NSF/RA-770626

PB 287351

# IMPORTANCE OF REINFORCEMENT DETAILS IN EARTHQUAKE-RESISTANT STRUCTURAL WALLS

by

A. E. Fiorato and R. G. Oesterle

Published in Proceedings of Workshop on Earthquake
Resistant Reinforced Concrete Building Construction
University of California
Berkeley

July 1977

PORTLAND CEMENT ASSOCIATION
RESEARCH AND DEVELOPMENT
CONSTRUCTION TECHNOLOGY LABORATORIES
5420 Old Orchard Road
Skokie, Illinois 60076

28 p

50272-101

**REPORT DOCUMENTATION PAGE**

1. REPORT NO. NSF/RA-770626

2.

3. Recipient's Accession No. PB287351

4. Title and Subtitle
Importance of Reinforcement Details in Earthquake-Resistant Structural Walls (Partial Proceedings of Workshop on ERCBC, July 1977, University of California at Berkeley)

5. Report Date
July 1977

6.

7. Author(s)
A.E. Fiorato, R.G. Oesterle

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Portland Cement Association
Research and Development Construction Technology Laboratories
5420 Old Orchard Road
Skokie, Illinois 60076

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C) ENV7414766
(G)

12. Sponsoring Organization Name and Address
Applied Science and Research applications (ASRA)
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Examples of detailing practices related to design and construction of reinforced concrete structural walls are discussed. Areas covered are confinement reinforcement in vertical boundary elements and anchorage of horizontal wall reinforcement. The functions of confinement reinforcement are illustrated using results from laboratory tests of structural walls. The four primary functions discussed are the increase in limiting strain capacity of concrete, the support of vertical reinforcement against inelastic buckling, the containment of concrete, and the improvement of shear capacity and stiffness. Recommendations for details of hoop and supplementary cross-tie reinforcement are made. Details for proper anchorage of horizontal wall shear reinforcement are suggested. Several areas of needed research are outlined.

17. Document Analysis a. Descriptors

Structural design
Concrete construction
Earthquake resistant structures
Elastic waves
Structural analysis
Reinforced concrete
Reinforcement (structures)
Stress analysis

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement
NTIS

19. Security Class (This Report)

20. Security Class (This Page)

21. No. of Pages
25

22. Price
[illegible]

(See ANSI-Z39.18)

See *Instructions on Reverse*

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

# Workshop on
# ERCBC

July 11-15, 1977

University of California
Berkeley

# IMPORTANCE OF REINFORCEMENT DETAILS IN EARTHQUAKE-RESISTANT STRUCTURAL WALLS

by

A. E. Fiorato
Assistant Manager
Structural Development Section
Portland Cement Association
Skokie, Illinois

R. G. Oesterle
Structural Engineer
Structural Development Section
Portland Cement Association
Skokie, Illinois

W. G. Corley
Director
Engineering Development Department
Portland Cement Association
Skokie, Illinois

## ABSTRACT

Examples of detailing practices related to design and construction of reinforced concrete structural walls are discussed. Areas covered are confinement reinforcement in vertical boundary elements and anchorage of horizontal wall reinforcement.

The functions of confinement reinforcement are illustrated using results from laboratory tests of structural walls. The four primary functions discussed are the increase in limiting strain capacity of concrete, the support of vertical reinforcement against inelastic buckling, the containment of concrete, and the improvement of shear capacity and stiffness. Recommendations for details of hoop and supplementary crosstie reinforcement are made.

Details for proper anchorage of horizontal wall shear reinforcement are suggested.

Several areas of needed research are outlined.

# IMPORTANCE OF REINFORCEMENT DETAILS
# IN EARTHQUAKE-RESISTANT STRUCTURAL WALLS

by

A. E. Fiorato
Assistant Manager
Structural Development Section
Portland Cement Association
Skokie, Illinois

R. G. Oesterle
Structural Engineer
Structural Development Section
Portland Cement Association
Skokie, Illinois

W. G. Corley
Director
Engineering Development Department
Portland Cement Association
Skokie, Illinois

## INTRODUCTION

Post-earthquake damage investigations over the past 25 years have provided valuable lessons on the importance of detailing. For severe earthquake loading it is inevitable that neglected details lead to major problems. The designer must be aware of the importance of proper detailing for seismic resistance. In addition, the contractor must be aware of the importance of proper construction practices so that the structure is built according to the design.

This paper gives examples of detailing practices related to design and construction of reinforced concrete structural wall systems. These are based primarily on experience gained in laboratory tests. They are supplemented by findings from post-earthquake damage investigations.

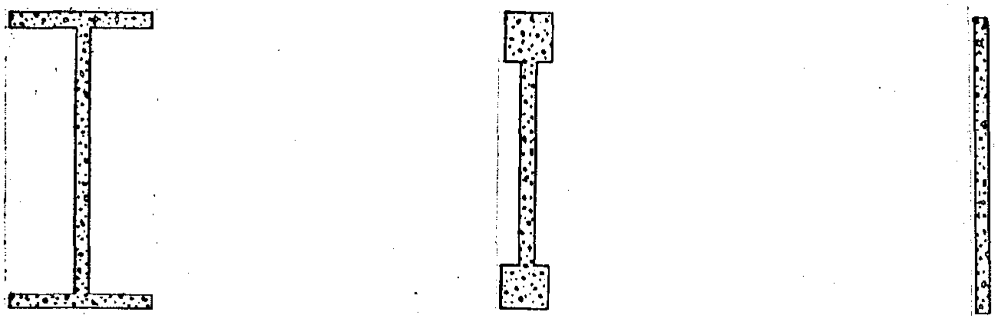
The areas covered include confinement reinforcement in vertical boundary elements and anchorage of horizontal wall reinforcement.

## CONFINEMENT REINFORCEMENT IN VERTICAL BOUNDARY ELEMENTS

Figure 1 illustrates several wall cross sections encountered in buildings. Each of these configurations can be designed with vertical boundary elements. For box-sections, flanged, and intersecting walls, the boundary element may be located at intersections. Barbell walls have column boundary elements at each end. For rectangular walls, the boundary element may be concealed within the thickness of the wall.

To perform effectively during severe earthquakes, vertical reinforcement in boundary elements must be confined by properly detailed transverse reinforcement. Transverse confinement reinforcement serves four primary functions:

1. It increases limiting strain capacity of the concrete core;
2. It supports vertical reinforcement against inelastic buckling;
3. Along with the vertical bars, it forms a "basket" to contain concrete within the core;
4. It increases the shear capacity and stiffness of the boundary elements.



(a) Flanged Section

(b) Barbell Section

(c) Rectangular Section

Fig. 1 Structural Wall Cross Section

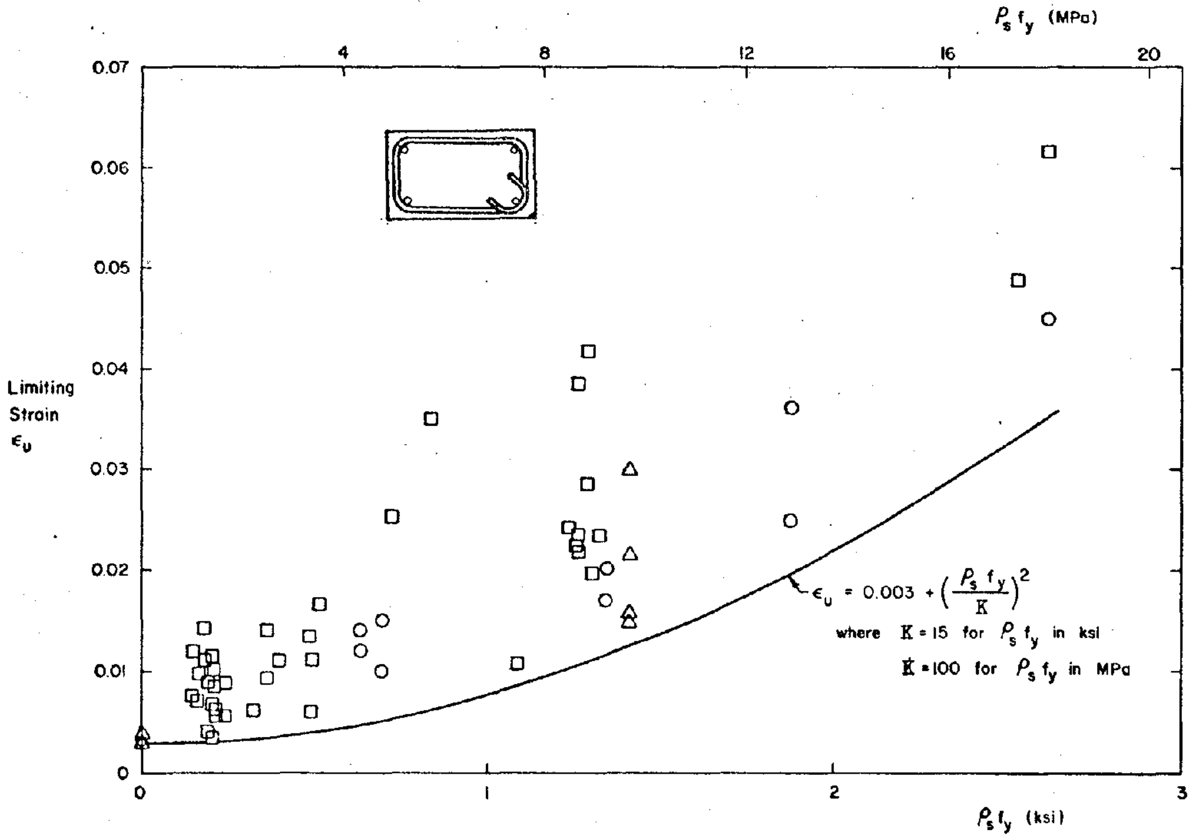


Fig. 2 Effect of Transverse Hoop Reinforcement on Limiting Strain Capacity of Concrete [5]

## Confinement to Increase Limiting Concrete Strains

The effectiveness of rectangular hoops as confinement reinforcement to increase compressive strain capacity of concrete has been investigated in tests of relatively large scale elements. 5 Rectangular hoop reinforcement meeting or exceeding the confinement requirements of Appendix A of the 1971 ACI Building Code 3 extended the limiting concrete strain beyond 0.015. This is considerably greater than the value of 0.003 for plain concrete.

