Verification Test Number

105

Scope

- Verify wall detailing checks
- Verify wall design resistance calculations
- Verify wall rotational ductility calculations
- Verify wall general and seismic checks

Files Used

Example 4 files

Procedure

Wall W1, Story 1, COMB2X MIN

The following calculations apply to all columns regions, since they have the same properties.

Design Forces

Axial force

$$N_{Ed} = -1{,}131\ KN$$

Bending moment about axis 2

$$M_{Ed2} = 6\ KNm$$

Bending moment about axis 3

$$M_{Ed3} = 1{,}532\ KNm$$

Shear force in direction 2

$$V_{Ed2} = 726\ KNm$$

Dimensions

Length

$$Length = 4{,}000\ mm$$

Height

$$Height = 3{,}000\ mm$$

Thickness

$$Thickness = 200\ mm$$

Cover to stirrups

$$cover = 25\ mm$$

Materials

Concrete nominal strength

$$f_c = 40\,MPa$$

Partial factor for concrete (Seismic)

$$\gamma_c = 1.50$$

Concrete design strength

$$f_{cd} = 26.7\,MPa$$

Concrete ultimate strain

$$\varepsilon_u = 0.0035$$

Concrete elastic modulus

$$E_c = 35\,GPa$$

Reinforcement steel yield stress

$$f_y = 460\,MPa$$

Reinforcement steel tension stress

$$f_t = 460\,MPa$$

Partial factor for reinforcement steel (Seismic)

$$\gamma_s = 1.15$$

Reinforcement steel design strength

$$f_{yd} = 400\,MPa$$

Reinforcement steel elastic modulus

$$E_s = 200\,GPa$$

Reinforcement

Main reinforcement diameter

$$d_{rL} = 16\,mm$$

Number of face 3 reinforcement bars

$$n_{r3} = 28$$

Face 3 reinforcement area

$$A_{s3} = 5{,}626\,mm^2$$

Total area of main reinforcement

$$A_s = 11{,}253\, mm^2$$

Shear reinforcement diameter

$$d_{rv} = 12\, mm$$

Number of shear reinforcement stirrups in direction 2

$$n_{rv2} = 1$$

Total area of shear reinforcement in direction 2

$$A_{v2} = 226\; mm^2$$

Shear reinforcement spacing

$$s_{rv} = 100\, mm$$

Detailing checks

Face 3 main reinforcement spacing

$$s_{rL,3} = \frac{Length - 2 \cdot cover - 2 \cdot d_{rv} - d_{rL}}{(n_{rL} - 1)} = \frac{4{,}000\; mm - 2 \cdot 25\; mm - 2 \cdot 12\; mm - 16\; mm}{(28 - 1)}$$

$$= 145\; mm$$

Minimum main reinforcement spacing

$s_{rL,min} = 50\, mm$ Check OK

Maximum main reinforcement spacing

$s_{rL,max} = 150\, mm$ Check OK

Reinforcement ratio

$$\rho = \frac{A_s}{Length \cdot Thickness} = \frac{11{,}253\; mm^2}{4{,}000\; mm \;\cdot\; 200\; mm} = 0.014 = 1.4\%$$

Minimum reinforcement ratio

$\rho_{min} = 0.50\%$ Check OK

Maximum reinforcement ratio

$\rho_{max} = 4.00\%$ Check OK

Design axial force resistance

Area of concrete

$$A_c = Length \cdot Thickness - A_s = 4{,}000\, mm \cdot 200\, mm - 11{,}253\, mm^2 = 788{,}747\, mm^2$$

Area of reinforcement

$$A_s = 11{,}253\, mm^2$$

Design axial force resistance

$$N_{Rd} = 0.80 \cdot \left(0.85 \cdot f_{cd} \cdot (A_c - A_s) + f_{yd} \cdot A_s\right)$$
$$= 0.80 \cdot \left(0.85 \cdot 26.7 \frac{N}{mm^2} \cdot 788{,}747\, mm^2 + 400 \frac{N}{mm^2} \cdot 11{,}253\, mm^2\right)$$
$$= 17{,}921\, KN$$

