

SHEAR WALLS - RESEARCH AND DESIGN PRACTICE

by

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SYNOPSIS

Experimental results on the behavior and strength of shear walls for earthquake resistant design are briefly reviewed. Tests conducted at Stanford University, MIT and the PCA Laboratories in the United States and the University of Tokyo, Japan are examined under the requirements of Section 11.16, Special Provisions for Walls, of the 1971 ACI Building Code. Also tests on spandrel beams conducted at the University of Canterbury, New Zealand, are examined in relationship with their influence in the overall shear wall behavior.

To illustrate the application of research findings and Code requirements to design practice an example is presented. The structure considered is a ten-story reinforced concrete office building subjected to gravity loads and seismic forces as stipulated in the Peruvian Building Code. Results presented include the variation of axial load, bending moment and shear force throughout the height of the wall and the required areas of vertical and horizontal steel reinforcement.

GLOSSARY

A_s = total area of vertical reinforcement at section, cm².

$A_{s\min}$ = minimum area of vertical or horizontal reinforcement, cm²/m.

c = distance from extreme compression fiber to neutral axis, m.

C = base shear coefficient.

d = distance from extreme compression fiber to resultant of tension force, m.

D = dead load, kg/m².

E = seismic load.

$\sqrt{f'_c}$ = square root of specified compressive strength of concrete, kg/cm².

f_y = specified yield strength of reinforcement, kg/cm².

h = thickness of shear wall, m.

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- H,V = base shear for seismic design, ton.
- K = horizontal force factor.
- l_w = depth or horizontal length of shear wall, m.
- L = live load, kg/m².
- M_u = design resisting moment at section, ton-m.
- N_u = design axial load at section, positive if compression, ton.
- P = weight of the structure, ton.
- U = seismic probability factor, also ultimate load.
- v_c = nominal permissible shear stress carried by concrete, kg/cm².
- v_u = nominal total design shear stress, kg/cm².
- V_u = total applied design shear force at section, ton.
- ϕ = capacity reduction factor (Section 9.2 ACI 318-71)

BACKGROUND

Shear walls are deep, relatively thin, vertically cantilevered or propped cantilevered reinforced concrete beams. Their primary function is to resist the combined effects of vertical and lateral forces due to gravity loads and wind or earthquake forces.

Prior to the publication of the ACI 318-71⁽¹⁾ the only provisions for design of shear walls in the United States were those contained in the Uniform Building Code⁽²⁾. Background for both of these provisions has been summarized by Cardenas et. al.⁽³⁾. Shear wall provisions in both the ACI and UBC Codes are intended to ensure adequate shear strength. Equally important, however, are considerations of flexural strength, energy absorption, reinforcement details and the means of avoiding undesirable types of damage in order to obtain a satisfactory structural performance.

This paper has two objectives. First, to present a brief review of experimental research on shear walls and its comparison with the provisions of ACI 318-71. Second, to illustrate the use of Code provisions to calculate the required areas of steel reinforcement to satisfy the combined effects of axial load, bending and shear.

TEST RESULTS REVIEWED

Stanford University and MIT. In the early 1950's, Benjamin and Williams^(4,5) conducted a large number of tests in one-story plain and reinforced concrete shear walls with and without openings. The test specimens were essentially reinforced concrete frames infilled with monolithic plain or reinforced concrete panels and subjected to static loads in the plane

of the wall. Later, in the same test program, Antebi et.al. (6) conducted dynamic tests on similar specimens. The dynamic loads simulated, however, were those due to blast from atomic weapons rather than those from earth quakes.

The design recommendations of both of these investigations were of limited use due to the restrictions imposed by the scope of their applicability in one case and the nature of the applied loads in the other.

Portland Cement Association . To develop design information on the behavior and strength characteristics of shear walls for high and low-rise buildings, the PCA Laboratories initiated an experimental investigation in 1968. A total of twenty-one specimens have been tested to date. The first thirteen specimens dealt primarily with the strength of rectangular shear walls for high and low-rise buildings (7,8). The last eight dealt with the strength of very low-rise walls (Height/Depth ratios of one-half or less) containing cross walls as boundary elements and subjected to load reversals.