A summary of results is shown in Fig. 2. The observed limiting strains, $\varepsilon_u$, are plotted as a function of the product the volumetric hoop reinforcement ratio, $\rho_s$, and the yield strength, $f_y$, of the transverse reinforcement. The curve represents a lower bound to the test results. All arrangements of rectangular hoops were effective in increasing limiting concrete strains.

Reversing load tests of isolated structural walls [7] have also indicated that confinement reinforcement provided in accordance with the 1971 ACI Building Code, [3] or the 1976 Uniform Building Code [9] is adequate to maintain the compressive strength of boundary elements under large rotational strains.

Design of confinement reinforcement according to a limiting strain criteria is not always necessary for structural walls. In many cases, the geometry of walls is such that they are considerably under-reinforced in flexure. Therefore, fracture of reinforcement in tension rather than concrete in compression is the limiting criteria. However, confinement is necessary for support of vertical reinforcement and containment of concrete in the compression zone.

## Confinement to Support Vertical Reinforcement and Contain Concrete Core

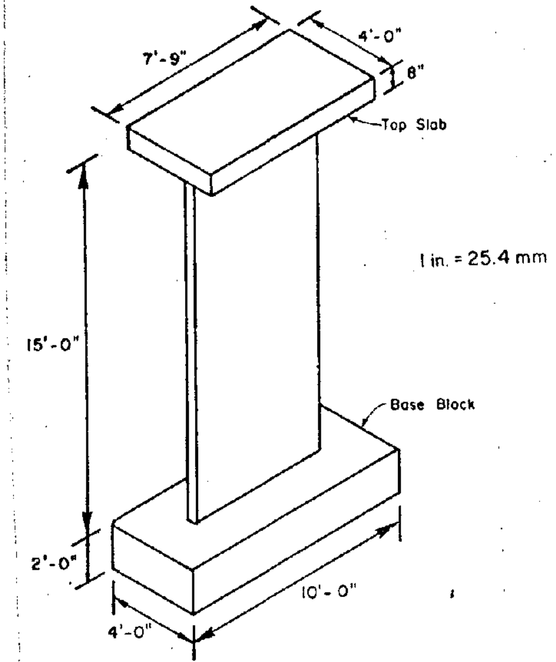
The functions of transverse reinforcement to restrain vertical bars against inelastic buckling and to contain the concrete core are of considerable importance. Comparison of two tests of isolated structural walls clearly illustrates this function.

The isolated walls tested were approximately 1/3-scale models of full-size walls. [7] Nominal dimensions of the specimens are given in Fig. 3(a). Each specimen was tested as a vertical cantilever with reversing loads applied through the top slab. The test set-up is shown in Fig. 3(b).

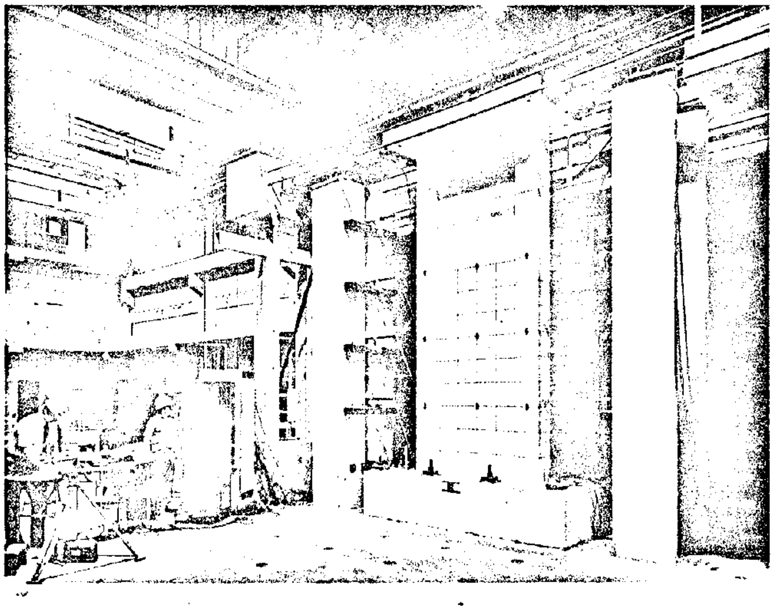
Reinforcement details for two of the specimens, B1 and B3, are shown in Figs. 4 and 5, respectively. These walls had barbell cross sections with vertical reinforcement in the boundary elements corresponding to 1.1% of the column areas. The walls were nominally identical except for the transverse reinforcement in the boundary elements.

Specimen B1, the unconfined wall, contained ordinary column ties designed according to Section 7.12 of the 1971 ACI Building Code. [3] The resulting tie spacing was 8 in. (203 mm), corresponding to 16 vertical bar diameters.

Specimen B3, the confined wall, had special transverse reinforcement designed according to Section A.6.4 of the 1971 Building Code. [3] This confinement was placed at a spacing of 1.33 in. (34 mm) over the first 6 ft (1.83 mm) of



(a) Nominal Dimensions of Test Specimens



(b) Test Set-Up

Fig. 3 Tests of Isolated Walls

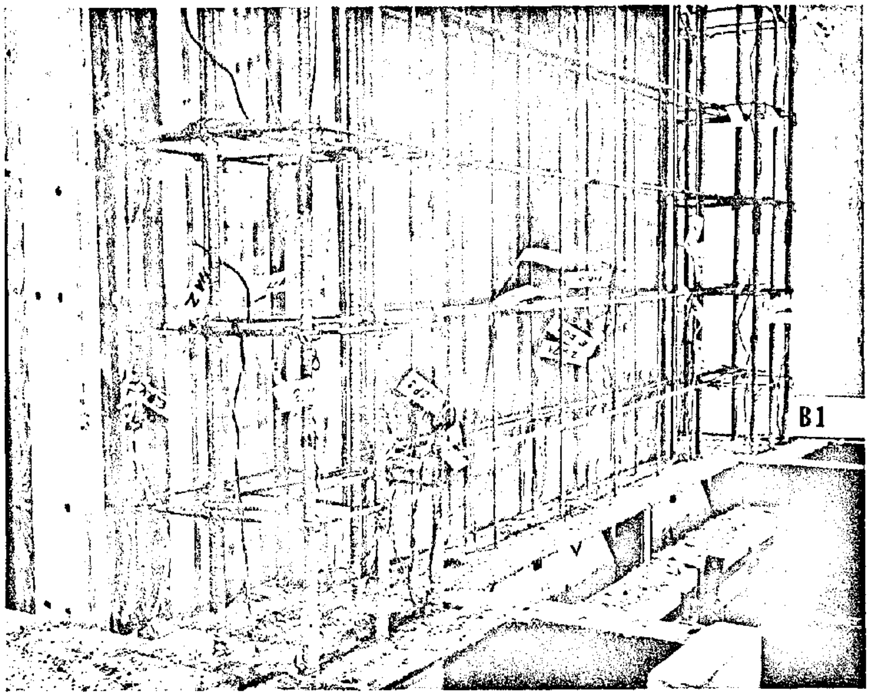


Fig. 4 Reinforcement for Specimen B1

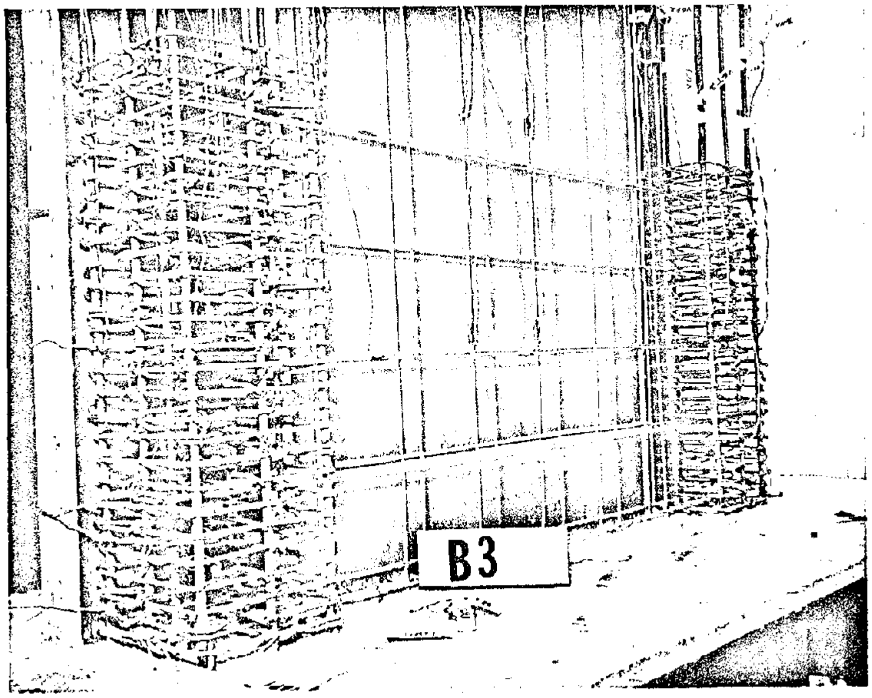


Fig. 5 Reinforcement for Specimen B3

the wall. Ordinary column ties were used over the remaining height of the wall. Confinement reinforcement spacing corresponded to 2.7 vertical bar diameters.

