DESIGN OF EARTHQUAKE-RESISTANT STRUCTURAL WALLS

by

W. G. Corley and J. M. Hanson[I]

SYNOPSIS

In the United States, provisions intended for design of walls subject to earthquake forces were first included in the 1967 Uniform Building Code. More recently, special provisions for shear walls were given in the 1971 ACI Building Code (ACI 318-71). Background information on the provisions is summarized. A procedure for calculating the strength and energy absorption capacity of walls is presented. Results of tests carried out in the Structural Development Laboratory of the Portland Cement Association are compared with behavior suggested by the design procedure.

BACKGROUND

It has been recognized that shear walls, when subjected to lateral loads caused by wind or earthquake, must resist high bending moments as well as shears. (1) Consequently, they should be designed as thin vertical beams restrained at the foundation.

To properly proportion shear walls to resist seismic forces, it is necessary to be able to predict their strength and ductility. This paper provides the basic tools for doing this. Details of the development of this information and a summary of relevant research are given elsewhere. (2,3) Of the research data available, tests in Japan, at Stanford University, at the Massachusetts Institute of Technology and at the Portland Cement Association are used for evaluation of the design procedure described here.

Prior to publication of the 1971 ACI Building Code (ACI 318-71) (4), the only provisions for design of shear walls in the United States were those contained in the Uniform Building Code (UBC) (5). The UBC design method relates the height-to-horizontal length ratio of the wall, h_w/ℓ_w, to the nominal total design shear stress, v_u. Lateral loads are assumed to be resisted either only by the concrete or by the concrete and the horizontal reinforcement. The nominal permissible shear stress carried by the concrete, v_c, on shear walls with low h_w/ℓ_w ratios is assumed similar to that in deep beams. For h_w/ℓ_w ratios of 2.7 or more, v_c is $2\sqrt{f'_c}$, as recommended for reinforced concrete beams.

The UBC also assumes that vertical or horizontal web reinforcement does not contribute in shear walls with h_w/ℓ_w ratios of 1.0 or less. Shear walls with h_w/ℓ_w ratios of 2.0 or more are considered to behave as beams. Consequently, total design shear strength for these walls is taken equal to the sum of concrete and steel contributions but no more than $10\sqrt{f'_c}$.

Based on the best information then available, the UBC provisions represented an advancement in design. More recent data (2,3) permitted improvements in these provisions as described in this paper.

[I] Manager, and Former Assistant Manager, respectively, Structural Development Section, Portland Cement Association, Skokie, Illinois.

DESIGN PROCEDURE

A shear wall must be designed to have adequate flexural strength, shear strength and energy absorption capacity. Design lateral loads are obtained by analysis based either on Code requirements or special structural dynamic studies. The shear wall is then proportioned for moments caused by these loads. Next, the wall is designed to have adequate energy absorption capacity and a shear strength somewhat greater than its flexural strength. Finally, details such as anchorage, bar spacing and continuity should be carefully considered.

Flexural Strength and Energy Absorption - The flexural strength of walls containing concentrated reinforcement can be calculated using assumptions of Sec. 10.2 of ACI 318-71 (4). For the common case of rectangular shear walls containing uniformly distributed vertical reinforcement, A_s, and subjected to combined axial load, N_u, bending, M_u, and shear, V_u, the strength of walls with a height equal to or greater than horizontal length may be calculated, when flexure governs, as

$$M_u = 0.5\, A_s f_y \ell_w \,(\, 1 + N_u/A_s f_y)\,(\, 1 - c/\ell_w) \quad \ldots.(1)$$

where f_y = specified yield strength of vertical reinforcement, ℓ_w = horizontal length of shear wall, and c = distance from extreme compression fiber to neutral axis. Once the flexural capacity is known, the energy absorption capacity may be calculated as the area under the moment versus rotation curve.(1)

Shear Strength - American design practice (4) is based on the premise that shear capacity of concrete beams is made up of two parts. One part is the shear carried by concrete, and the other part is the shear carried by web reinforcement. Web reinforcement is required only for that portion of the total shear that exceeds the limit of the shear carried by the concrete.

Shear stress, v_c, attributed to the concrete in a wall of thickness, h, may be taken as the lesser of

$$v_c = 3.3\sqrt{f'_c} + \frac{N_u}{4\ell_w h} \text{ or } v_c = 0.6\sqrt{f'_c} + \frac{\ell_w(1.25\sqrt{f'_c} + 0.2N_u/\ell_w h)}{M_u/V_u - \ell_w/2}$$

The contribution of reinforcement to shear strength of concrete beams has traditionally been based on the "truss analogy." Applied to shear walls, this contribution, expressed in terms of nominal shear stress, v_s, and the horizontal shear reinforcement ratio, ρ_h, is $v_s = \rho_h f_y$.

Based on these equations, shear capacities of walls with rectangular cross sections and minimum shear reinforcement are plotted in Fig. 1. The curves have been plotted for f'_c of 5000 psi and f_y of 60,000 psi. The diagram shows that for these conditions, the minimum shear strength of low-rise walls is of the order of $5.4\sqrt{f'_c}$, and that of high-rise walls is of the order of $4.1\sqrt{f'_c}$. In addition, a recommended limiting shear stress of $10\sqrt{f'_c}$ is shown. Attainment of shear stresses of this magnitude requires careful reinforcement detailing.

