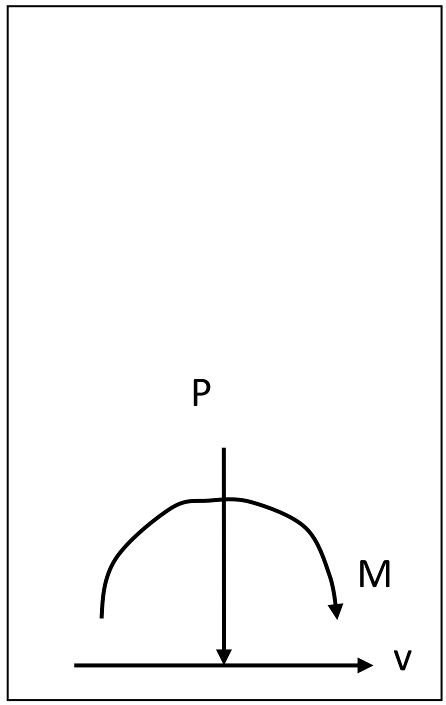
EARTHQUAKE-RESISTANT DESIGN OF SPECIAL DUCTILE REINFORCED CONCRETE SHEAR WALLS

Cantilever or Pier (Uniform Section) Design



Introduction

The wall is under seismic in-plane lateral load and this induces M, V, and P design actions at any typical horizontal section. As with other brittle-matrix seismic structural elements, the design intention is to maximize the ductile (i.e. flexural) failure mode and suppress the brittle failure modes of shear, sliding, and rebar pullout.

The wall's deformation is mainly a combination of both the flexural and shear types. For aspect ratios above about 2, the deformation is dominated by flexural response which maximizes energy absorption and the element behaves as a beam-column. For aspect ratios below about 2, the wall behaves as a deep beam and internal struts/ties form. Regardless of the aspect ratio, energy absorption is maximized if the vertical and horizontal reinforcement are uniformly distributed along the wall. However for the lower aspect ratio case, the amount of vertical rebar must not be less than the amount of horizontal rebar. The shear mode of failure is suppressed by ensuring that sufficient horizontal rebar is used.

The reversing moment at the wall's hinging regions mean that cracks alternately open and close and this facilitates sliding of the wall. This has the effect of pinching the hysteresis loop which forms a plateau as the wall slides before locking in the cycle, with an attendant reduction in loop area hence energy absorption capacity. For this reason, the R value for special ductile shear walls is substantially less than for special ductile frames.

To maximize the wall's ductility a boundary element is used to confine the concrete core in the zone of high compressive stress. The concept is the same as for the confinement region of seismic columns – the ductility is maximized if the ultimate compressive strain is increased. There are two ways of determining when a BE is needed (in the U.S code) and both are indirect but based on empirical observation. They are the displacement-based approach, and the stress-based approach. In the former, the neutral axis (NA) depth for the case of the typical strain (0.003), is compared with a critical value that depends on the displacement of the wall. If exceeded, a BE is required. The deeper the NA, the less ductile a section is, hence the more the compressive rebar needed for the same ductility at a concrete strain of 0.003, and this becomes impractical at the critical value. The BE enables a higher compressive strain hence ductility at a lower amount of compressive rebar. The displacement-based approach can only be used if the element will have, under ultimate conditions, just one hinge in the wall, hence is for cantilever walls only. In the stress-based approach, a BE is provided if the compressive stress exceeds a critical value. The vertical rebar in a BE can be estimated using the P_0 equation for a column with P_0 determined from (M/L) + P/2. The transverse rebar in a BE is determined by empirical equations as for special ductile columns.

To determine the amount of horizontal rebar outside the BE zone, the applied (i.e. ultimate) shear is compared with the probable shear capacity (ϕV_n). Likewise for the vertical rebar, the ultimate moment is compared with the probable moment capacity. The moment capacity must be based on consideration of strain compatibility therefore a nonlinear equation must be solved to determine the NA location.

