatic problems associated with the suggested details; and
4. to develop design recommendations for the seismic detailing of the hinge region of oversized columns to reduce the moment transfer between the columns and foundations.

THE PROBLEM

Bridge foundations in seismic regions are designed to withstand the plastic hinging moments that develop at the bases of bridge columns. In columns that are oversized for architectural or other reasons, this approach results in excessively large foundations. Various hinge details for the bases of bridge columns have been proposed to reduce the plastic moments transferred to the foundations, and hence, reduce foundation sizes and costs.

The basic concept inherent in the modified hinge details is to provide a reduced moment capacity in the plastic hinging region at the bases of the columns. This is accomplished by placing a layer of easily compressed material at the base of the column. This layer provides partial discontinuity between the column and the foundation. The discontinuity results in a smaller effective cross-section at the column base and, thus, a reduced hinge capacity in the column. To a great extent, the modifications that have been suggested have been based on engineering judgment, and the behavior and safety of the moment-reducing details have not been fully established.

CURRENT PRACTICE

Codified guidelines for the design of moment-reducing hinge details do not currently exist. As a result, there is considerable variation in the specifications, and even the use, of these details.

One approach to the design of the moment-reducing hinge detail is to determine the size of the hinge required soley on the basis of the axial compressive capacity of the section, and to design for shear across the section by providing the amount of longitudinal steel required on the basis of shear friction theory. A horizontal joint consisting of 1/4-in. to 1/2-in. thick expansion joint material is provided at the throat region around the hinge perimeter to create partial discontinuity between the column and the footing. To further reduce the moment developed at the hinge section, the longitudinal bars are sometimes clustered at the center of the hinge, and the hinge is treated as a pin with no moment capacity. Both circular and rectangular arrangements of the reinforcement in the hinges have been used. Normally, only nominal transverse steel is provided. Occasionally, no transverse steel is used. An example design for a column incorporating a hinge of this type is shown in Figure 1a.

Several questions about the behavior of this hinge detail under seismic loading can be raised. The hinge design is based on the axial load capacity of the section, and research (1) has shown that reinforced concrete columns tested under axial loads close to the maximum ACI (2) allowable axial load exhibit significantly reduced ductility. Also, even though the hinge is assumed to be a pin connection, substantial moment will actually develop at the hinge section, even if the longitudinal bars are clustered. This will result in an increase in the shear and axial load in the column over that assumed for design. Prying action, due to contact of the column edges with the top of the footing, will develop under inelastic loading if insufficient horizontal joint thickness is provided. This prying action will lead to higher moments and increased degradation in the hinge. Because of the sharp changes in section properties at the hinge, plastic deformations in the hinge will be concentrated at the location of the horizontal discontinuity, resulting in increased distress in the hinge. Finally, the assumed design forces for the footing are unconservative, as the actual moment transferred by the hinge to the footing is not considered.

Other designs have been proposed to spread the zone of plastic action over a greater vertical length. These have included providing both horizontal and vertical discontinuity in the moment-reducing hinge detail. Increased discontinuity joint thicknesses are also specified to prevent contact of the outer column with the footing. An example design for a hinge incorporating both horizontal and vertical discontinuity is shown in Figure 1b.

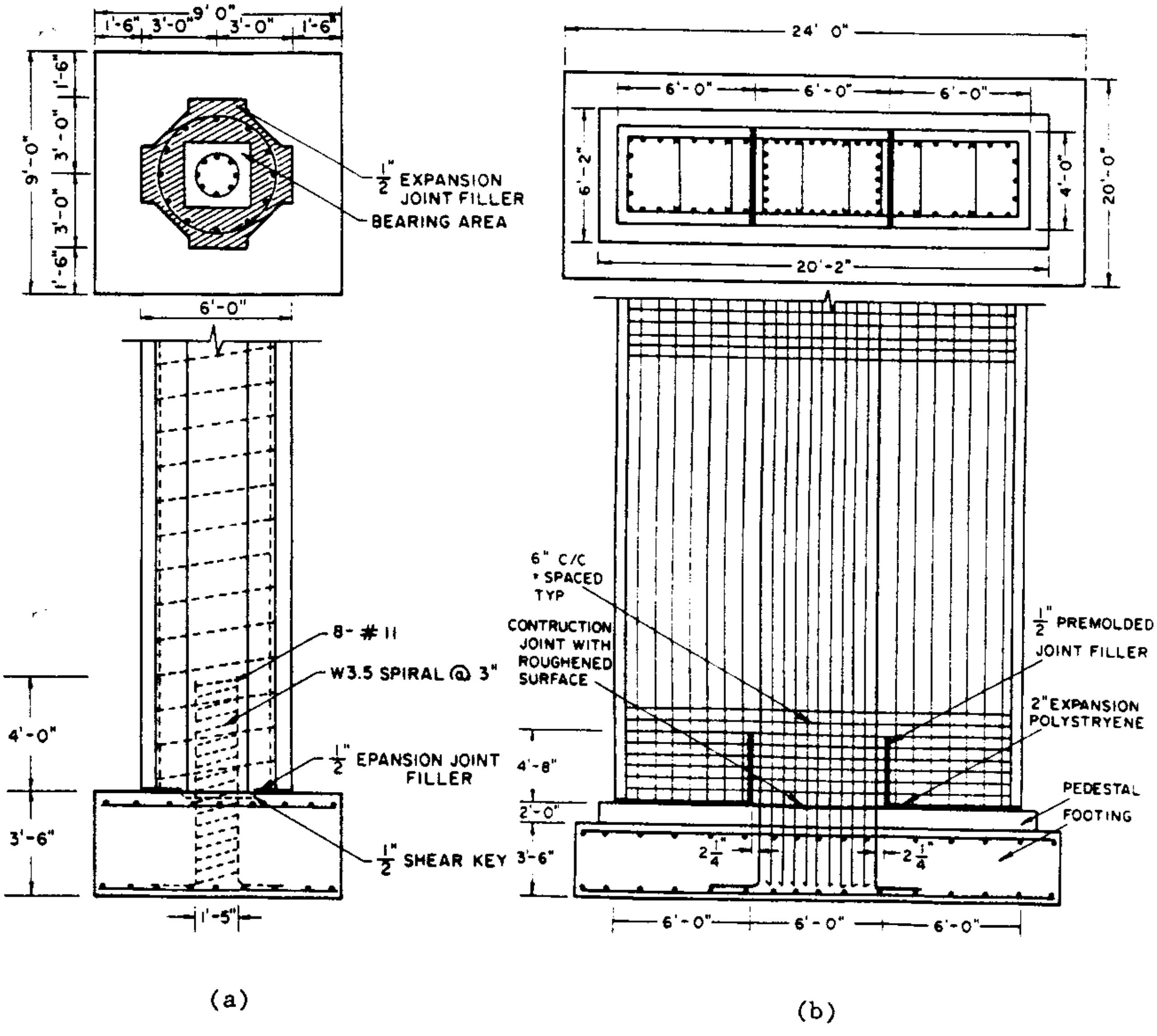


Figure 1 Moment-reducing hinge details for the bases of bridge columns.

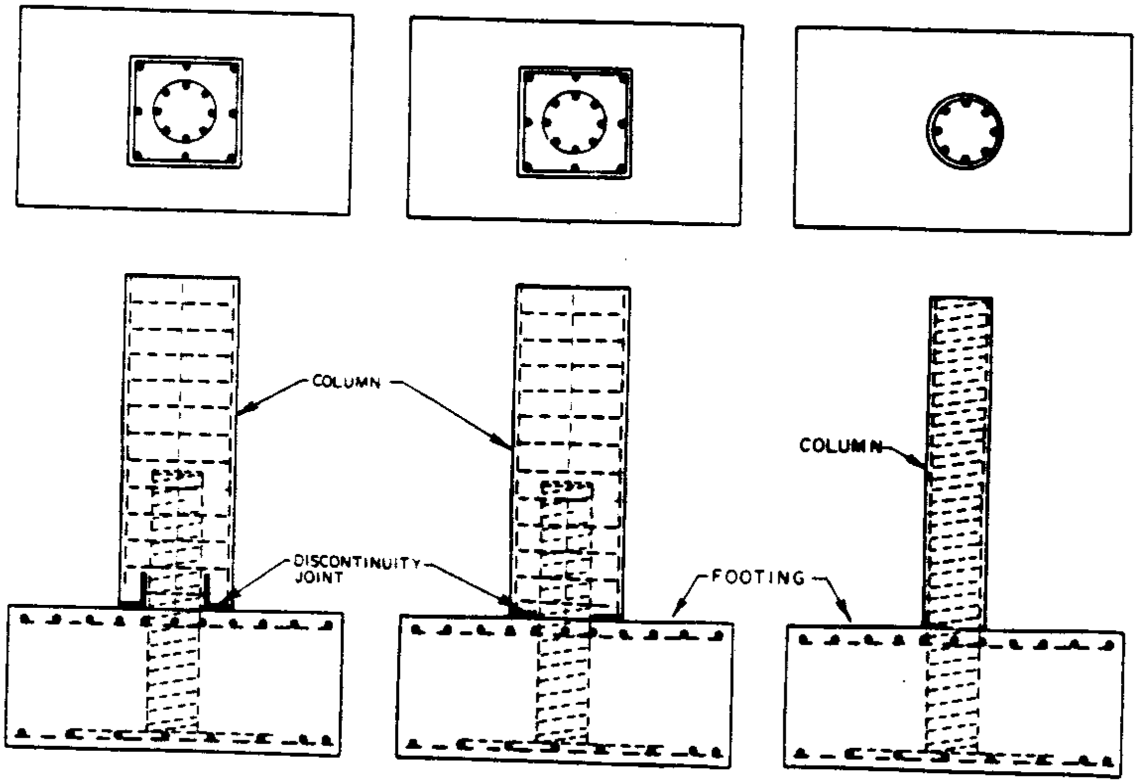
EXPERIMENTAL TESTING PROGRAM

TEST SPECIMENS AND PARAMETERS

Experimental tests were conducted on reinforced concrete column specimens incorporating several moment-reducing hinge details. Each test specimen consisted of a single column member connected at the base to a rectangular footing. The specimens were subjected to increasing levels of cycled inelastic displacements under a constant axial load.