Figure 1 is a photograph of one of the high-rise shear wall test specimens used in the PCA investigation. The test specimen, as shown, is rotated 90° with respect to the actual position of a shear wall in a building. The approximately quarter scale specimens were 6 ft. 3 in. deep, 21 ft. high (horizontal dimension in the photograph) and 3 in. thick. The portion of the specimen to the far end of the photograph represents the foundation of the cantilevered wall. Loading rods extending through the test floor apply the simulated static lateral forces. Posttensioning rods, running horizontally in the photograph, apply the simulated gravity loads. In the design of the test specimens the interaction existing between frames and shear walls in buildings and its effect on lateral force distribution was considered. Also considered was the application of axial compressive loads to assess their effects on strength and ductility.

Results of these tests were used to formulate Section 11.16, Special Provisions for Walls, of the ACI 318-71. Important features considered in the development of the provisions (3) are the effect on shear strength of the M/V ratio, the effect of axial tensile or compressive loads and the premise that the shear strength of reinforced concrete members is the sum of two parts. One corresponds to the shear carried by the concrete and the other due to the shear carried by the web reinforcement.

University of Tokyo, Japan . Relatively few of the results of tests conducted on shear walls in Japan are available in the English literature. Those available resulted from translations carried out at the University of Illinois and the PCA Laboratories. On the basis of this limited information, it was concluded that Japanese investigators were mainly concerned with the strength of low-rise walls with and without openings, surrounded by a reinforced concrete or steel frame and subjected to load reversals.

Japanese shear wall provisions, as opposed to those in current American practice, are based on the premise that the entire shear force is to be carried by shear web reinforcement when a certain limiting nominal concrete stress is exceeded.

University of Canterbury, New Zealand . Shear walls in buildings are often pierced with openings throughout its height. The members connecting these perforated walls are called coupling or spandrel beams. In many cases, the behavior and strength of the spandrels during earthquakes affects the manner in which loads are resisted by the system of pierced walls. Tests conducted by Paulay (12,13) have dealt primarily with the strength of spandrel beams. One of the important conclusions of Paulay's work (13) was that in order to avoid excessive compressive forces in spandrels the nominal ultimate shear stress should be limited to $10\sqrt{f'_c}$ psi. as suggested by the ACI Code for beams. This requirement seems reasonable where great energy absorption is required or spandrels designed for a relatively large number of incursions into the yielding of the flexural reinforcement.

COMPARISON OF ACI CODE PROVISIONS WITH TEST RESULTS

Figure 2 shows a comparison of the ACI 318-71 provisions for shear strength of shear walls with test results previously described. Results considered are those reported by Benjamin and Williams (4,5), Antebi et. al. (6), Cardenas, et. al. (3), Mito and Kokusho (9), Ogura et.al. (10) and Tsuboi et. al. (11).

The comparison is made between calculated and measured shear strength values. The solid line represents equality between calculated and measured nominal shear stresses. The dashed line indicates consideration of the ACI capacity reduction factor, ϕ , equal to 0.85. Comparison of measured and calculated values indicates that the design provisions are satisfactory in all ranges of its applicability.

DESIGN APPLICATION

To illustrate the design procedure, a ten-story frame-shear wall building was selected. Figure 3 shows the plan and elevation dimensions. The structure is a metric system equivalent of that used by Goldberg (14) and MacLeod (13) in solving the interaction between walls and frames. Forces acting on the structure were calculated in accordance with the Peruvian Building Code (16). To estimate the interaction between frames and walls the Component Stiffness Method (15) was used. It was considered that for this type of structure the accuracy of this approximate method was satisfactory.