The hysteretic response of Specimens B1 and B3 is illustrated in the load versus top deflection relationships in Figs. 6 and 7. The maximum loads sustained by these walls corresponded to a nominal shear stress of [3]$\sqrt{f'_c}$ psi (0.3 $\sqrt{f'_c}$ MPa).

Deterioration in strength and stiffness of Specimen B1 was caused by damage to the boundary elements by alternate tensile and compressive yielding. This led to buckling of the main vertical reinforcement. Because of the reversing inelastic loads, buckling of vertical reinforcement was more critical than it would be for monotonic loading. In addition, shear distortions resulted in relatively large eccentricities in the compressive force on each bar. Buckling was accompanied by loss of concrete not contained by the vertical and transverse reinforcement when the boundary element was in tension. A photograph of the buckled reinforcement is shown in Fig. 8.

The confinement hoops in Specimen B3 did not significantly increase the strength or maximum rotation as compared to Specimen B1. However, the hoops maintained the integrity of the boundary elements by delaying bar buckling and containing the concrete core. Photographs of the two walls at the same load increment in Figs. 9 and 10 clearly show the effectiveness of the confinement. For equivalent levels of load, the confined wall suffered less damage and thus could have been reparied more easily.

The development of criteria for transverse reinforcement as a function of inelastic buckling of vertical reinforcement requires additional investigation. For example, Bresler and Gilbert [2] have considered tie requirements for columns subjected to monotonic compression. However, no work has been done on the effects of reversing stresses in the inelastic range.

## Confinement to Provide Shear Capacity

Transverse hoop reinforcement in vertical boundary elements improves shear capacity and stiffness. This function was also observed in the tests of isolated walls described previously.

Two specimens, B2 and B5, were constructed with nominally identical reinforcement except for the transverse confinement. Both walls had barbell cross sections with vertical reinforcement in the boundary elements of about 3.7% of the column area. Photographs of the reinforcement are shown in Figs. 11 and 12.

The unconfined wall, Specimen B2, had ordinary column ties at a spacing of 8 in. (203 mm) or 10.7 bar diameters. The confined wall, B5, had hoops spaced at 1.33 in. (34 mm) or 1.8 bar diameters over the first 6 ft (1.83 m) of the wall. Ordinary column ties were used over the remaining height of the wall.

Load versus top deflection relationships for the two specimens are given in Figs. 13 and 14. The capacity of both walls was limited by web crushing. Specimen B2 reached a capacity corresponding to a nominal shear stress of 7.2 $\sqrt{f'_c}$ psi (0.60 $\sqrt{f'_c}$ MPa). Specimen B5 reached 8.8 $\sqrt{f'_c}$ psi (0.73 $\sqrt{f'_c}$ MPa).