The specimens were arranged in groups of three: one specimen incorporated a hinge detail with horizontal discontinuity only (CA series); one specimen incorporated a hinge detail with both horizontal and vertical discontinuity (WA series); and one reference or control specimen consisted of a column with the same dimensions and reinforcement as the hinge connection of the specimens incorporating the moment-reducing hinge details (CON series). These three types of specimens are shown in Figure 2.

Tests were performed on two sizes of specimens: small-scale specimens of approximately 1/20-scale and moderate-scale specimens of approximately 1/6-scale. More than fifty 1/20-scale specimens were tested. The small-scale study provided a cost efficient parametric study and also guided the selection of variables for the larger-scale tests. Fourteen 1/6-scale specimens were tested. The larger 1/6-scale tests resulted in a more realistic representation of the hinging behavior in actual bridge columns, and size effects were less than in the small-scale tests. The dimensions and reinforcement for a typical 1/6-scale column specimen are shown in Figure 3.



(a) WA detail

(b) CA detail

(c) CON detail

Figure 2 Hinge details studied in this project.

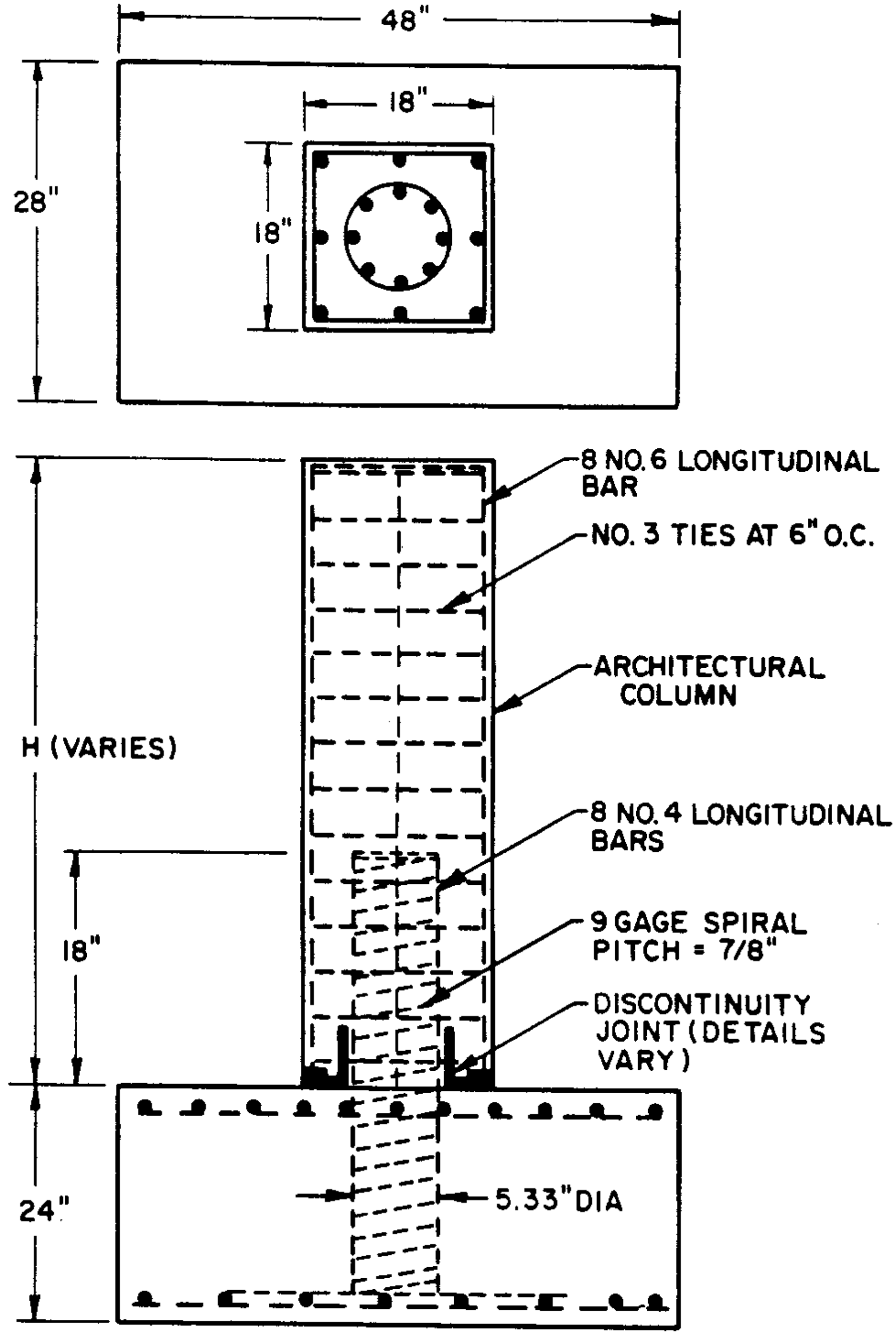


Figure 3 Typical 1/6-scale specimen dimensions and reinforcement.

The parameters investigated in the experimental testing program included the following: column aspect ratio, magnitude of axial load, amount of both longitudinal and transverse reinforcement, vertical discontinuity length, thickness of horizontal discontinuity, column shape, hinge cross-sectional shape (circular and square), and low-cycle fatigue characteristics. The details of the specimens of the 1/6-scale testing program are summarized in Table 1. Additional details of the testing program can be found in references 3,4, and 5.

TEST SETUP AND PROCEDURES

The test setup and procedures for the 1/20-scale and 1/6-scale specimens were similar. Figure 4 shows the test setup for the 1/6-scale specimens. The footing of the test column was anchored to a laboratory strong floor. Axial load was first applied to the top of the column using a 55-kip actuator operated in force control. Axial loads were maintained at a constant level during a test. Lateral force was then applied slightly below the top of the column using a 22-kip actuator operated in displacement control. An analog signal of a prescribed ramp function was generated by a personal computer and sent to the servocontroller of the 22-kip actuator. Strain gages were used to monitor the strains in the longitudinal and transverse reinforcement within the hinging region, and linear variable displacement transformers (LVDT's) were mounted to the sides of the columns to measure rotations at the column base. All data were recorded intermittently on the same personal computer used to generate control signals for the horizontal actuator.

Table 1 Summary of the 1/6-Scale Testing Program

Specimen No.	Variable Studied	Aspect Ratio (H/D)	Axial Load ($P/f'_c A_c$)	Yield Displacement (in.)	Measured Yield Moment (in.-kips)	Measured Peak Moment (in.-kips)	Measured Peak Moment / ACI Predicted Moment	Maximum Applied Shear Load (kips)
CA1	aspect ratio	2.50	0.24	0.30	181	270	1.52	6.0
WA1	"	2.50	0.24	0.30	133	212	1.19	4.7
CON1	"	*	0.24	0.30	72	179	1.01	4.0
CA2	hinge detail	1.25	0.24	0.15	162	279	1.57	12.4
WA2	"	1.25	0.24	0.15	142	250	1.40	11.1
CON2	"	**	0.24	0.15	93	209	1.18	9.3
CA3	axial load	1.25	0.35	0.15	166	277	1.56	12.3
WA3	"	1.25	0.35	0.15	135	240	1.35	10.7
CON3	"	***	0.35	0.15	92	213	1.20	9.5
CA4	low-cycle fatigue	1.25	0.24	0.15	138	271	1.52	12.0
WA4	"	1.25	0.24	0.15	130	236	1.33	10.5
WA5	joint height	1.25	0.24	0.15	129	240	1.35	10.7
CA6	repeatability	2.50	0.24	0.15	164	276	1.55	6.1
WA6	"	2.50	0.24	0.15	140	229	1.29	5.1

* circular control column with the same height as Units CA1 and WA1
** circular control column with the same height as Units CA2 and WA2
*** circular control column with the same height as Units CA3 and WA3

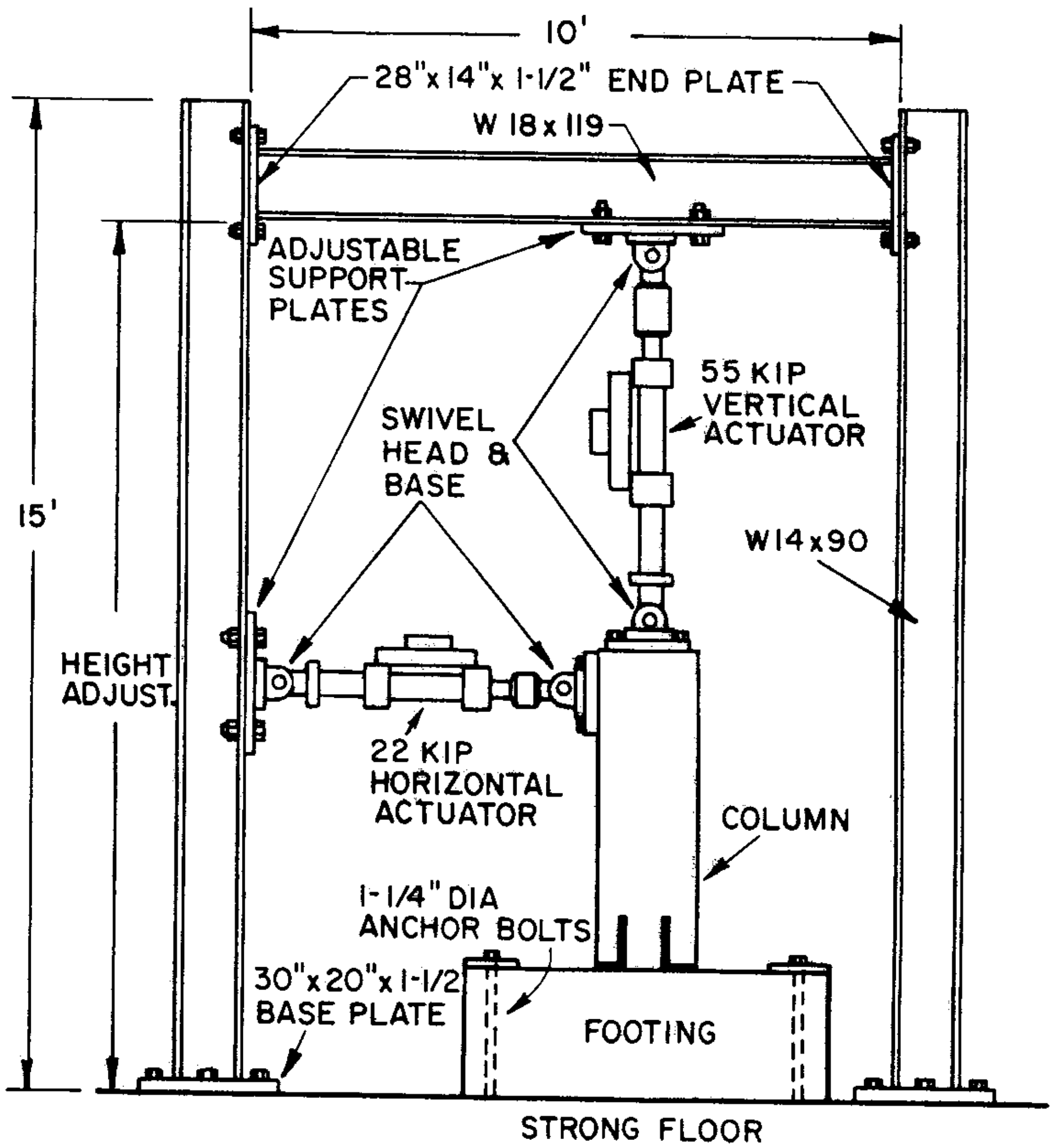


Figure 4 Test setup for the 1/6-scale specimens.