In addition to the overall dimensions listed for the structure in Fig. 3 and those for beams and columns listed in Ref. (15) the following data was used : $D = 700 \text{ kg/m}^2$.; $L = 300 \text{ kg/m}^2$.; $f'_c = 210 \text{ kg/cm}^2$.; $f_y = 2800 \text{ kg/cm}^2$. In accordance with the Peruvian Building Code, the base shear is $H = UKCP$. For this structure $U = 1.2$; $K = 0.8$; also $C_x = 0.065$; $C_y = 0.054$ and $P = 8282 \text{ ton}$. (calculated for $D + 0.25 L$). The values of the base shear in the x and y directions is $H_x = 516.6 \text{ ton}$. and $H_y = 426.6 \text{ ton}$. It was considered that the distribution of the equivalent static lateral seismic forces had a triangular shape with its maximum value at the top of the structure.

Figure 4 shows diagrams for the variation of axial load, bending moment and shear force in one of the two end shear walls. Due to the symmetry of the structure no torsion was considered so that both walls have the same forces.

Proportioning of Vertical Reinforcement . Using Load Factors specified in the ACI 318-71, it was found that the critical loading condition for bending at the base of the wall corresponds to $U = 0.9 D + 1.43 E$. Considering that most of the gravity load is due to dead load the design values are $N_u = 0.9 \times 518 = 466.2$ ton. and $M_u = 1.43 \times 4531 = 6479.3$ ton.-m. The required area of uniformly distributed vertical reinforcement can be calculated using the simplified Eq. 2 of Ref (3) :

$$M_u = 0.5 \phi A_s f_y \ell_w (1 + N_u / (A_s f_y)) (1 - c / \ell_w) \dots \dots \dots (1)$$

The area of uniformly distributed vertical reinforcement calculated from Eq. (1) is $A_s = 300$ cm². which is equivalent to having two layers of vertical rods $\phi 1\frac{1}{2}$ " at 15 cms. between centers on each layer. Reinforcement for other sections along the height of the wall can be calculated in a similar fashion. It should be kept in mind, however, that the minimum area of vertical reinforcement prescribed in the ACI Code for seismic design in $A_s \text{ min.} = 0.0025 \times 15 \times 1830 = 68.6$ cm². or two layers of vertical rods $\phi 3\frac{3}{8}$ " at 36 cms. between centers on each layer.

Proportioning of Web Shear Reinforcement . In accordance with Section 11.16 of the ACI 318-71, the design shear force at the critical section, a distance $\ell_w/2$ from the base of the wall is $H_u = V_u = 1.43 \times 176 = 251.7$ ton.. The calculated nominal shear stress is $v_u = V_u / \phi h d = 251.7 \times 10^3 / (0.85 \times 15 \times 0.8 \times 1830) = 13.5$ kg/cm². The ratio $M_u / V_u \ell_w$ at the critical section is $1.43 \times 2835 / (1.43 \times 176 \times 18.3) = 0.88$. The shear stress carried by the concrete is given by the lesser value of Eq. 11.32 and 11.33 of the ACI 318-71 which in the metric system are:

$$v_c = 0.87 \sqrt{f'_c} + N_u / (4 \ell_w h) \dots \dots \dots (2)$$

$$v_c = 0.16 \sqrt{f'_c} + \ell_w (0.33 \sqrt{f'_c} + 0.2 N_u / (\ell_w h)) / (M_u / V_u - \ell_w / 2) \dots (3)$$

In this particular case Eq. (3) controls and yields $v_c = 15.4$ kg/cm². This shear stress carried by the concrete is larger than the calculated ultimate nominal shear stress $v_u = 13.5$ kg/cm². .Consequently the required amount of horizontal shear reinforcement throughout the height of the wall corresponds to the specified minimum or $A_s \text{ min.} = 0.0025 \times 15 \times 100 = 3.75$ cm²/m.. This is equivalent to having two layers of horizontal rods $\phi 3\frac{3}{8}$ " at 36 cms. between centers on each layer.