COMPARISON OF DESIGN PROVISIONS WITH TEST RESULTS

The design provisions for shear strength of shear walls are plotted in Fig. 2 with experimental results. Details of the tests and of calculations used for the comparison are summarized elsewhere.(2)

In Fig. 2, the solid line represents equality between calculated and measured shear stresses. The dashed line represents consideration of a capacity reduction factor, ϕ, equal to 0.85. The two PCA test results plotted under the solid line are for specimens where the shear failure was observed to have been precipitated by loss of anchorage of the flexural reinforcement. The PCA test result marked with an R corresponds to the specimen (shown in Fig. 3) subject to load reversals. Comparison of measured and calculated strengths in Fig. 2 indicates that the design provisions are satisfactory.

CONCLUDING REMARKS

The design procedure suggested requires that flexural strength, as well as shear strength, must be considered in proportioning of a shear wall. Equations are given for determining the design flexural capacity of rectangular walls with uniformly distributed vertical reinforcement and for determining shear capacity. In the design of shear walls, considerations such as energy absorption, lateral stiffness, and detailing of reinforcement need special attention.

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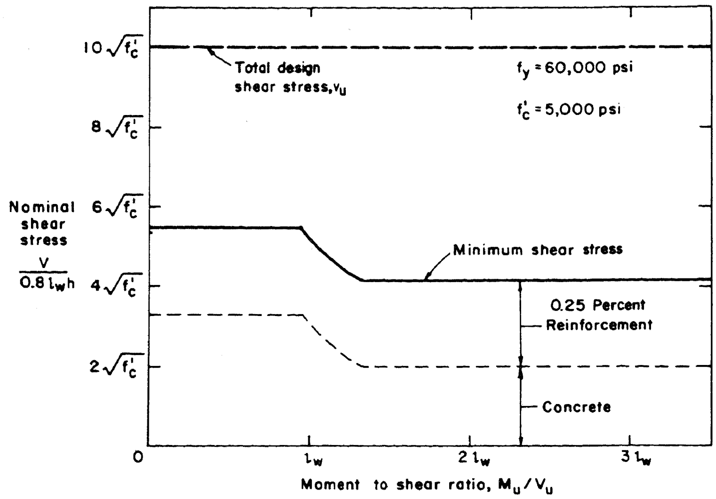

FIG. 1 MINIMUM SHEAR STRENGTH - RECTANGULAR CROSS SECTION

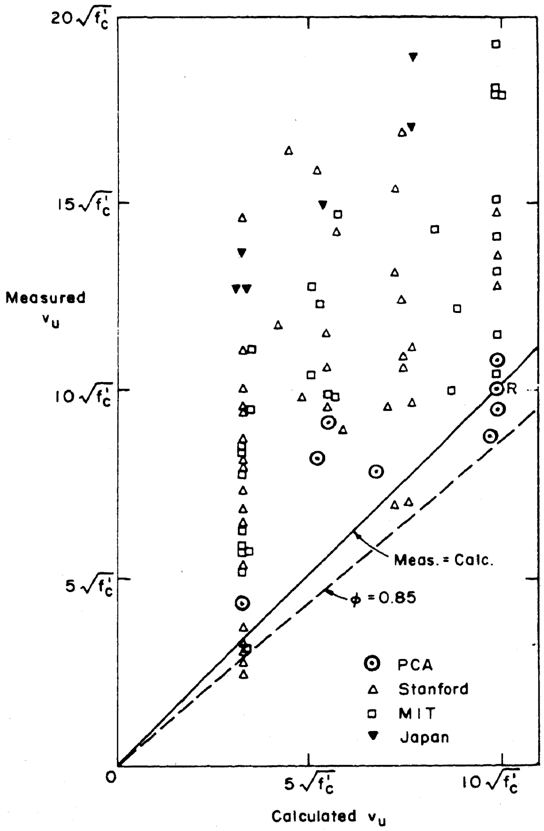

FIG. 2 COMPARISON OF MEASURED AND CALCULATED STRENGTHS

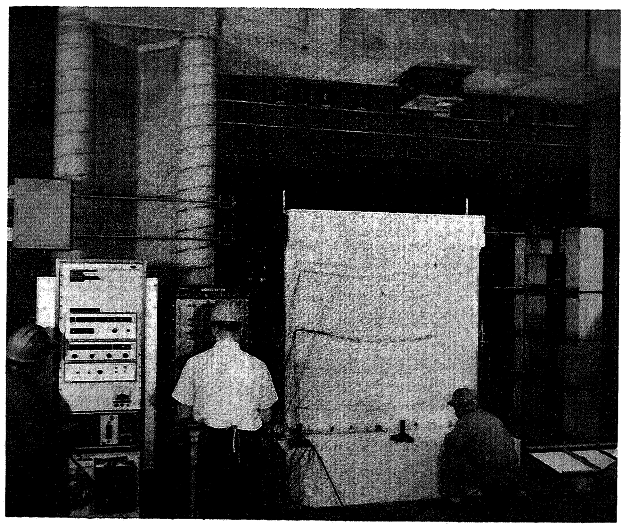

FIG. 3 SHEAR WALL TESTED UNDER REVERSED LOADS