The determination of the yield displacement, Δ_y, and the loading sequence were similar to the procedures used by Priestley, Park, et al. (6,7,8). However, preliminary tests showed that the ultimate moment capacities and stiffnesses, and hence the yield displacements, varied in columns with different details. To better compare the hinging behavior of columns with different hinge details, parallel sets of columns were subjected to the same displacement history. The typical loading sequence used for the tests was two cycles at displacement ductility factors (i.e., multiple values of Δ_y) of μ = 1, 2, 4, 6, 8, 10, and 12, unless premature failure of the specimen stopped the testing.

TEST RESULTS AND DISCUSSION

The test results for all 1/6-scale test specimens are presented in Table 1. Column performance was evaluated with respect to the moment capacity and displacement ductility attained, the overall hysteresis behavior, and degradation and energy dissipation characteristics. Rather than discuss the results of each specimen individually, results of groups of specimens are presented to facilitate correlation of the influence of various parameters with column performance and to obtain behavioral trends.

GENERAL BEHAVIOR

Hysteresis Behavior

Figure 5 shows typical load-displacement hysteresis curves for 1/6-scale columns incorporating details CA and WA and a comparable control column (Units CA2, WA2, and CON2). These columns were subjected to an

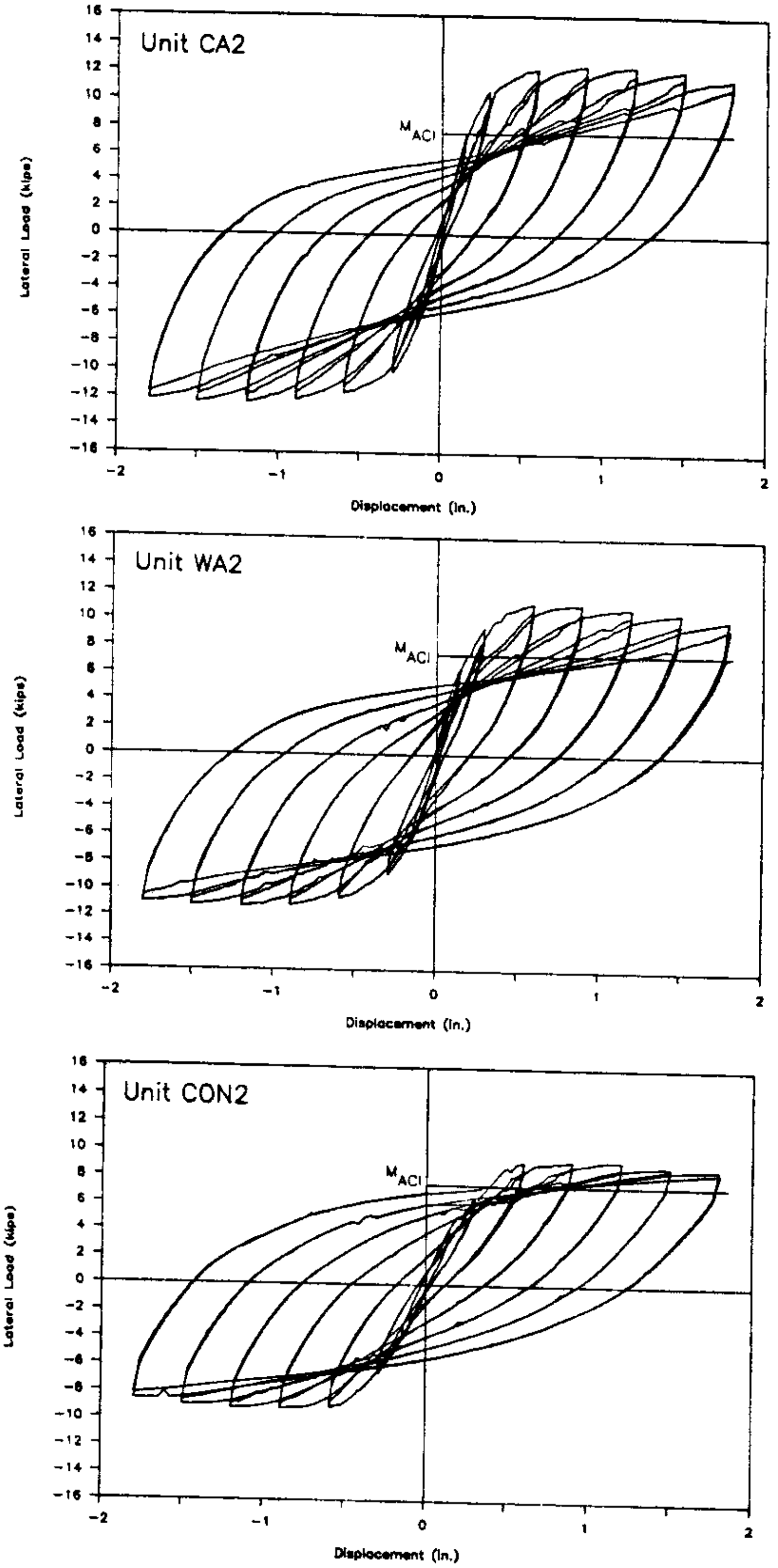


Figure 5 Load-displacement hysteresis curves for Units CA2, WA2 and CON2.

axial load level of $0.24f'_cA_g$. The aspect ratio for the columns incorporating the modified details was 1.25, measured with respect to the outer column, which corresponded to an aspect ratio of 3.75 for the control column. Longitudinal and volumetric reinforcing ratios in the hinges were 5.7 percent and 1.46 percent, respectively. The lateral loads presented in these plots are the true loads on the specimens, including P–Δ effects and secondary effects from the axial load. The hysteresis curves for all three specimens are very stable, even at displacement levels of μ = 12. No evidence of any sudden drop in load-carrying capability was observed, and the plastic hinges continued to absorb energy throughout the tests.

The theoretical ultimate lateral load, calculated on the basis of ACI methods and using measured material strengths with a material reduction factor of 1, is also shown in each of these figures. Figure 5 shows that the measured flexural strength was substantially enhanced above the ACI-predicted values. This strength enhancement was caused by increases in concrete strength and ductility due to the confinement provided by the spiral, and by the increased strength of the steel in the strain hardening region. Results from the 1/6-scale tests indicated average enhancement values of 1.17, 1.35 and 1.52 for control columns, columns with detail WA, and columns with detail CA, respectively. The greater strength enhancement in the columns with the modified hinge details was due to the additional confinement provided by the outer column surrounding the hinge detail. Figure 5 also shows that the hysteresis curves for the column incorporating detail CA are more pinched than those for the column with detail WA and the control column. This indicates a reduced energy dissipation capacity in the hinge with the CA detail.

Shear Degradation

Figure 6 shows the plots of the shear strength envelope curves for Units CA1, WA1, and CON1. The shear strength envelope curve is obtained by plotting the maximum shear force attained at each peak displacement level with respect to that displacement. The columns with the moment-reducing details exhibited less strength degradation than did the control column. This effect may have been due to the additional confinement provided around the hinge region by the outer column. Figure 6 also shows that the column with detail CA exhibited the greatest stiffness and the control column exhibited the least stiffness. Two reasons can be cited for the difference in stiffnesses observed in these specimens. First, the elastic stiffness of the control column was less than that of the outer columns with the moment-reducing details. The second reason is that the moment-reducing details "pinched" the rebars crossing the column-to-foundation connection, thereby inducing larger strain values in the rebars of the moment-reducing details.

The strain profiles of the longitudinal bars measured at the base of these columns, shown in Figure 7, illustrate this pinching effect. The largest strains were measured in the column with detail CA, and the strains in the column with detail WA and the control column were considerably lower. By examining the distributions of the strains over the vertical height of the columns, it can also be seen in the figure that the plastic hinging action in the column with detail CA was largely concentrated at the throat region of the hinge. In contrast, the plastic