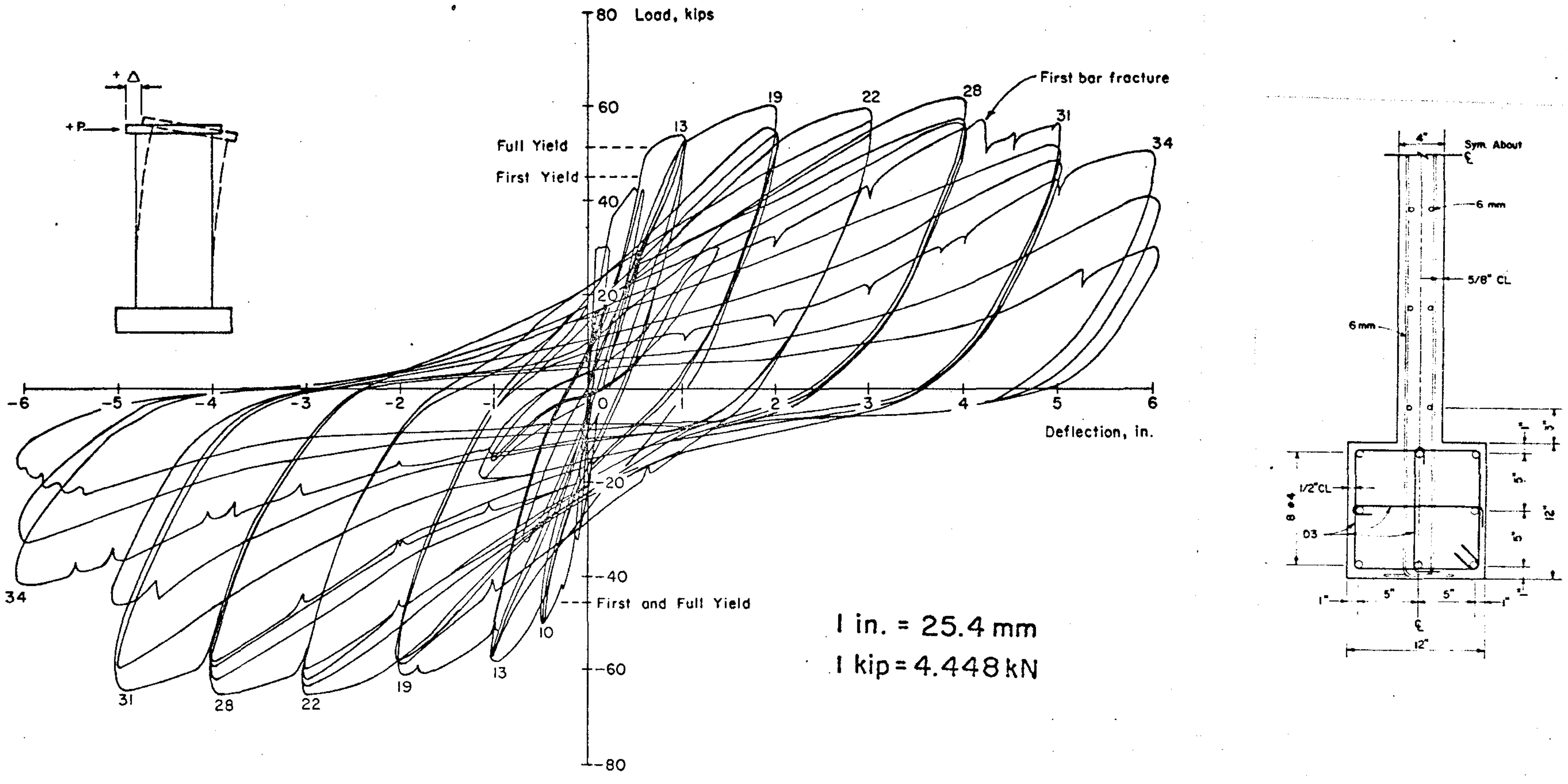


Fig. 6 Load Versus Deflection Relationship for Specimen B1

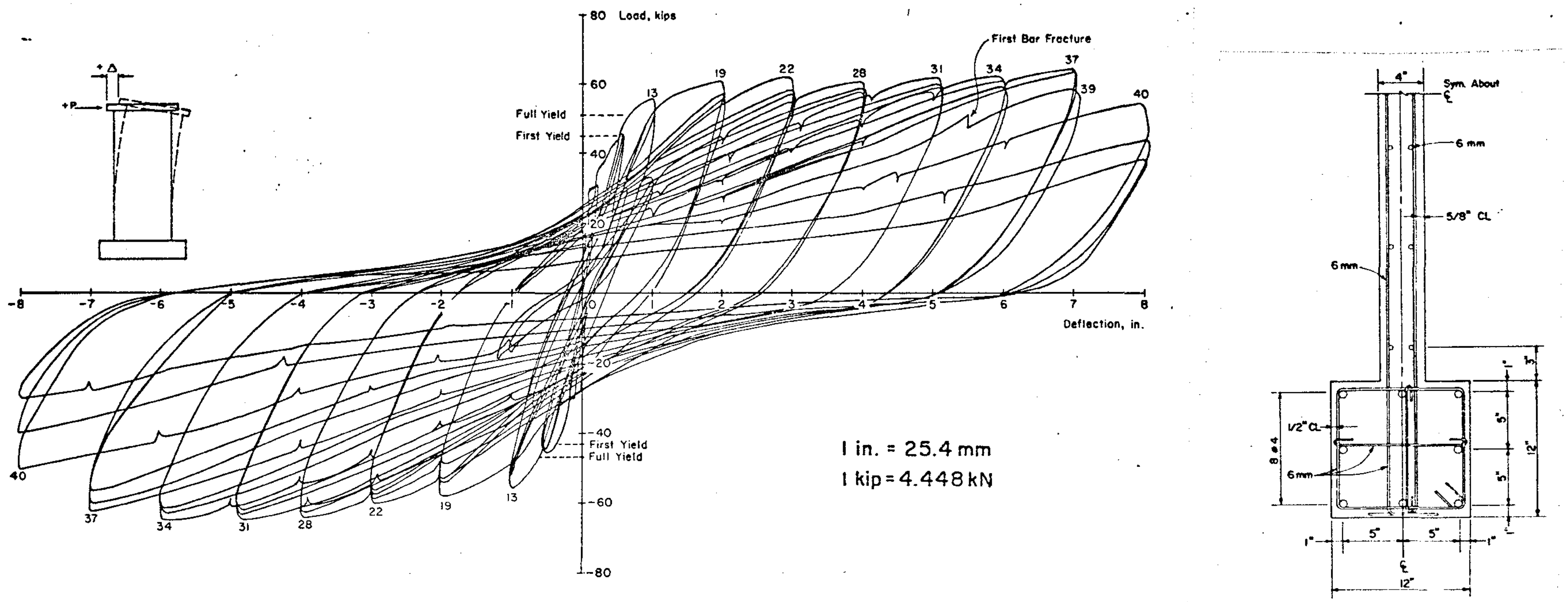


Fig. 7 Load Versus Deflection Relationship for Specimen B3

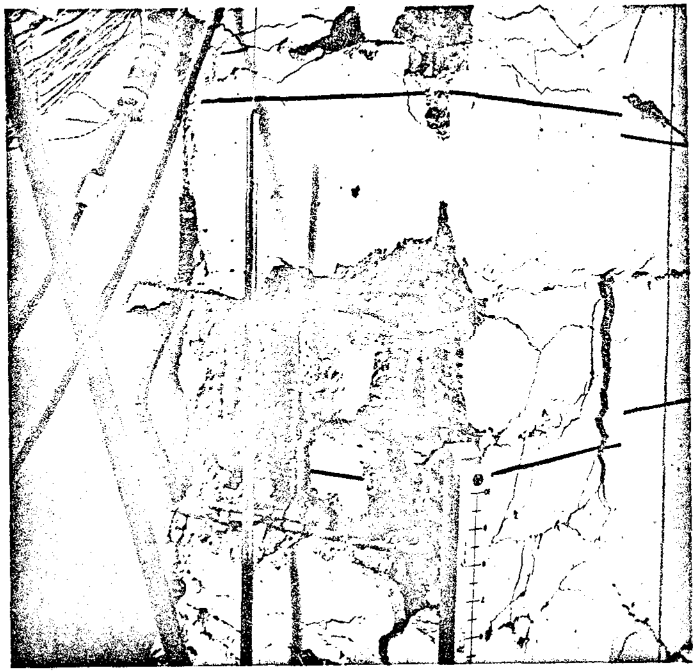


Fig. 8   Buckled Reinforcement in Specimen B1

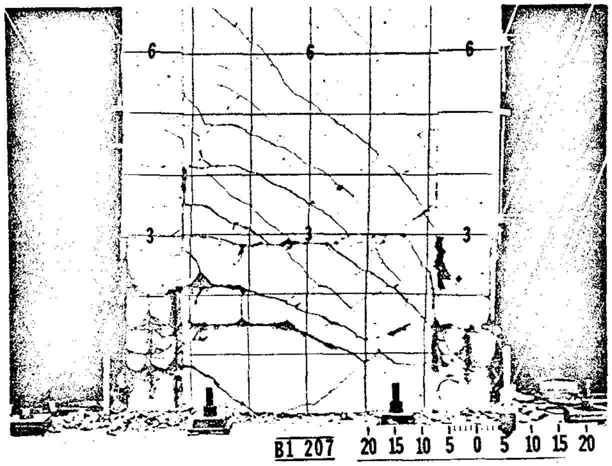


Fig. 9   Specimen B1 During Load Cycle 34

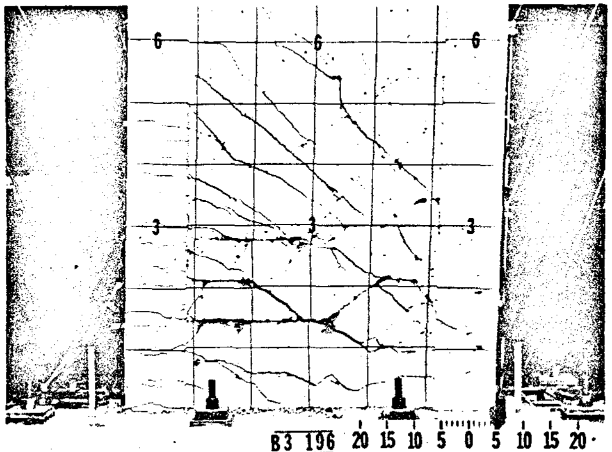


Fig. 10   Specimen B3 During Load Cycle 34

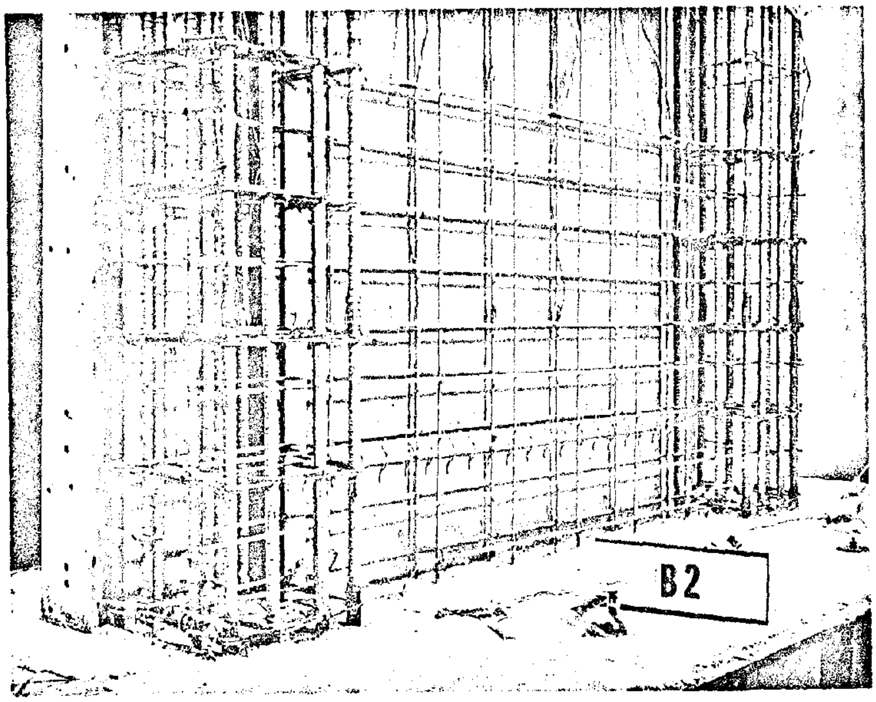


Fig. 11 Reinforcement for Specimen B2

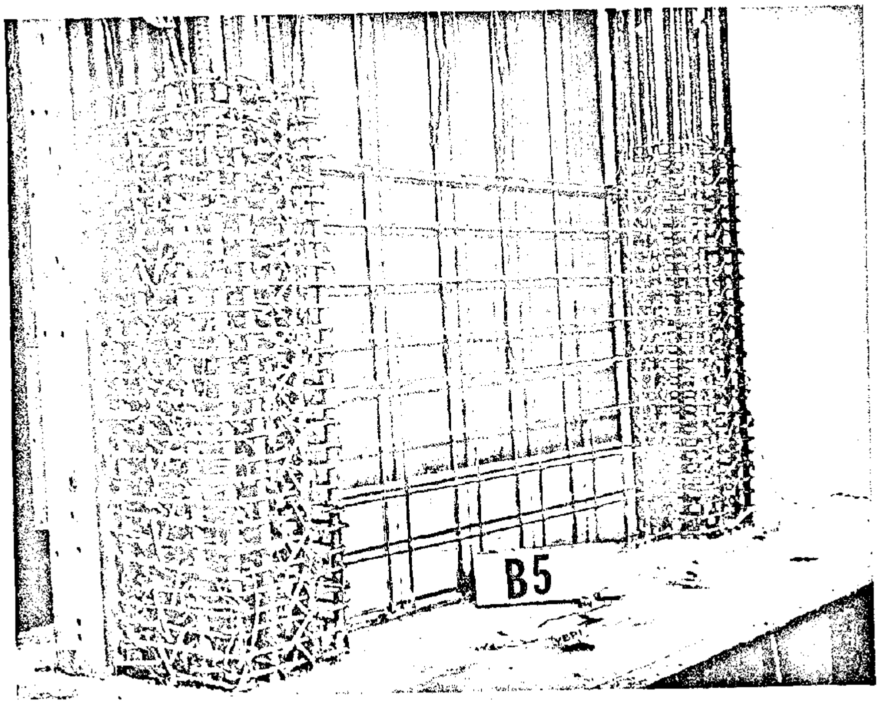


Fig. 12 Reinforcement for Specimen B5

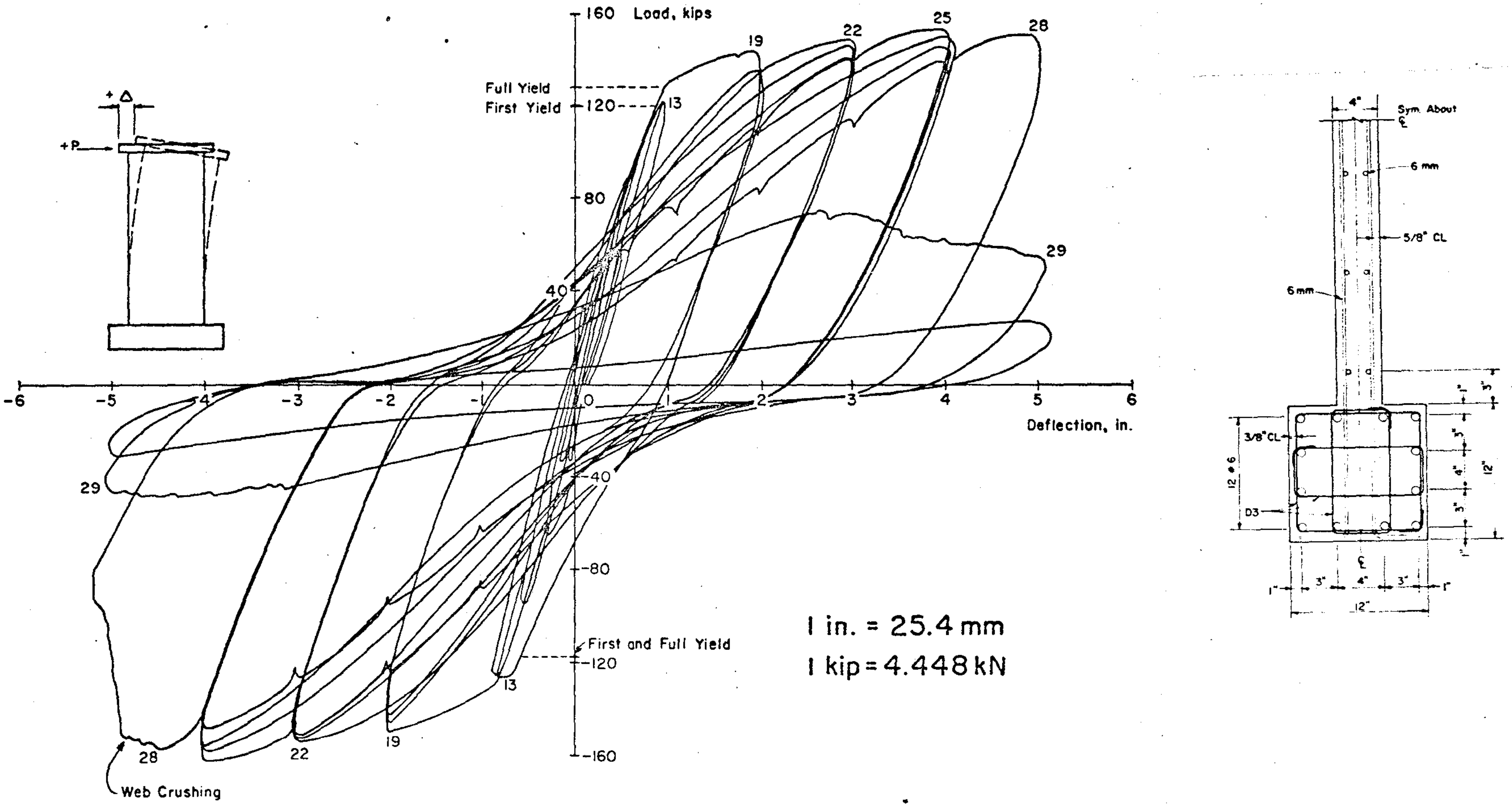
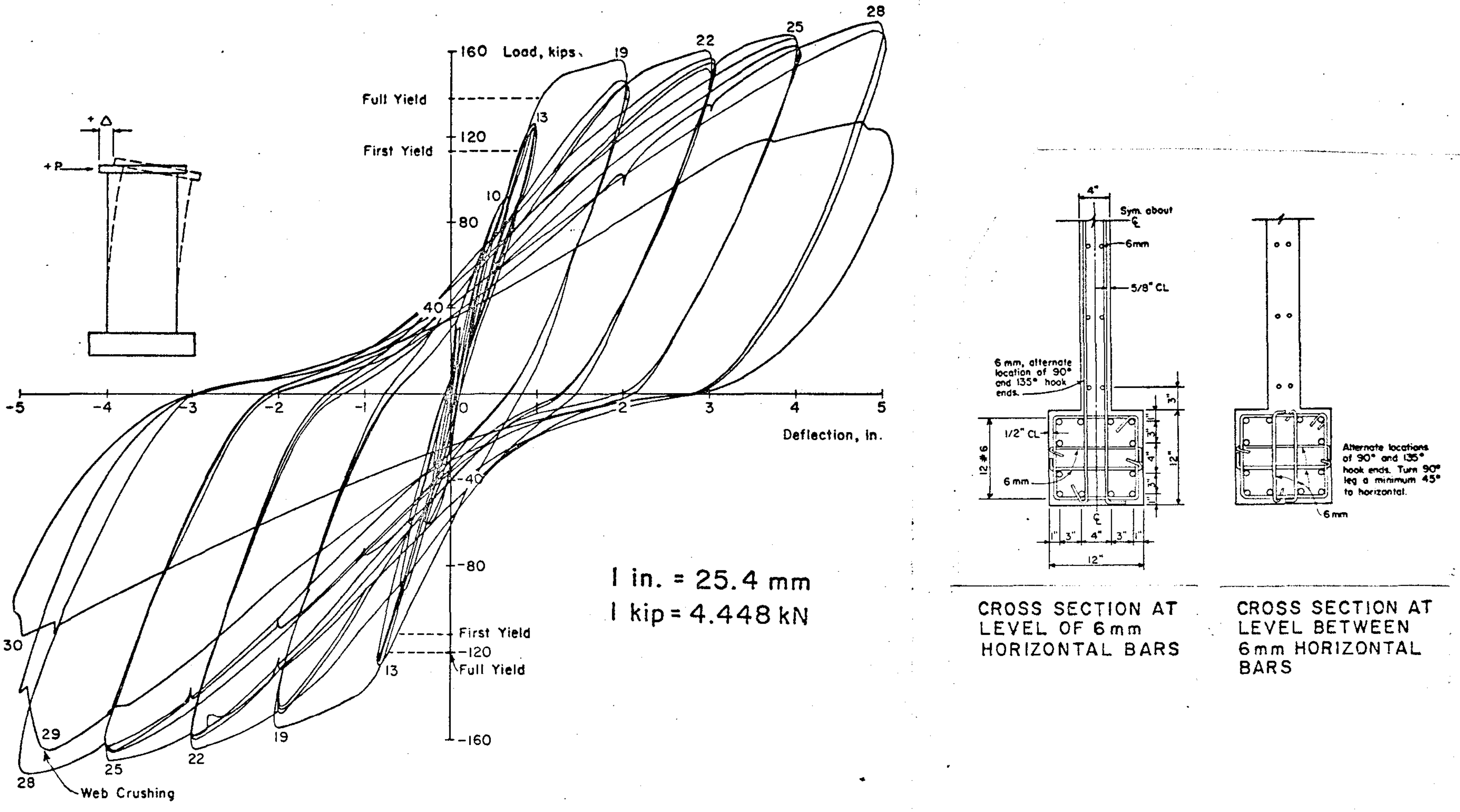


Fig. 13 Load Versus Deflection Relationship for Specimen B2



1 in. = 25.4 mm
1 kip = 4.448 kN

CROSS SECTION AT LEVEL OF 6mm HORIZONTAL BARS

CROSS SECTION AT LEVEL BETWEEN 6mm HORIZONTAL BARS

Fig. 14 Load Versus Deflection Relationship for Specimen B5

In Specimen B2, without confinement, the boundary elements deteriorated prior to web crushing. Several bars buckled and concrete was lost from the core of the columns as loads were reversed. In the last load cycle, the boundary elements were badly damaged near the base as shown in Fig. 15. Subsequently, web crushing occurred and the column was destroyed. Specimen B2 after web crushing is shown in Fig. 16.

In Specimen B5, confinement hoops prevented bar buckling and loss of concrete from the core of the boundary elements. They also reinforced the boundary elements for shear as can be seen in Fig. 17. Because of the confinement, Specimen B5 could be repaired simply by replacing the damaged web concrete.

Comparison of observed deformations in Specimens B2 with those of B5 indicated that confinement reinforcement decreased shear distortions for equivalent horizontal deflections. The improvement in shear stiffness was attributed to the confined boundary elements acting as stiff dowels.