CONCLUDING REMARKS

The main objective of this paper was to present in one document a brief review of the experimental research on shear walls and its application to design practice. No attempt was made to list test results for they are contained in the references indicated. In the design example only the required areas of flexural and shear reinforcement were calculated. It has

to be emphasized again that considerations of energy absorption, reinforcement details and the means of avoiding undesirable types of damage are equally important to obtain a satisfactory structural performance. Those aspects were considered beyond the scope of this paper.

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BIBLIOGRAPHY

1. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-71)," American Concrete Institute, Detroit, 1971, 78 pp.
2. Uniform Building Code, International Conference of Building Officials, Pasadena, California, 1967 and 1970 Editions.
3. Cardenas, A.E., Hanson, J.M., Corley, W.G., and Hognestad, E., "Design Provisions for Shear Walls," to be published in the ACI Journal. Also PCA R/D Ser. 1494, Feb. 1972.
4. Benjamin, J.R. and Williams, H.A., "The Behavior of One-Story Reinforced Concrete Shear Walls," Journal of the Structural Division, ASCE, Vol. 83, No. ST3, May 1957. Also Transactions ASCE, Vol. 124, 1959, pp. 669-708.
5. Benjamin, J.R. and Williams, H.A., "Behavior of One-Story Reinforced Concrete Shear Walls Containing Openings," ACI Journal, Proc. Vol.55, pp. 605-618, November 1958.
6. Antebi, J., Utku, S. and Hansen, R.J., "The Response of Shear Walls to Dynamic Loads," MIT Department of Civil and Sanitary Engineering, (DASA - 1160), Cambridge, Mass., August 1960.
7. Cardenas, A.E. and Magura, D.D., "Strength of High-Rise Shear Walls - Rectangular Cross Sections," ACI Committee 442 Symposium Volume on Response of Buildings to Lateral Forces. Also PCA R/D Ser. 1498, April 1972.
8. Cardenas, A.E., "Strength of Low-Rise Shear Walls - Rectangular Cross Sections," to be published by the Portland Cement Association, Skokie, Illinois.
9. Muto, K. and Kokusho, K., "Experimental Study on Two-Story Reinforced Concrete Shear Walls," Muto Laboratory, University of Tokyo, Tokyo, Japan. Translated by T. Akagi, University of Illinois, Urbana, Illinois, August 1959.
10. Ogura, K., Kokusho, K. and Matsoura, N., "Tests to Failure of Two-Story Rigid Frames with Walls," Part 24, Experimental Study No. 6, Japan Society of Architects Report No. 18, February 1952. Translated by T. Akagi, University of Illinois, Urbana, Illinois, August 1959.

11. Tsuboi, Y., Suenaga, Y and Shigenobu, T., "Fundamental Study on Reinforced Concrete Shear Wall Structures - Experimental and Theoretical Study of Strength and Rigidity of Two-Directional Structural Walls Subjected to Combined Stresses M.N.Q.". Transactions of the Architectural Institute of Japan, No. 131, January 1967. PCA Foreign Literature Study No. 536, November 1967.
12. Paulay, T., "Coupling Beams of Reinforced Concrete Shear Walls," Proc. ASCE, Vol. 97, No. ST3, pp.843-862, March 1971.
13. Paulay, T., "Simulated Seismic Loading of Spandrel Beams," Proc. ASCE, Vol. 97, No. ST9, pp. 2407-2419, Sept. 1971.
14. Goldberg, J.E., "Analysis of Multistory Buildings Considering Shear Wall and Floor Deformations," Tall Buildings, Pergamon Press, 1967, pp. 349-373.
15. MacLeod, I.A., "Shear Wall - Frame Interaction - A Design Aid with Commentary," Portland Cement Association Special Publication SP 011. 01D, 1971.
16. Reglamento Nacional de Construcciones, Titulo V, Cap. IV, pp. 25-34, Lima, Perú, 1970.