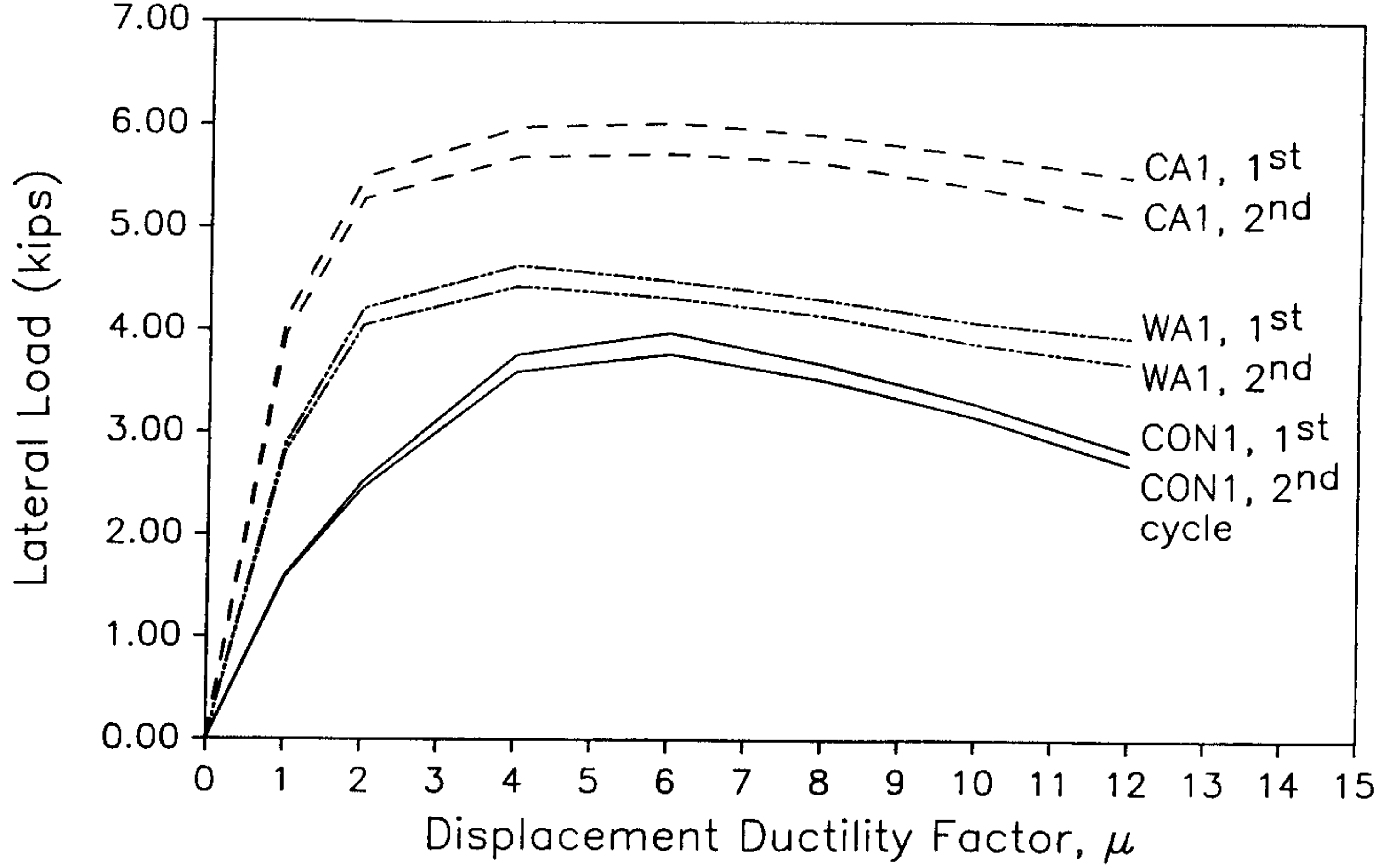


Figure 6 Shear strength envelope curves for Units CA1, WA1 and CON1.

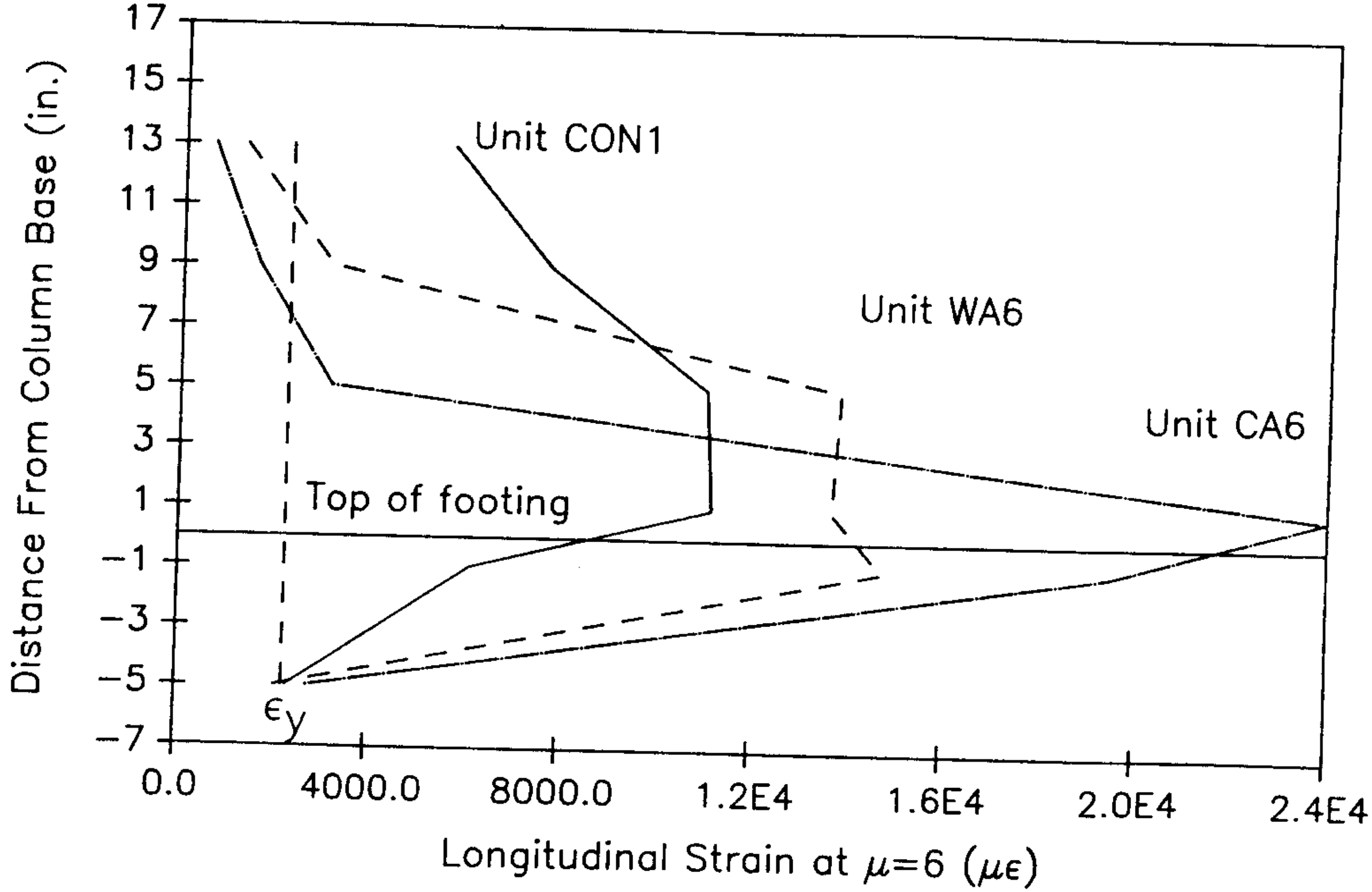


Figure 7 Longitudinal bar strain profiles.

action was distributed over a greater vertical length of the hinge region in the column with the WA detail and in the control column.

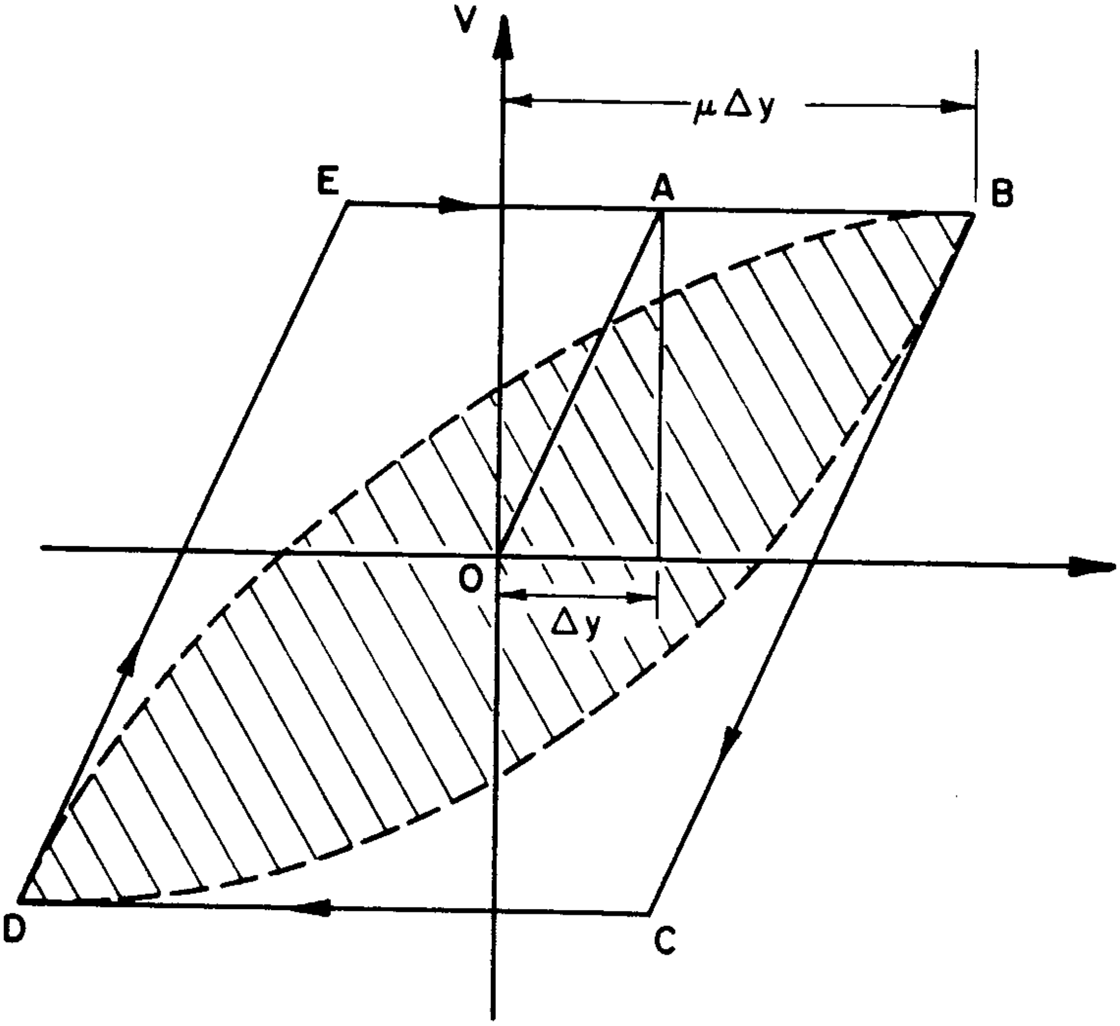
Energy Dissipation

The energy dissipated by a column during a particular load cycle is represented by the area enclosed by the load-displacement hysteresis curve. The energy dissipated by a perfectly elasto-plastic system during a complete displacement cycle, as shown in Figure 8, is the area of the parallelogram BCDE. For a particular displacement ductility factor, μ, the ideal plastic energy dissipated, E_p, can be computed as:

$$E_p = 4(\mu-1)V_p\Delta_y$$

where V_p is the maximum shear force attained at that displacement level (7). In order to evaluate quantitatively the energy dissipation capability of the various hinge details, the measured energy dissipation was divided by the E_p value of the column for the same displacement ductility factor. This ratio will be referred to as the relative energy dissipation index.