Neutral axis for bending about axis 2 at ultimate resistance

Depth to tension reinforcement centre

$$d_{t2} = Thickness - cover - d_{rv} - \frac{d_{rL}}{2} = 200\ mm - 25\ mm - 12\ mm - \frac{16\ mm}{2}$$
$$= 155\ mm$$

Depth to compression reinforcement centre

$$d_{c2} = cover - d_{rv} - \frac{d_{rL}}{2} = \ 25\ mm\ +\ 12\ mm\ +\ \frac{16\ mm}{2} = 45\ mm$$

Neutral axis depth

$$c_2 = 40.4\ mm$$

Concrete stress-block parameters

$$\beta = 0.380$$
$$\beta_1 = 2 \cdot \beta = 0.760$$

Concrete stress-block actual compressive force

$$F_{c2} = 0.85 \cdot \beta_1 \cdot c_2 \cdot f_c \cdot Length$$
$$= 0.85 \cdot 0.760 \cdot 0.0404\ m \cdot 40E + 3\ KN/m^2 \cdot 4.000\ m$$
$$= 4{,}176\ KN$$

Tension reinforcement actual stress

$$f_{s2} = \varepsilon_u \cdot E_s \cdot \frac{(d_{t2} - c_2)}{c_2} = 0.0035 \cdot 200E + 3\ N/mm^2 \cdot \frac{(155\ mm - 40.4\ mm)}{40.4\ mm}$$
$$= 1{,}986\ N/mm^2 \le f_y = 460\ N/mm^2$$

$$f_{s2} = f_y = 460\ N/mm^2$$

Tension reinforcement actual force

$$F_{s2} = A_{s2} \cdot f_{s2} = 5{,}626\ mm^2 \cdot 460\ N/mm^2 = 2{,}588\ KN$$

Compression reinforcement actual stress

$$f_{s2'} = \varepsilon_u \cdot E_s \cdot \frac{(c_2 - d_{c2})}{c_2} = 0.0035 \cdot 200E + 3\ N/mm^2 \cdot \frac{(40.4\ mm - 45\ mm)}{40.4\ mm}$$
$$= -80\ N/mm^2 \leq f_y = 460\ N/mm^2$$

Compression reinforcement actual force

$$F_{s2'} = A_{s2'} \cdot f_{s2'} = 5{,}626\ mm^2 \cdot (-80\ N/mm^2) = -450\ KN$$

Force unbalance

$$\text{Force Unbalance} = \frac{F_{c2} + F_{s2'} - F_{s2} - N_{Ed}}{F_{c2} + F_{s2'}}$$
$$= \frac{4{,}176\ KN - 450\ KN \text{ - } 2{,}588\ KN \text{ -}1{,}131\ KN}{4{,}176\ KN - 450\ KN}$$
$$= -0.002 = 0.2\%$$

Design bending moment resistance about axis 2

Concrete stress-block design compressive force

$$F_{cd2} = 0.85 \cdot \beta_1 \cdot c_2 \cdot f_{cd} \cdot Length$$
$$= 0.85 \cdot 0.760 \cdot 0.0404\ m \cdot 26.7E + 3\ KN/m^2 \cdot 4.000\ m$$
$$= 2{,}787\ KN$$

Tension reinforcement design stress

$$f_{sd2} = \varepsilon_u \cdot E_s \cdot \frac{(d_{t2} - c_2)}{c_2} = 0.0035 \cdot 200E + 3\ N/mm^2 \cdot \frac{(155\ mm - 40.4\ mm)}{40.4\ mm}$$
$$= 1{,}986\ N/mm^2 \leq f_{yd} = 400\ N/mm^2$$

$$f_{sd2} = f_{yd} = 400\ N/mm^2$$

Tension reinforcement design force

$$F_{sd2} = A_{s2} \cdot f_{sd2} = 5{,}626\ mm^2 \cdot 400\ N/mm^2 = 2{,}250\ KN$$