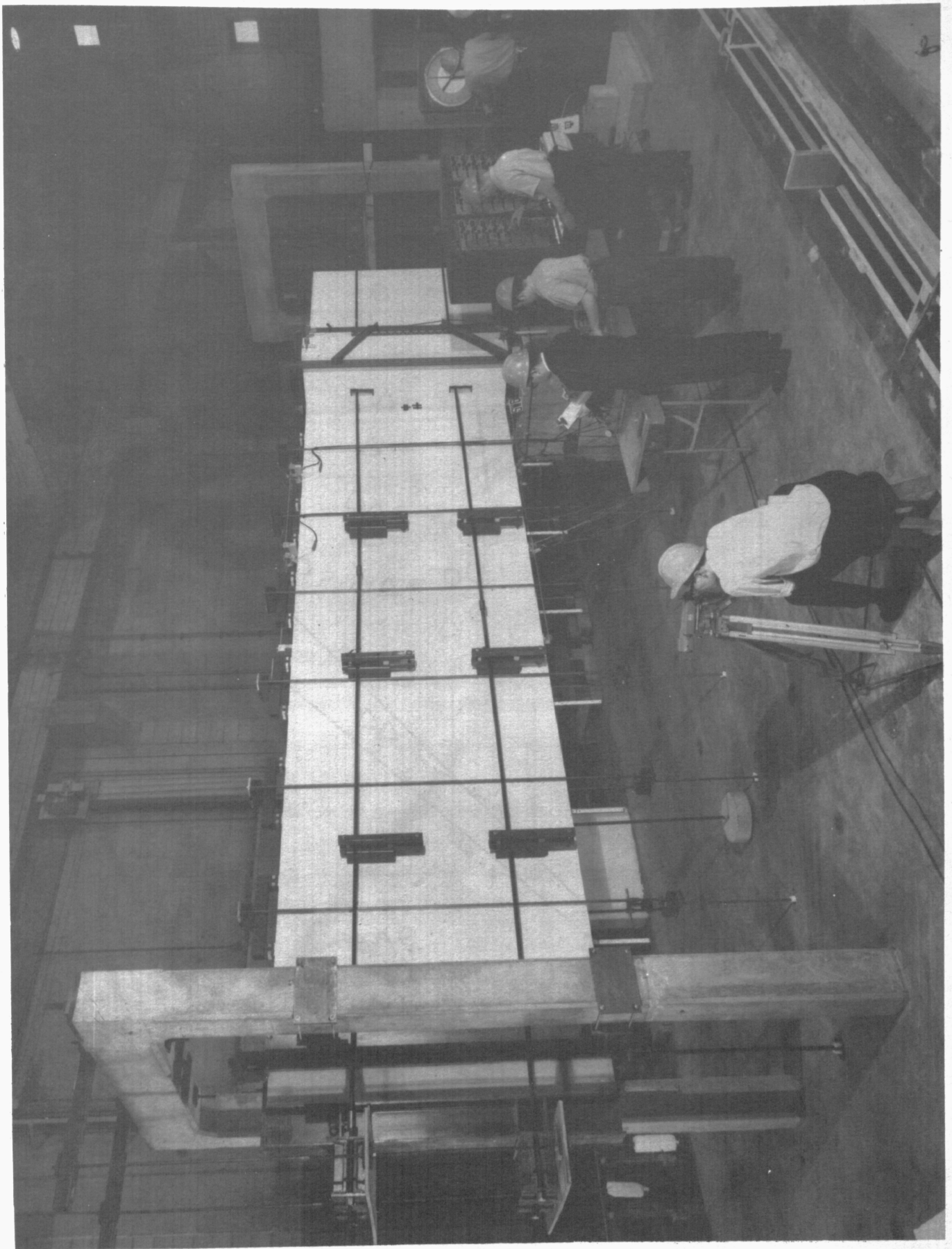


FIG. 1 PCA SHEAR WALL INVESTIGATION - TEST SETUP