The energy dissipation effectiveness of Units CA2, WA2, and CON2 are shown in Figure 9. The low values of E/E_p at $\mu = 2$ and $\mu = 4$ for the control column, Unit CON2, are due to the inexact definition of the actual yield displacement in the different columns. The result is that the response of the control column is still largely elastic at these displacement levels. Figure 9 shows that the control column exhibited the greatest energy dissipation effectiveness, and the column with detail CA exhibited the least effectiveness. The reduced effectiveness in the columns with moment-reducing details may be due to the confining of the plastic action at the base of the column, particularly with the CA detail.



$$E_p = 4(\mu - 1)V\Delta_y$$

Figure 8 Actual and idealized perfectly elasto-plastic hysteresis curves.

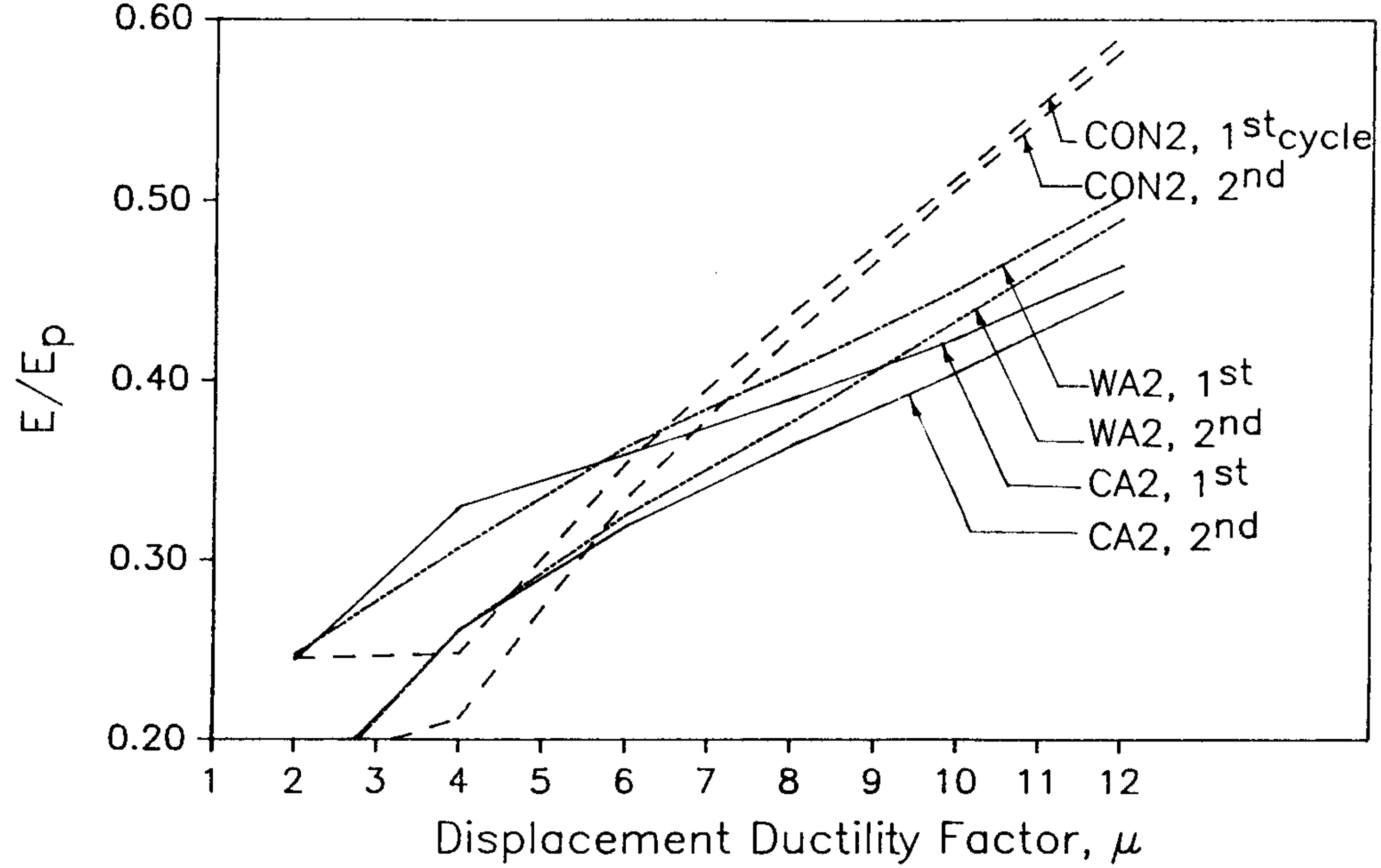


Figure 9 Relative energy dissipation index curves for Units CA2, WA2, and CON2.

EFFECT OF VARIOUS PARAMETERS ON COLUMN PERFORMANCE

Aspect Ratio

To evaluate the effects of column aspect ratio on the behavior of the hinge details, 1/6-scale test results for modified columns with aspect ratios of 2.5 (Units WA1 and CA1) and 1.25 (Units WA2 and CA2) and comparable control columns with aspect ratios of 7.5 (Unit CON1) and 3.75 (Unit CON2) were compared. The hysteresis curves for Units WA2, CA2, and CON2 and Units WA1, CA1, and CON1 are shown in Figures 5 and 10, respectively. The hysteresis curves for the two sets of specimens are similar, indicating that flexure dominated the behavior of the columns, even those with low aspect ratios.

The shear strength envelope curves for the two sets of specimens are shown in Figure 11. To account for the different lateral load levels associated with columns of different heights, the shear force, V, is plotted normalized with respect to the yield shear force, V_y. The figure shows that greater strength degradation occurred in the columns with the higher aspect ratio.

Level of Axial Load

To examine the effect of level of axial load on hinge performance, 1/6-scale Units WA2, CA2, and CON2 and Units WA3, CA3, and CON3 were tested with axial load levels of $0.24f'_cA_g$ and $0.35f'_cA_g$, respectively. The shear strength envelope curves for these specimens are shown in Figure 12. The figure shows that higher axial load resulted in greater degradation in the control columns. However, axial load seemed to have little effect in the columns with the modified hinge details, particularly in the column with the CA detail. The reason that these columns were

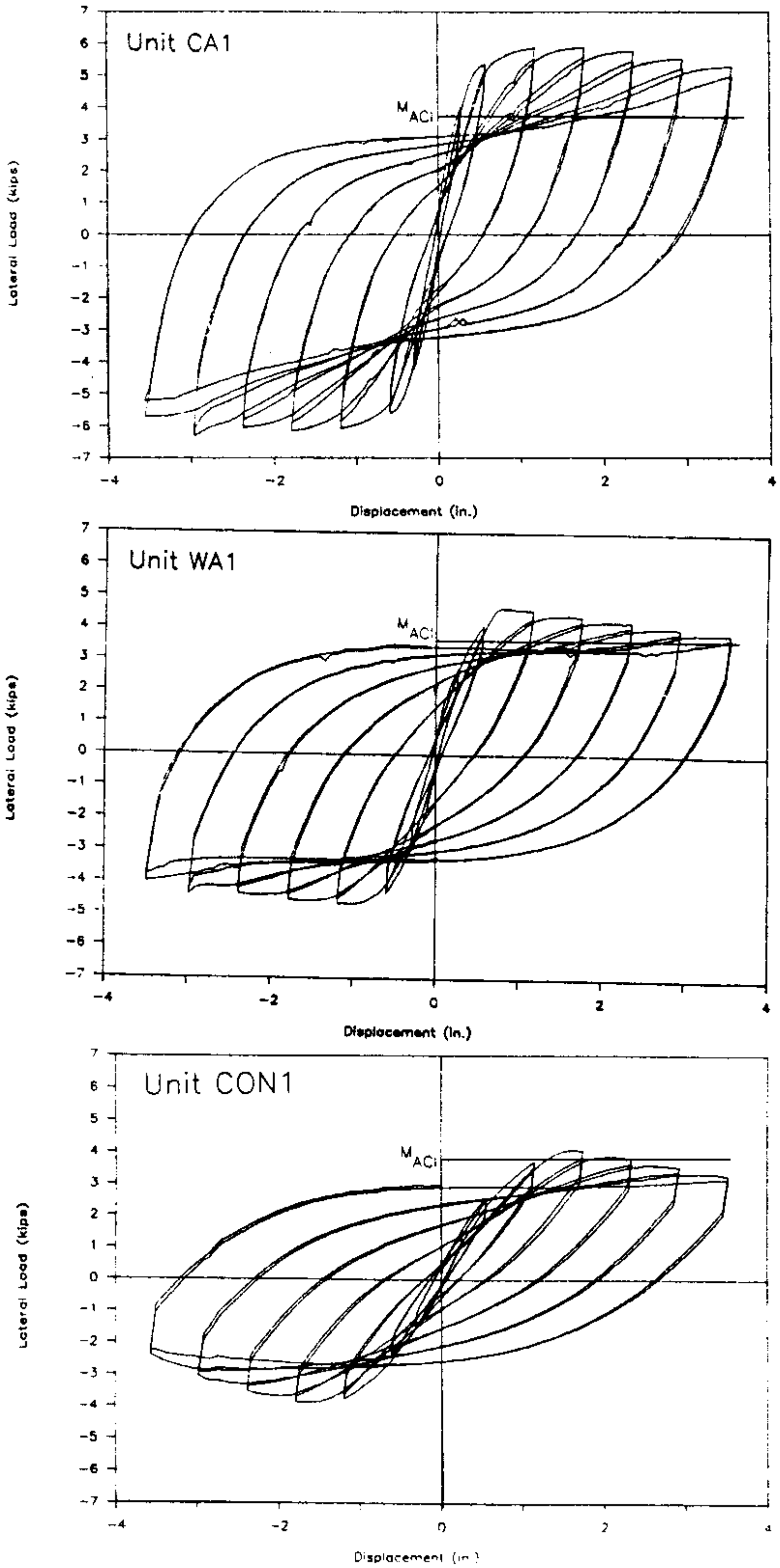


Figure 10 Load-displacement hysteresis curves for Units CA1, WA1, and CON1.