Although only the lower 6 ft (1.83 m) of the boundary elements were confined, the primary zone of damage did not extend above this level. Strain gage data indicated that the only hoops stressed significantly were in the lower 3 ft (0.91m).

Confinement in Specimens B3 and B5 was provided by rectangular hoops. No spiral reinforcement was used. Tests at the University of California, Berkeley [1], indicate that, for vertical boundary elements of structural walls, closely spaced ties were as effective as spirals.

The benefits of transverse reinforcement for supporting vertical reinforcement, containing concrete, and improving shear resistance have also been illustrated under "field conditions". Figure 18 shows photographs of two columns in the grount story of the same building taken after the 1971 San Fernando earthquake. The effects of confinement provided by the spiral reinforcement are apparent.

## Recommended Details

Recommended Details of confinement reinforcement for columns of ductile moment resisting frames are shown in Fig. 19. The detail shown for the square column was used for isolated wall Specimen B3 shown in Figs. 5 and 7.

The use of supplementary crossties with $180^\circ$ hooks at each end caused numerous construction problems. Hoops and crossties had to be fabricated as a unit that was then slipped over the vertical reinforcement. To alleviate this assembly problem, the supplementary crossties for Specimen B5 were detailed with one $135^\circ$ hook and one $90^\circ$ hook as shown in Fig. 14. This arrangement permitted placement of crossties after the hoops were in place. The crossties were alternated end for end as construction progressed up the wall. Also, crossties parallel to the plane of the web were not provided at levels where the horizontal web reinforcement was anchored into the columns.

Reinforcement for Specimen B5 performed well, consequently it appears suitable for use as boundary element confinement.