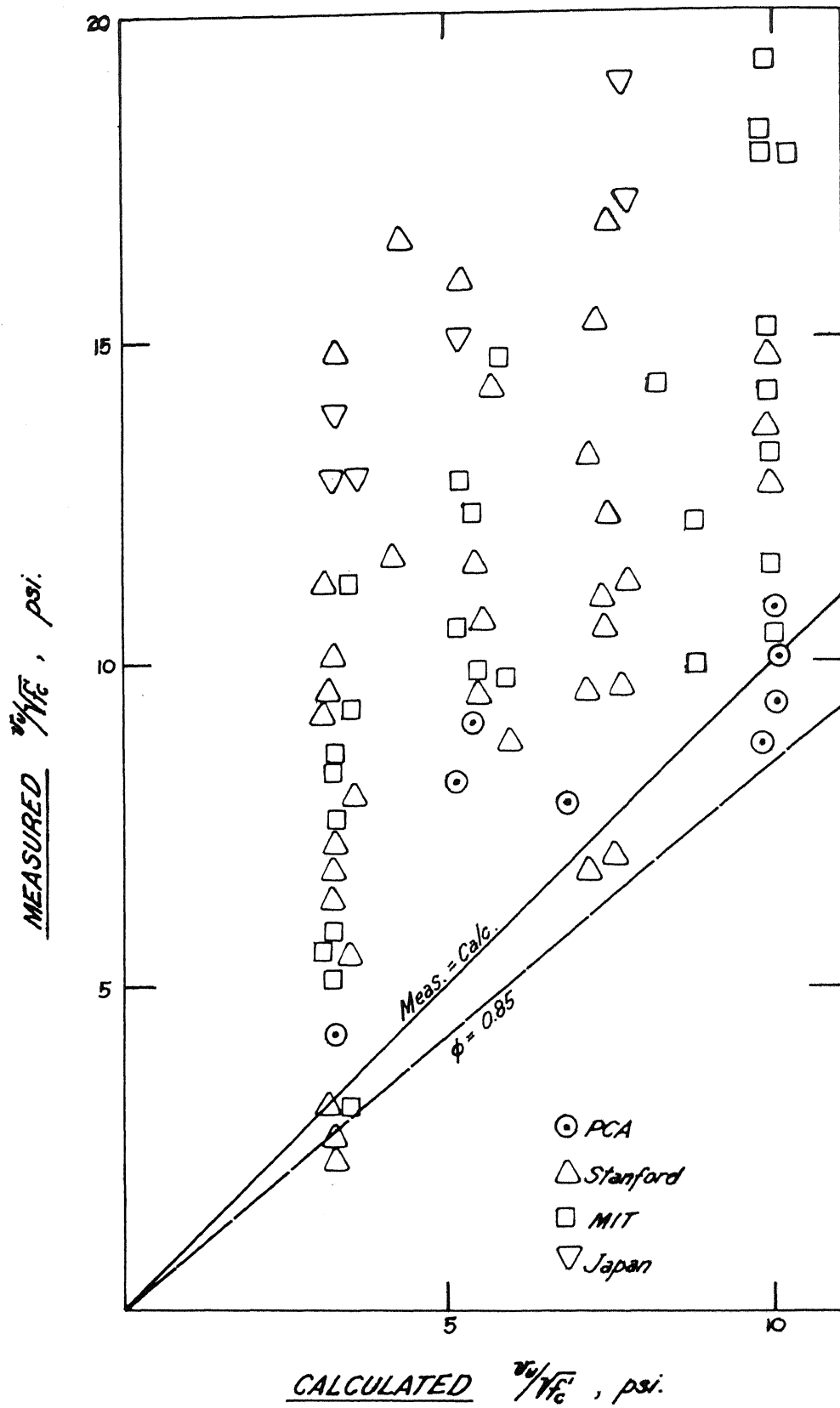


FIG. 2 COMPARISON OF ACI PROVISIONS WITH TEST RESULTS