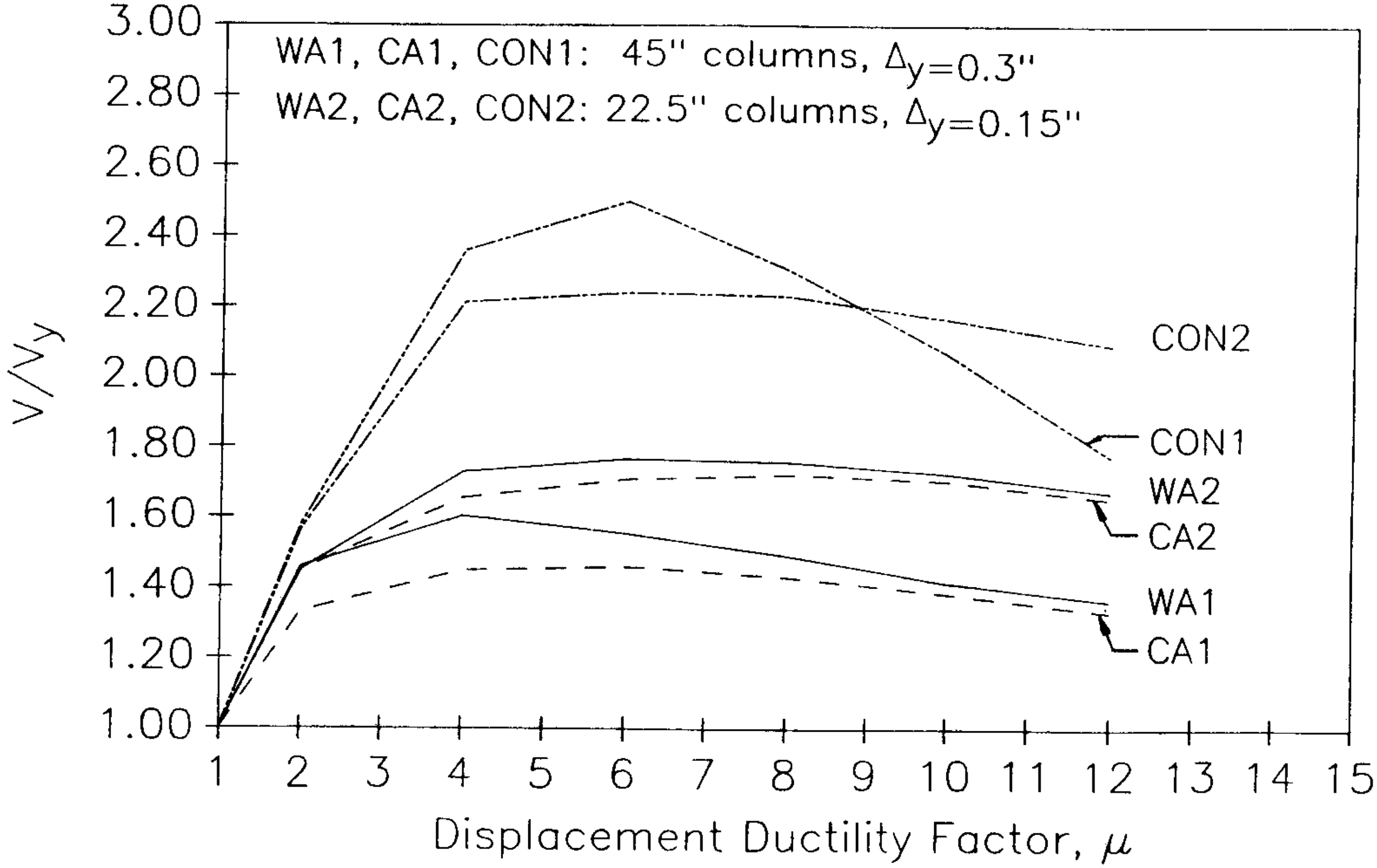


Figure 11 Shear strength envelope curves for Units CA1, WA1 and CON1 and Units CA2, WA2 and CON2.

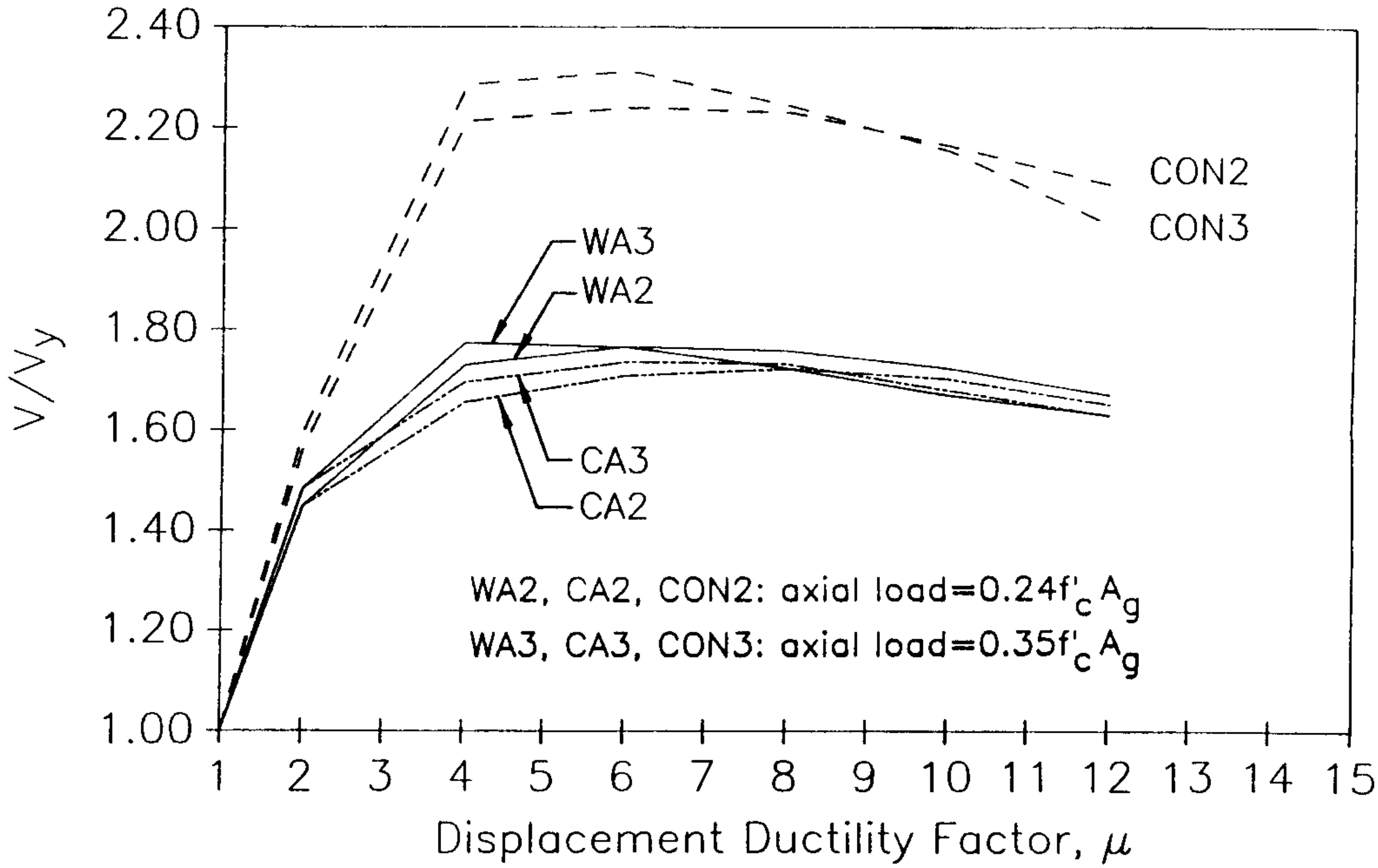


Figure 12 Shear strength envelope curves for Units CA2, WA2 and CON2 and Units CA3, WA3 and CON3.

relatively unaffected by axial load level may be the confining effect provided around the hinge region by the outer column.

Horizontal Discontinuity Joint Thickness

When insufficient discontinuity joint thickness was provided in the moment-reducing hinge details, large prying forces developed from contact of the edges of the outer column with the top of the footing. This prying action resulted in greatly increased strains in the longitudinal bars and larger moments than that in columns with no prying action. Energy dissipation effectiveness was also reduced by the prying forces.

Detail WA Vertical Joint Height

The test results indicated that the moment-reducing hinge detail that provided vertical and horizontal discontinuity demonstrated a greater plastic hinge length and lower longitudinal bar strains than the hinge detail that provided only horizontal discontinuity. As the length of vertical discontinuity was increased from one to two hinge diameters, the behavior of the column approached that of the unmodified control columns.

Longitudinal Reinforcing Ratio

To evaluate the influence of the longitudinal reinforcing ratio on hinge performance, small-scale specimens with hinge reinforcing ratios of 4, 6, and 8 percent were tested. In general, the behaviors of the specimens with the different longitudinal steel contents were similar. However, less degradation and greater energy dissipation effectiveness were observed in the columns with the larger reinforcing ratios.