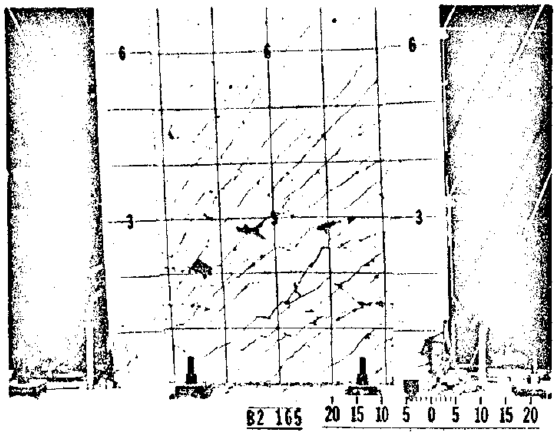


Fig. 15 Specimen B2 Immediately Prior to Web Crushing

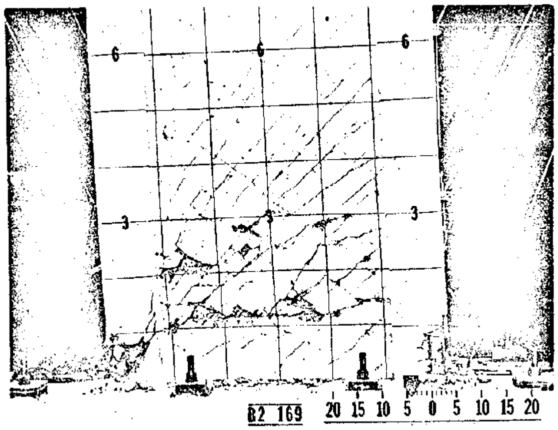


Fig. 16 Specimen B2 After Web Crushing

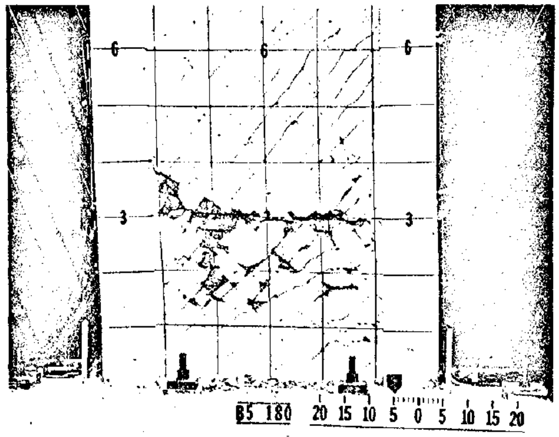
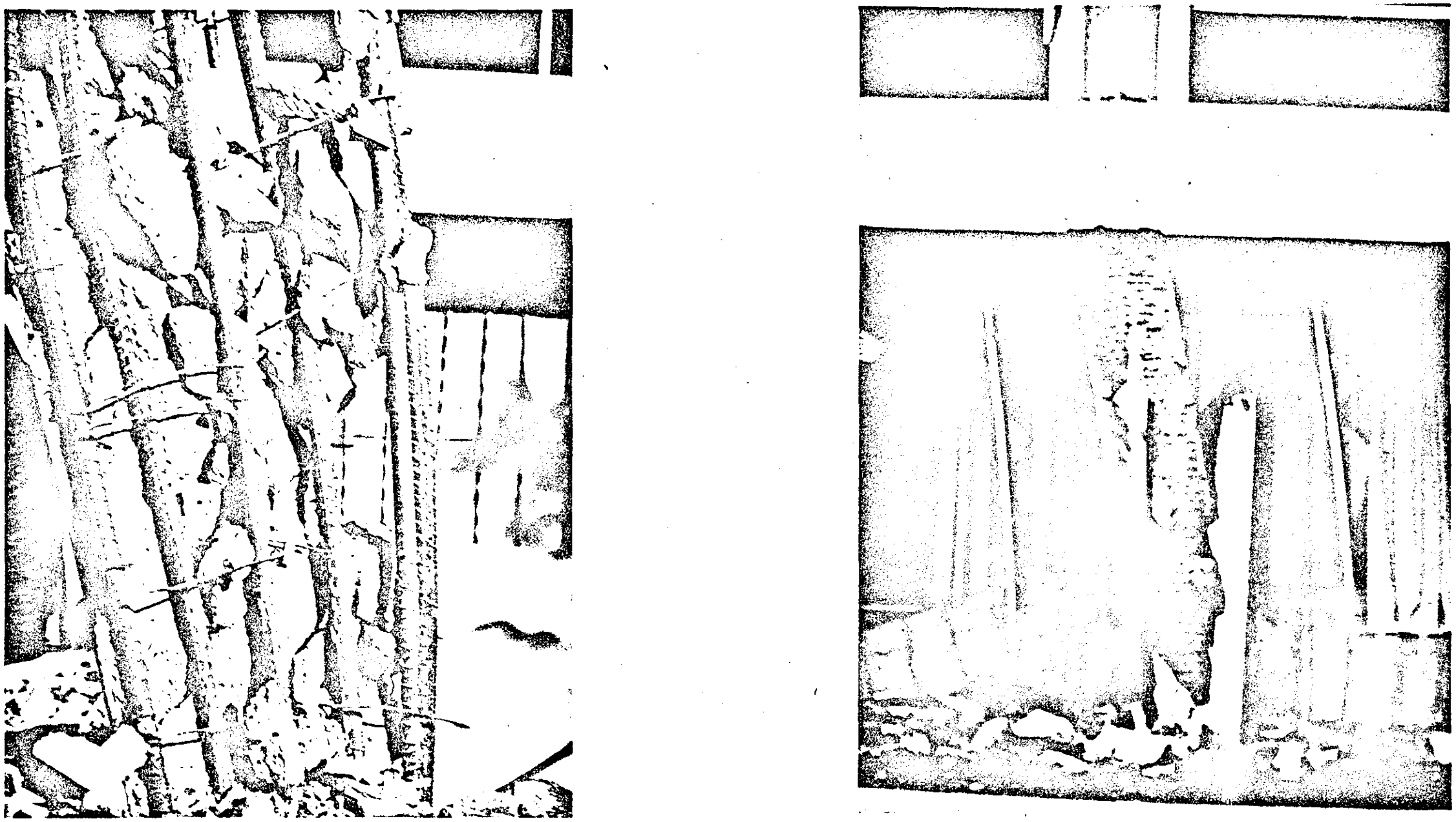


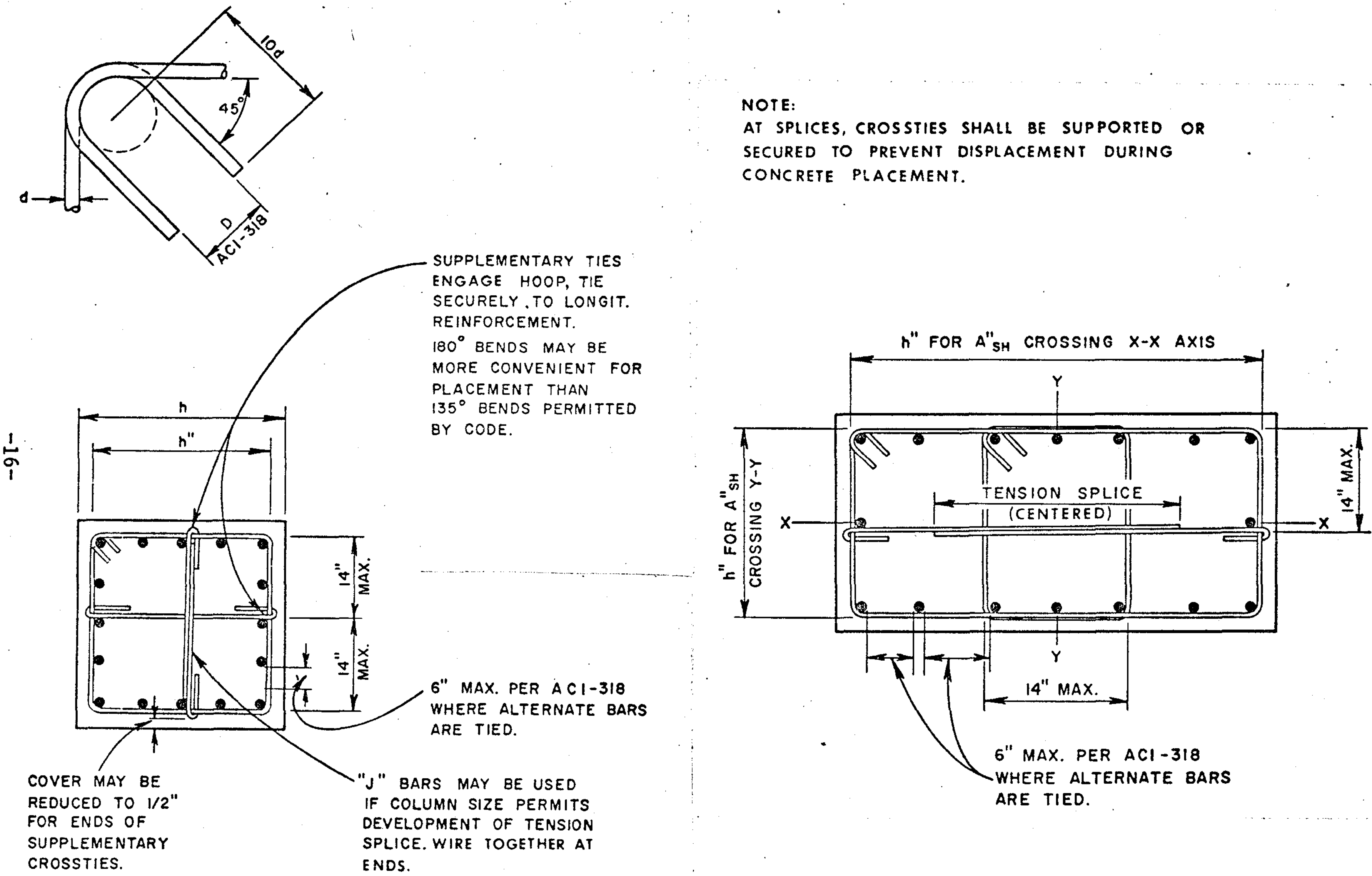
Fig. 17 Specimen B5 After Web Crushing



(a) Ordinary Tied Column

(b) Spiral Column

Fig. 18 Performance of Columns in 1971 San Fernando Earthquake



NOTE:
AT SPLICES, CROSSTIES SHALL BE SUPPORTED OR SECURED TO PREVENT DISPLACEMENT DURING CONCRETE PLACEMENT.