Compression reinforcement design stress

$$f_{sd2'} = \varepsilon_u \cdot E_s \cdot \frac{(c_2 - d_{c2})}{c_2} = 0.0035 \cdot 200E + 3\ N/mm^2 \cdot \frac{(40.4\ mm - 45\ mm)}{40.4\ mm}$$
$$= -80\ N/mm^2 \leq f_y = 400\ N/mm^2$$

Compression reinforcement design force

$$F_{sd2'} = A_{s2'} \cdot f_{sd2'} = 5{,}626\ mm^2 \cdot (-80\ N/mm^2) = -450\ KN$$

Bending moment design resistance

$$M_{Rd2} = F_{sd2'} \cdot \left(\frac{Thickness}{2} - d_{c2}\right) + F_{cd2} \cdot \left(\frac{Thickness}{2} - \beta \cdot c_2\right) + F_{sd2} \cdot \left(d_{t2} - \frac{Thickness}{2}\right)$$
$$= -450\ KN \cdot \left(\frac{0.200\ m}{2} - 0.045\ m\right) + 2{,}787\ KN \cdot \left(\frac{0.200\ m}{2} - 0.380 \cdot 0.0404\ m\right) +$$
$$+ 2{,}250\ KN \cdot \left(0.155\ m - \frac{0.200\ m}{2}\right)$$
$$= 335\ KN$$

Neutral axis for bending about axis 3 at ultimate resistance

Neutral axis depth

$$c_3 = 840\ mm$$

Depth to tension reinforcement centre

$$d_{t3} = c_3 + \frac{(Length - c_3)}{2} = 840\ mm + \frac{(4{,}000\ mm - 840\ mm)}{2}$$
$$= 2{,}420\ mm$$

Depth to compression reinforcement centre

$$d_{c3} = \frac{c_3}{2} = \frac{840\ mm}{2} = 420\ mm$$

Tension reinforcement area

$$A_{s3t} = A_s \cdot \frac{(Length - c_3)}{Length} = 11{,}253\ mm^2 \cdot \frac{(4{,}000\ mm - 840\ mm)}{4{,}000\ mm} = 8{,}890\ mm^2$$

Compression reinforcement area

$$A_{s3c} = A_s \cdot \frac{c_3}{Length} = 11{,}253\ mm^2 \cdot \frac{840\ mm}{4{,}000\ mm} = 2{,}363\ mm^2$$

Concrete stress-block parameters

$$\beta = 0.380$$
$$\beta_1 = 2 \cdot \beta = 0.760$$

Concrete stress-block actual compressive force

$$F_{c3} = 0.85 \cdot \beta_1 \cdot c_3 \cdot f_c \cdot Thickness$$
$$= 0.85 \cdot 0.760 \cdot 0.840\ m \cdot 40E+3\ KN/m^2 \cdot 0.200\ m$$
$$= 4{,}341\ KN$$

Tension reinforcement actual stress

$$f_{s3} = \varepsilon_u \cdot E_s \cdot \frac{(d_{t3} - c_3)}{c_3} = 0.0035 \cdot 200E + 3\ N/mm^2 \cdot \frac{(2{,}420\ mm - 840\ mm)}{840\ mm}$$
$$= 1{,}317\ N/mm^2 \leq f_y = 460\ N/mm^2$$
$$f_{s3} = f_y = 460\ N/mm^2$$

Tension reinforcement actual force

$$F_{s3} = A_{s3t} \cdot f_{sz} = 8{,}890\ mm^2 \cdot 460\ N/mm^2 = 4{,}089\ KN$$

Compression reinforcement actual stress

$$f_{s3'} = \varepsilon_u \cdot E_s \cdot \frac{(c_3 - d_{c3})}{c_3} = 0.0035 \cdot 200E + 3\ N/mm^2 \cdot \frac{(840\ mm - 420\ mm)}{840\ mm}$$
$$= 350\ N/mm^2 \leq f_y = 460\ N/mm^2$$