RULES FOR SEISMIC SHEAR WALLS

1. No. of curtains of rebar:
   If $V_u > 2A_{cv}\sqrt{f_c'}$ must provide 2 curtains. A_{cv} = wall length x thickness
   If $V_u < A_{cv}\sqrt{f_c'}$ and wall thickness > 250mm, must provide 2 curtains per ACI 14.3
   If $V_u < A_{cv}\sqrt{f_c'}$ and wall thickness < 250mm, may provide 1 curtain

2. Minimum Rebar and Maximum Spacing:
   If $V_u > A_{cv}\sqrt{f_c'}$, $\rho_v = 0.0025$; $\rho_n = 0.0025$ ρ_v = total area vertical bars/(wall length x thickness); ρ_n refers to horizontal rebar

If $V_u < A_{cv} \sqrt{f_c'}$, $\rho_v = 0.0012$ for HTS #5 bar or smaller, else 0.0015
$\rho_n = 0.0020$ for HTS #5 bar or smaller, else 0.0025

If the wall's height to width ratio < 2, $\rho_v > \rho_n$
The maximum spacing of vertical or horizontal rebar is 450mm.

3. If a special BE is required using the Displacement-Based Approach:
   Minimum height is greater of:
   - wall length
   - $M_u/4V_u$

   Minimum length is greater of:
   - c/2 (c: NA depth)
   - c-0.1 x wall length

4. If a special BE is required using the Stress-Based Approach:
   Minimum height is to the section where the compressive stress decreases to $0.15f_c'$
   Minimum length is the same as for the displacement-based approach. [Note: The compressive stress is P/A + M/Z, where A and Z are the cross-sectional area and section modulus of the entire section, respectively.]

5. Special BE Transverse Rebar:-
   - Total rebar required = $0.09sh_cf_c'/f_{yh}$, where s is the vertical spacing, h_c is the center-to-center core dimension; apply to each direction.
   - Maximum s is smallest of:
     - Wall thickness/4
     - 6 times the diameter of the largest longitudinal bar
     - $s_x = 10+[(35-h_x)/3]$ in cm; h_x is the maximum horizontal spacing of the legs which is a maximum of 35 cm c/c; 10 cm < s_x < 15 cm.
   - The transverse reinforcement shall extend down into the support at least the development length of the largest longitudinal rebar in the BE except if the BE terminates in a mat or footing in which case, the transverse rebar must extend 300mm into the footing or mat.

6. If a special BE is not required, but $V_u > A_{cv} \sqrt{f_c'}$, and $\rho_v > 400/f_y$ at the wall's boundary, then transverse rebar as for a special BE is required over a length of the wall the larger of c/2 and c-0.1 x wall length. The maximum spacing of the transverse rebar in this "non-special BE", is 200mm.

7. If a special BE is not required, but $V_u < A_{cv} \sqrt{f_c'}$, the outermost vertical rebar must be engaged with a horizontal rebar with a standard hook, or enclosed in U-bars of the same size, spacing, and spliced to the horizontal rebar.

8. If there is a BE, the horizontal rebar in the wall outside the BE must be anchored in the BE core, to develop its f_y

PROCEDURE FOR THE SEISMIC DESIGN OF RC SHEAR WALLS

1. Input wall data, loading data, and trial steel data.
2. Calculate ϕV_n:
   - Determine ϕ:
     - If $h_w/l_w > 2$, $\phi = 0.85$
     - If $V_n > 3M_n/2h_w$, $\phi = 0.85$
       else, $\phi = 0.60$
   - Determine α_c:
     - If $h_w/l_w > 2$, $\alpha_c = 2$
     - If $h_w/l_w < 1.5$, $\alpha_c = 3$
     - Otherwise, $\alpha_c = 6\text{-}2\ h_w/l_w$

   - $V_n = A_{cv}(\alpha_c\sqrt{f_c'} + \rho_n f_y)$

3. Check that $V_u \leq \phi V_n$; revise the horizontal rebar if not.
4. Determine if 2 curtains required.
5. Determine if ρ_v must > ρ_n.
6. Determine min. steel requirements.
7. Adjust vertical and horizontal rebar to within limits of 4 to 6.
8. **Calculate ϕM_n and NA depth, c, using strain compatibility.**
   - ϕ varies linearly from 0.9 to 0.65 for $P_u = 0.0$ to $0.1A_gf_c'$ or P_b, respectively
9. Check that $M_u \leq \phi M_n$; revise the vertical rebar if not.
10. Determine if BE's required:-
    - Displacement-Based – Required if $c > L_w/(600(\delta_u/h_w))$, where $\delta_u/h_w >= 0.007$, and δ_u is the inelastic displacement of the wall
    - Stress-Based – Required if $\sigma_{comp} > 0.2f_c'$
11. Determine dimensions of BE if required.
12. Determine transverse rebar in BE if required
13. Determine no. of legs of transverse rebar, if required.
14. Detail the wall paying attention to anchorage.