SUPPLEMENTARY TIES ENGAGE HOOP, TIE SECURELY TO LONGIT. REINFORCEMENT.
180° BENDS MAY BE MORE CONVENIENT FOR PLACEMENT THAN 135° BENDS PERMITTED BY CODE.

6" MAX. PER ACI-318 WHERE ALTERNATE BARS ARE TIED.

COVER MAY BE REDUCED TO 1/2" FOR ENDS OF SUPPLEMENTARY CROSSTIES.

"J" BARS MAY BE USED IF COLUMN SIZE PERMITS DEVELOPMENT OF TENSION SPLICE. WIRE TOGETHER AT ENDS.

6" MAX. PER ACI-318 WHERE ALTERNATE BARS ARE TIED.

Fig. 19 Column Details for Ductile Moment Resisting Frames [8]

Based on observations from the isolated wall tests, a tension splice detail such as that shown for the rectangular column in Fig. 19 should not be used for vertical boundary elements in this hinging region. Because of severe cracking that can develop in the boundary elements under inelastic load reversals, it is likely that tension splices in the crossties would not be effective. This is particularly important if a spliced supplementary tie parallel to web of the wall is considered for shear resistance. Lap spliced crossties are not recommended for use in structural wall boundary elements within a hinging region.

Not all walls have column boundary elements. For rectangular walls and for intersecting or flanged walls other details are required. Figures 20 and 21 show examples of confinement details that can be used to build in boundary elements.

## ANCHORAGE OF HORIZONTAL WALL REINFORCEMENT

Current code provisions permit horizontal reinforcement in the web of the wall to extend staight into the vertical boundary element. No hook is required on the end of horizontal bars. This type of horizontal reinforcement anchorage is shown in Fig. 22.

Reversing load tests of isolated walls indicate that straight bars may not provide adequate anchorage. The crack pattern developed in an isolated wall test specimen is shown in Fig. 23. Horizontal cracks in the tension boundary element propogate into diagonal web cracks. The horizontal cracks usually form at the levels of the horizontal bars because these bars form a weak plane against tension in the column. If the horizontal web reinforcement had been anchored into the column without an end hook, it is doubtful that it would have been as effective in resisting the shear forces. This is indicated by the observation that the hooks tended to open at later stages in the tests.

Within hinging regions of structural walls, it is recommended that horizontal web reinforcement be extended across the boundary element and terminated with a standard 90° bend. This was done for Specimen B3 shown in Fig. 7.

For walls subjected to levels of shear corresponding to $8\sqrt{f'_c}$ psi ($0.66\sqrt{f'_c}$ MPa) to $10\sqrt{f'_c}$ psi ($0.83\sqrt{f'_c}$ MPa), consideration should be given to the detail used for Specimen B5 shown in Fig. 14. With this detail, the wall reinforcement is anchored with either a 90° or a 135° hook. These are alternated end for end over the height of the wall.

As an alternative to the details given above, it appears that the horizontal bars could be terminated in the core of the boundary element with 90° bends in a vertical plane. However, the horizontal bar could not be considered to act as a supplementary crosstie if this detail is used.

## RECOMMENDATIONS FOR RESEARCH

1. Provisions for confinement reinforcement in the 1971 ACI Building Code [3, 4] and the 1976 UBC Building Code [8,9] are based on criteria primarily related to increasing the strain capacity of the concrete and retaining the compressive strength of the core. The volume of required hoop