Transverse Reinforcing Ratio

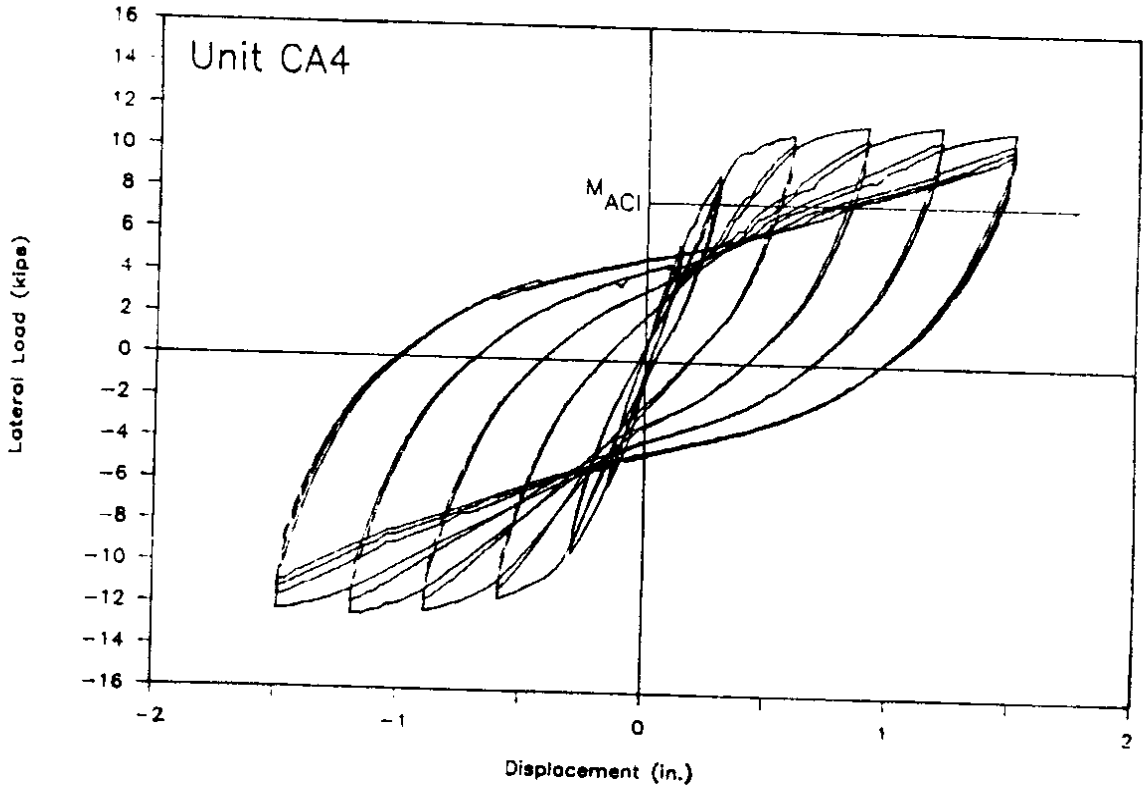
Small-scale specimens with spiral reinforcing ratios in the hinge of 0, 0.94, and 3.2 percent were tested. Greater degradation and less energy dissipation capability were observed in the specimens with no transverse reinforcement, particularly in the specimen incorporating both horizontal and vertical discontinuity in the hinge detail. However, no failure occurred in the specimens because of the confinement provided around the hinge region by the outer column. There was little difference in behavior between the specimens with 0.94 and 3.2 percent transverse reinforcement.

Circular vs. Square Hinge Cross-Section

The performance of columns incorporating square moment-reducing hinge details was compared to that of columns with circular hinge details in the small-scale study. Test results indicated that columns with square hinges experienced significantly more rapid strength degradation than did columns with circular hinges.

Effects of Low-Cycle Fatigue

In the small-scale study, fracture of the longitudinal bars was observed in columns incorporating detail CA when they were subjected to repeated loadings at large displacement levels. This result was taken as evidence of greater distress in the longitudinal reinforcement in detail CA than in detail WA. To further examine the low-cycle fatigue characteristics of the moment-reducing hinge details, tests were conducted on Units WA4 and CA4 in the 1/6-scale study. Both units were cycled to a displacement level of $\mu = 10$ and then subjected to multiple cycles at this displacement level. The hysteresis curves for these specimens are shown in Figure 13. For both specimens, very little degradation occurred after the completion of the second cycle at $\mu = 10$. The hinges continued to exhibit stable plastic behavior even after being cycled up to 16 times at that displacement level.



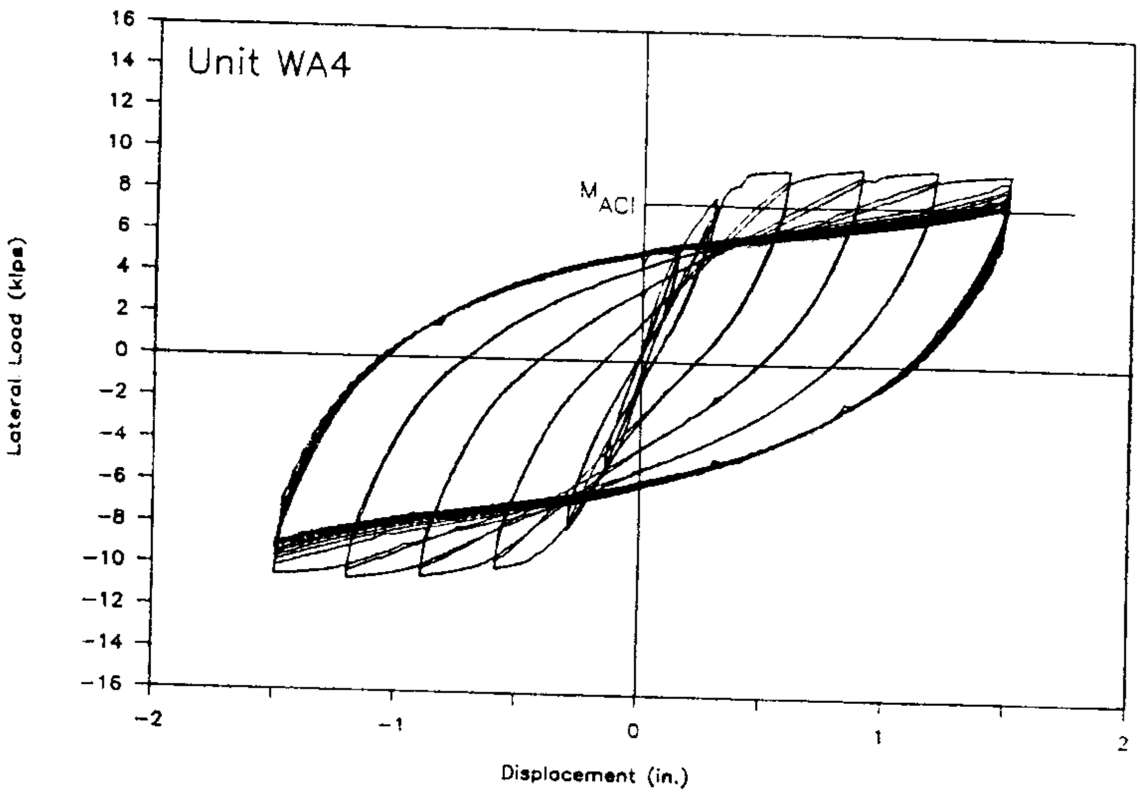


Figure 13 Load-displacement hysteresis curves for Units CA4 and WA4.

APPLICATIONS AND IMPLEMENTATION

DESIGN RECOMMENDATIONS

On the basis of the results of this investigation and a survey of the literature, the following preliminary recommendations are proposed for the design of moment-reducing hinge details. There are two applications for the proposed hinge detail. The first application is to reduce the moment capacity in a column that has been oversized for architectural or other reasons. For this case, the column-foundation connection is designed to carry the required forces resulting from the bridge analysis. The second application is to create as near as possible a pinned connection. For this case, the recommended procedures result in a hinge connection with the smallest possible moment capacity that is capable of carrying the required forces.

1. From equilibrium requirements for the column, determine the design shear force, V_u, on the basis of the flexural overstrength, M_p, of the plastic hinging region at the top of the column. The overstrength moment is calculated as

$$M_p = \phi_o M_n$$

where M_p = plastic moment of section

M_n = ideal nominal moment of section

ϕ_o = overstrength factor, specified in AASHTO as 1.3

2. Determine the required hinge area from the greatest area of the following:

   i. shear friction theory:

$$A_g \geq V_u/(0.2\phi f'_c)$$

$$A_g \geq V_u/(\phi 800)$$

where A_g = gross area of hinge section, in^2

V_u = design shear force, lbs

f'_c = concrete compressive strength, psi

ϕ = strength reduction factor, taken as 0.85

ii. maximum allowable doagonal shear:

$$A_c = V_u/(\phi 10\sqrt{f'_c})$$

where A_c = core area of section (A_g - cover area), in^2

ϕ = 0.85

iii. axial stress limit of $0.7f'_c$ (to insure ductility):

$$A_g = P_u/(\phi 0.7f'_c)$$

where P_u = factored design axial load, lbs

ϕ = 0.75 for circular, spirally-reinforced sections

3. Determine the longitudinal steel required from the greatest of the following:

i. shear friction theory:

$$A_{vf} \geq V_u/(\phi \mu f_y)$$

where μ = coefficient of friction = 1.0

f_y = yield strength of longitudinal steel, psi

ϕ = 0.85

ii. the minimum longitudinal reinforcement permitted by AASHTO:

$$A_l = 0.01\ A_g$$

where A_l = area of longitudinal reinforcement, in^2

iii. for the case of a single column or an oversized column in which a reduced moment capacity is desired, the longitudinal steel area required on the basis of design loads resulting from the bridge analysis.

4. Determine the plastic moment capacity of the column base hinge:

$$M_{pbh} = \phi_o M_n$$

where M_{pbh} = plastic moment capacity of the base hinge

M_n = ACI nominal moment capacity of the hinge

ϕ_o = overstrength factor. To account for the increased moment strength enhancement of the moment-reducing hinge detail, use $\phi_o = 1.6$.

5. As applicable, revise the calculated shear force and axial load (developed from framing action) to reflect the actual moment capacity of the hinge at the base of column.

6. Repeat steps 2 through 5 until the design loads converge within 10 percent.

7. Determine the spiral reinforcing ratio required on the basis of the greater of the following:

i. confinement requirements:

$$\rho_s \geq 0.45\{(A_g/A_c)-1\}f'_c/f_y\{0.5+1.25P_u/(\phi f'_c A_g)\}$$

and

$$\rho_s \geq 0.12(f'_c/f_y)\{0.5+1.25P_u/(\phi f'_c A_g)\}$$

where $\{0.5+1.25P_u/(\phi f'_c A_g)\} \geq 1.0$

$\phi = 0.75$

ii. diagonal shear requirements ($V_u = \phi V_c + \phi V_s$):

$$\rho_s \geq 0.2/f_y\{(V_u/\phi A_c)-2\sqrt{f'_c}\}$$

and

where $s = 4A_{sp}/(\rho_s d_c)$

A_{sp} = cross-sectional area of spiral bar

d_c = outside diameter of spiral

s = spacing of spiral

$\phi = 0.85$

8. Detail the moment-reducing hinge:
   - Provide a 1/2 in.-thick vertical discontinuity joint with a height equal to the hinge diameter.
   - Provide a length of 1.25 times the rebar development length for the longitudinal bars above the top of the vertical discontinuity joint for anchorage into the column, and ensure proper anchorage into the footing.
   - The horizontal discontinuity joint thickness should be at least 2 inches (in some cases, greater thicknesses may be needed to prevent contact of the outer column edge with the footing).
   - Clear spacing of the spiral reinforcement should not be greater than 6 times the hinge longitudinal bar diameter, nor 3 inches.
   - A 1/2 in. shear key should be provided at the column-to-footing connection.
9. The design of footing should be based on the maximum axial load and the actual plastic moment at base of column.