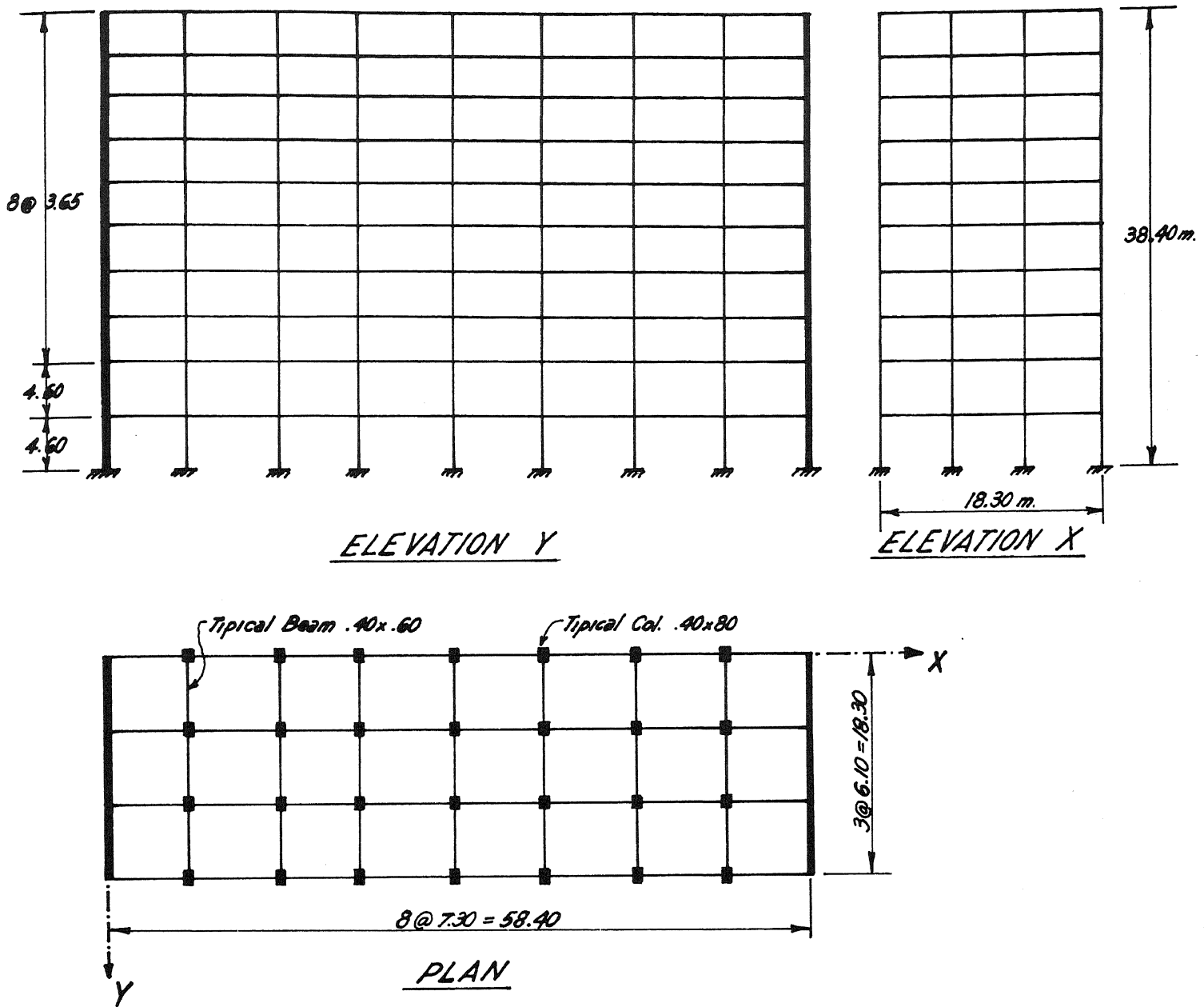


FIG. 3 DESIGN EXAMPLE - PLAN AND ELEVATION