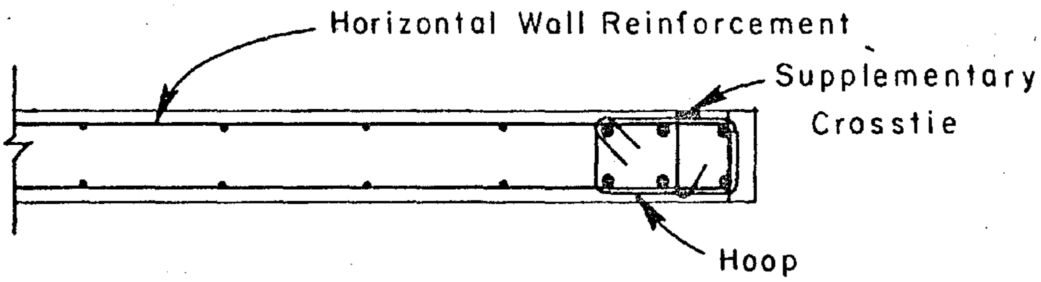


Fig. 20 Confined boundary Element Concealed in Rectangular Wall

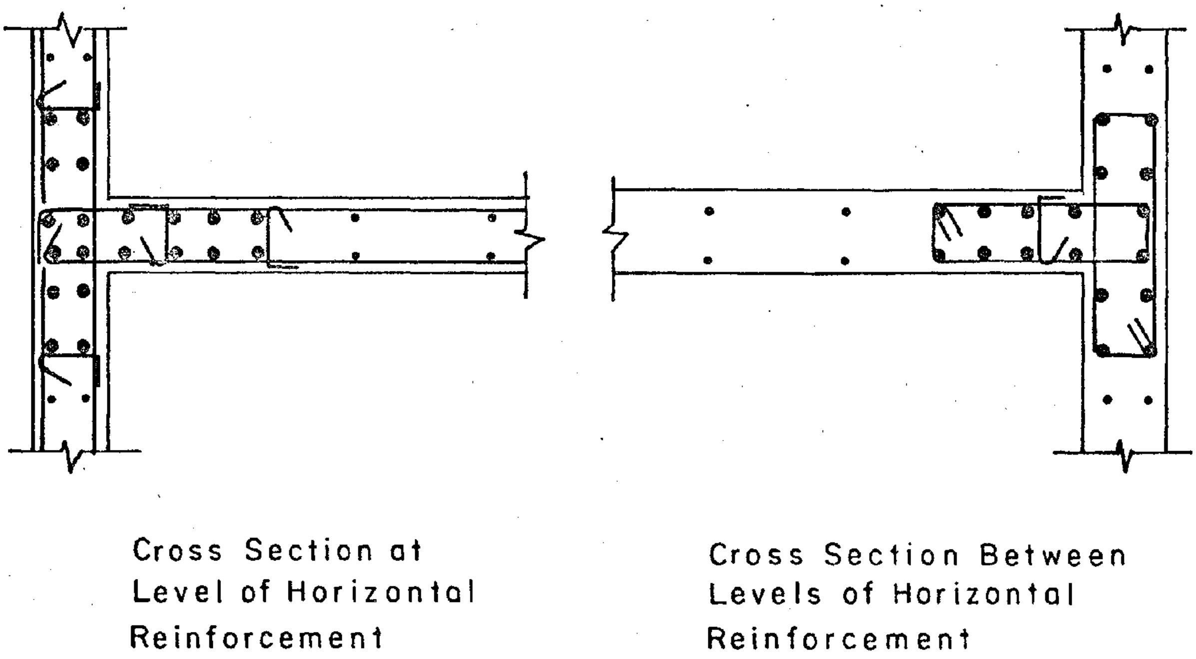


Fig. 21 Confined Boundary Element Concealed at Intersection of Walls

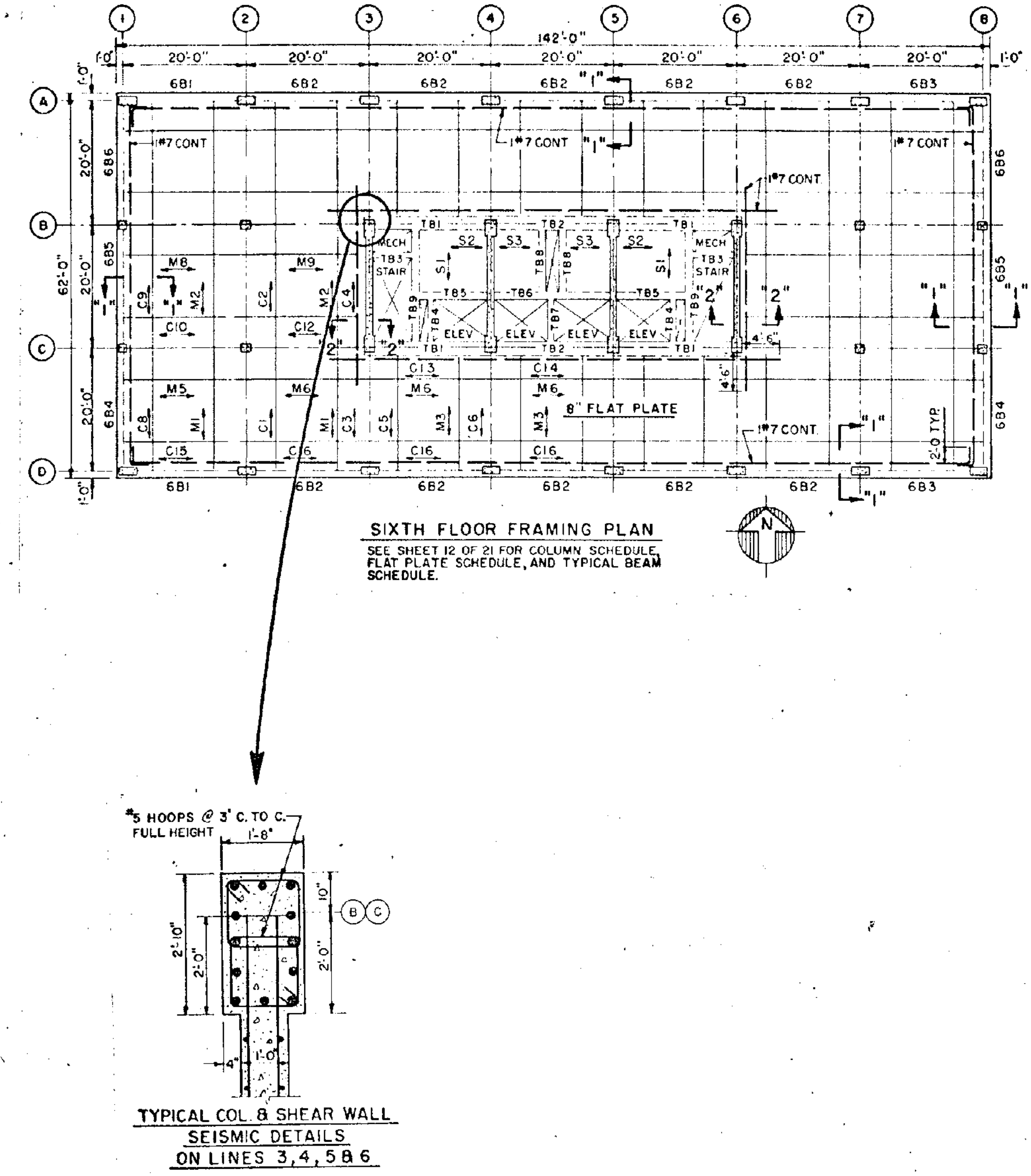


Fig. 22 Example of Structural Wall with Vertical Boundary Elements [6]

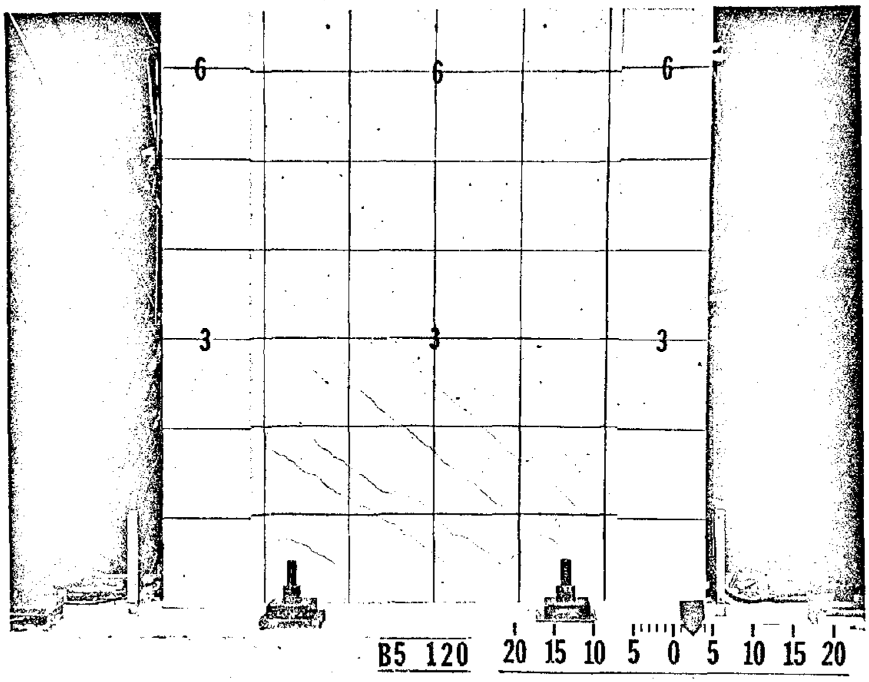


Fig. 23 Crack Pattern for Specimen B5

reinforcement was devised to provide the same average compressive stress in the rectangular core as would exist in the core of an equivalent circular spiral compression member. Research should be carried out to determine design criteria for required hoop size and spacing to delay inelastic bar buckling and to contain the concrete core.

2. Criteria for confinement reinforcement based on a limiting concrete strain can be important for walls with boundary elements having a high percentage of vertical reinforcement. Research is needed to determine the adequacy of confinement details for walls with a maximum six percent vertical reinforcement in the boundary elements.

3. Current codes require transverse confinement reinforcement over the full height of the vertical boundary element for structural walls under certain conditions. This provision should be investigated both analytically and experimentally. Tests of isolated cantilever walls indicate that confinement is only needed within the hinging region of the wall. If first mode effects dominate response, significant savings in reinforcement could result.

4. Research is needed on practical reinforcement details, especially for confinement reinforcement. Tests should be carried out to develop simple, economical and effective details. In addition, field trials should be made.

5. Tests of reinforcement splices for earthquake resistant construction are needed. Specifically, little information exists on the reliability of lap splices under severe seismic loading.

## ACKNOWLEDGMENTS

This paper was written at the Structural Development Section of the Portland Cement Association, Dr. H. G. Russell, Manager. The wall test results are based upon research supported by the National Science Foundation under Grant No. ENV74-14766 and the Portland Cement Association. M. Fintel is Overall Project Director. Any opinions, findings and conclusions are those of the authors and do not necessarily reflect the views of the National Science Foundation.

# REFERENCES

1. Bertero, V. V., Popov, E. P., Wang, T. Y. and Vallenas, J., "Seismic Design Implications of Hysteretic Behavior of Reinforced Concrete Structural Walls", Proc. Sixth World Conference on Earthquake Engineering, New Delhi, 1977 (in print).

2. Bresler, B. and Gilbert, P. H., "Tie Requirements for Reinforced Concrete Columns", Jour. ACI, Proc. Vol. 58, No. 5, Nov. 1961, pp. 555-570.

3. "Building Code Requirements for Reinforced Concrete (ACI 318-71)", American Concrete Institute, Detroit, 1970, 78 pp.

4. "Commentary on Building Code Requirements for Reinforced Concrete (ACI 318-71)", American Concrete Institute, Detroit, 1971, 96 pp.

5. Kaar, P. H., Fiorato, A. E., Carpenter, J. E. and Corley, W. G., "Limiting Strains of Concrete Confined by Rectangular Hoops", Research and Development Bulletin, Portland Cement Association, 1977 (in print).

6. "Manual of Standard Practice for Detailing Reinforced Concrete Structures (ACI 315-74)", American Concrete Institute, Detroit, 1974, 167 pp.

7. Oesterle, R. G., Fiorato, A. E., Johal, L. S., Carpenter, J. E., Russell, H. G. and Corley, W. G., "Earthquake Resistant Structural Walls - Tests of Isolated Walls", Report to National Science Foundation, Portland Cement Association, Nov. 1976, 44 pp. (Appendix A, 38 pp.; Appendix B, 233 pp.).

8. "Recommended Lateral Force Requirements and Commentary", Seismology Committee, Structural Engineers Association of California, San Francisco, 1975.

9. "Uniform Building Code", International Conference of Building Officials, Whittier, California, 1976, 728 pp.

# IMPORTANCE OF REINFORCEMENT DETAILS IN EARTHQUAKE-RESISTANT STRUCTURAL WALLS

by

A. E. Fiorato
Assistant Manager
Structural Development Section
Portland Cement Association
Skokie, Illinois

R. G. Oesterle
Structural Engineer
Structural Development Section
Portland Cement Association
Skokie, Illinois

W. G. Corley
Director
Engineering Development Department
Portland Cement Association
Skokie, Illinois

## DRAFT RECOMMENDATIONS

1. CONFINEMENT OF VERTICAL BOUNDARY ELEMENTS OF STRUCTURAL WALLS CAN BE ACHIEVED USING SUPPLEMENTARY CROSSTIES HAVING A 90° HOOK AT ONE END AND A 135° HOOK AT THE OPPOSITE END. THE CROSSTIES SHOULD BE ALTERNATED END FOR END OVER THE HEIGHT OF THE ELEMENT.

2. CROSSTIES WITHIN THE HINGING REGION OF BOUNDARY ELEMENTS SHOULD NOT BE MADE WITH TENSION LAP SPLICES.

   Under load reversals tensile cracks will propogate through the boundary element. These cracks would make the splice ineffective.

3. HORIZONTAL WALL REINFORCEMENT SHOULD BE TERMINATED WITH A 90° OR 135° HOOK WHEN ANCHORED IN A VERTICAL BOUNDARY ELEMENT.

   If the bends are made in a horizontal plane, the bars can be hooked around the outside vertical boundary element reinforcement. Another approach would be to terminate the bars within the core of the boundary element with the 90° bends in a vertical plane.