DESIGN EXAMPLE

This example illustrates the application of the proposed design recommendations. The design forces used in the example were obtained from the example problem presented in Appendix A of the 1983 AASHTO Guide Specifications for Seismic Design of Highway Bridges [9].

The column has a clear height of 22 ft and an overall diameter of 4 ft. The factored design axial load and moment for this column are: P_u =

1141 kips and M_u = 3804 kip-ft. The specified concrete compressive strength, f'_c, is 4000 psi, and a yield strength of f_y = 60,000 psi is specified for both the longitudinal and transverse reinforcement. The slenderness ratio for the column selected for the example is slightly greater than that for which slenderness effects may be neglected, and thus slenderness effects should be considered. However, for simplicity, slenderness is not considered in this example.

Using the appropriate strength reduction factors and the ACI column chart, the column requires 43 No. 10 bars for longitudinal reinforcement. This yields a longitudinal reinforcing ratio of $\rho_1 = 0.03$, which is within the limits specified in AASHTO.

The design for the moment-reducing hinge detail is presented in the step-by-step procedure of the recommendations outlined previously.

Step 1. The column shear force, obtained by considering the column overstrength plastic moment capacity, is:

$$V_u = M_p/L_u = \phi_o M_n/L_u$$

$$= 1.3 \text{ X } 5406/22 = 319 \text{ kips}$$

where L_u is the height of the column. The nominal moment capacity M_n = 5406 kip-ft is obtained for the column by using the ACI design chart for a longitudinal reinforcing ratio of 3 percent and a clear cover of 2 in., with the strength reduction factor taken as unity.

Step 2. The required circular hinge area is determined on the basis of the following:

i. shear friction theory:

$$A_g \geq V_u/(0.2\phi f'_c)$$

$$= 319/(0.2 \times 0.85 \times 4) = 469 \text{ in}^2$$

$$A_g \geq V_u/\phi 800$$

$$= 319 \times 1000/(0.85 \times 800) = 469 \text{ in}^2$$

ii. maximum allowable diagonal shear:

$$A_c \geq V_u/(\phi 10\sqrt{f'_c})$$

$$A_c \geq \frac{319000}{0.85 \times 10 \times \sqrt{4000}} = 593 \text{ in}^2$$

On the basis of the required core area, a core diameter of 28 in. is required. With a 2 in. cover, the core and gross areas required are $A_c = 615$ in^2 and $A_g = 804$ in^2, respectively.

iii. axial stress limit of $0.7f'_c$:

$$A_g \geq P_u/(\phi 0.7f'_c)$$

$$A_g \geq 1141/(0.75 \times 0.7 \times 4) = 543 \text{ in}^2$$

Therefore, a gross hinge area of $A_g = 804$ in^2 should be provided.

Step 3. On the basis of shear friction theory, the longitudinal steel required is:

$$A_{vf} \geq V_u/(\phi \mu f_y)$$

$$A_{vf} \geq 319/(0.85 \times 1 \times 60) = 6.25 \text{ in}^2$$

Since this is less than 1 percent of the gross hinge area, a total of 8 No. 9 bars will be used to provide a longitudinal reinforcing ratio of 1 percent.

Step 4. The plastic moment capacity of the base hinge is:

$$M_{pbh} = \phi_o M_{nbh}$$

$$M_{pbh} = 1.6 \times 991 = 1586 \text{ kip-ft}$$

Step 5. Using the preliminary design of the base hinge, the column shear force is revised to reflect the actual moment capacity at the base of the column. The revised column shear force resulting from the plastic moments developed at the both the top and bottom of the column is found as follows:

$$\text{revised } V_u = (M_{pth} + M_{pbh})/L_u$$

$$= (1.3 \text{ X } 5406 + 1.6 \text{ X } 991)/22 = 392 \text{ kips}$$

where M_{pth} and M_{pbh} are the plastic moments at the top and bottom of the column, respectively.

Step 6. Because of the plastic moment at the base hinge, the column shear force is increased by 23 percent. The design of the base hinge is revised by repeating steps 2 through 5 until the shear force converges within 10 percent. A final base hinge with a gross diameter of 35 in. and 10 No. 9 longitudinal bars is obtained. The plastic moment capacity of the hinge, $\phi_o M_{nbh}$, is 2035 kip-ft.

Step 7. The transverse reinforcement required, based on confinement, is the greater of:

$$\rho_s \geq 0.45\{(A_g/A_c)-1\}f'_c/f_y\{0.5+1.25P_u/(\phi f'_c A_g)\}$$

$$\rho_s \geq 0.45(\frac{962}{755} - 1)\ \frac{4}{60}\ (0.5 + 1.25 \text{ X } \frac{1141}{0.75 \text{ X } 4 \text{ X } 962})$$

$$\rho_s \geq 0.0082$$

and

$$\rho_s \geq 0.12(f'_c/f_y)\{0.5+1.25P_u/(\phi f'_c A_g)\}$$

$$\rho_s \geq 0.12 \text{ X } (4/60)(0.5 + 1.25 \text{ X } \frac{1141}{0.75 \text{ X } 4 \text{ X } 962})$$

$\rho_s \geq 0.008$

The volumetric ratio required, based on shear considerations, is:

$$\rho_s \geq 2/f_y\{(V_u/\phi A_c)-2\sqrt{f'_c}\}$$

$$\rho_s \geq \frac{2}{60} \text{ X } \left(\frac{412}{0.85 \text{ X } 755} - \frac{2 \text{ X } \sqrt{4000}}{1000}\right)$$

$\rho_s \geq 0.017$

Therefore, a transverse reinforcement ratio of 1.7 percent is provided with a #5 spiral at a pitch of 2.5 in.

Step 8. A cross-sectional view showing the details of the moment-reducing hinge is given in Figure 14.

For the column selected for the example, the plastic moment capacities of the column and the hinge, including the overstrength factors, are 7028 kip-ft and 2035 kip-ft, respectively. In comparison to a foundation connection consisting of the constant cross-section and reinforcement provided in the column, a column incorporating the moment-reducing hinge detail reduces the moment transferred to the foundation by 70 percent.

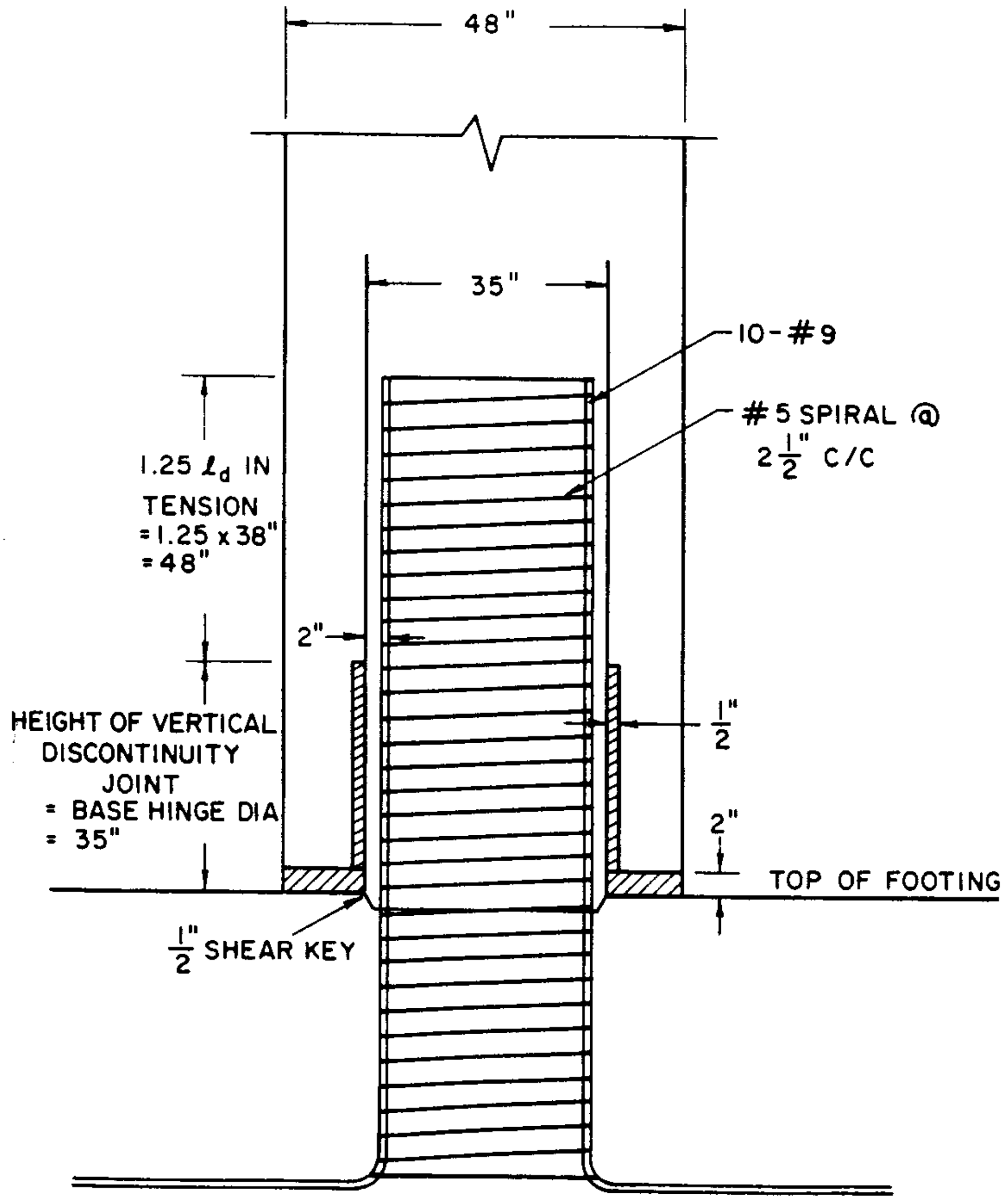


Figure 14 Cross-section of the moment-reducing hinge detail for the design example.

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