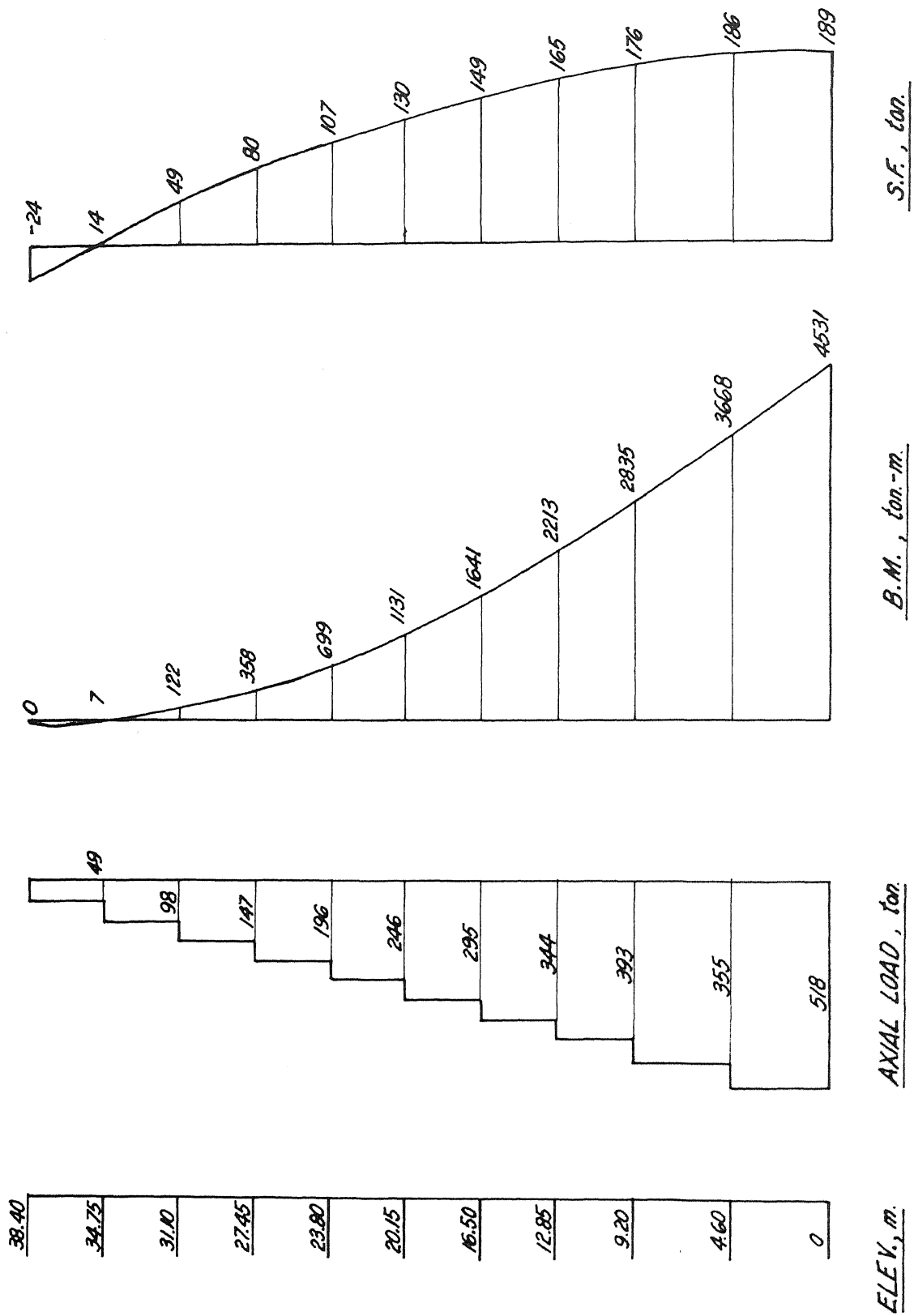


FIG. 4 DESIGN EXAMPLE - CALCULATED FORCES