Compression reinforcement actual force

$$F_{s3'} = A_{s3c} \cdot f_{s3} = 2{,}363\ mm^2 \cdot 350\ N/mm^2 = 827\ KN$$

Force unbalance

$$\text{Force Unbalance} = \frac{F_{c3} + F_{s3'} - F_{s3} - N_{Ed}}{F_{c3} + F_{s3'}}$$
$$= \frac{4{,}341\ KN + 827\ KN - 4{,}089\ KN - 1{,}131\ KN}{4{,}341\ KN + 827\ KN}$$
$$= -0.010 = 1.0\%$$

Design bending moment resistance about axis 3 (method 1)

Concrete stress-block design compressive force

$$F_{cd3} = 0.85 \cdot \beta_1 \cdot c_3 \cdot f_{cd3} \cdot Thickness$$
$$= 0.85 \cdot 0.760 \cdot 0.840\ m \cdot 26.7E + 3\ KN/m^2 \cdot 0.200\ m$$
$$= 2{,}898\ KN$$

Tension reinforcement design stress

$$f_{sd3} = \varepsilon_u \cdot E_s \cdot \frac{(d_{t3} - c_3)}{c_3} = 0.0035 \cdot 200E + 3\ N/mm^2 \cdot \frac{(2{,}420\ mm - 840\ mm)}{840\ mm}$$
$$= 457\ N/mm^2 \leq f_{yd} = 400\ N/mm^2$$

$$f_{sd3} = f_{yd} = 400\ N/mm^2$$

Tension reinforcement design force

$$F_{sd3} = A_{s3t} \cdot f_{sd3} = 8{,}890\ mm^2 \cdot 400\ N/mm^2 = 3{,}556\ KN$$

Compression reinforcement design stress

$$f_{sd3'} = \varepsilon_u \cdot E_s \cdot \frac{(c_3 - d_{c3})}{c_3} = 0.0035 \cdot 200E+3\ N/mm^2 \cdot \frac{(840\ mm - 420\ mm)}{840\ mm}$$

$$= 350\ N/mm^2 \leq f_{yd} = 400\ N/mm^2$$

Compression reinforcement design force

$$F_{sd3'} = A_{s3'} \cdot f_{sd3'} = 2{,}363\ mm^2 \cdot 350\ N/mm^2 = 827\ KN$$

Bending moment design resistance

$$M_{Rd3} = F_{sd3'} \cdot \left(\frac{Length}{2} - d_{c3}\right) + F_{cd3} \cdot \left(\frac{Length}{2} - \beta \cdot c_3\right) + F_{sd3} \cdot \left(d_{t3} - \frac{Length}{2}\right)$$

$$= 827\ KN \cdot \left(\frac{4.0\ m}{2} - 0.420\ m\right) + 2{,}898\ KN \cdot \left(\frac{4.0\ m}{2} - 0.380 \cdot 0.840\ m\right) +$$

$$+ 3{,}556\ KN \cdot \left(2.420\ m - \frac{4.0\ m}{2}\right)$$

$$= 8{,}605\ KN$$

Design bending moment resistance about axis 3 (method 2)

Bending moment design resistance (Park & Paulay, Reinforced Concrete Structures, 1975)

$$M_{Rd3} = 0.5 \cdot A_s \cdot f_y \cdot l_w \cdot \left(1 + \frac{N_u}{A_s \cdot f_y}\right) \cdot \left(1 - \frac{c_3}{l_w}\right)$$

$$= 0.5 \cdot 11{,}253\ mm^2 \cdot 400\ \frac{N}{mm^2} \cdot 4{,}000\ mm \cdot \left(1 + \frac{1{,}131\ KN}{11{,}253\ mm^2 \cdot 400\ \frac{N}{mm^2} \cdot}\right) \cdot \left(1 - \frac{0.840\ m}{4{,}000\ mm}\right)$$

$$= 9{,}002\ KN$$

Neutral axis for bending about axis 2 at first yield

Neutral axis depth

$$c_{yld} = 49\ mm$$

Concrete stress-block actual compressive force

$$F_{c2} = \left(\frac{f_y}{2}\right) \cdot \left(\frac{E_c}{E_s}\right) \cdot \left(\frac{c_{yld}^2}{d_t - c_{yld}}\right) \cdot Length$$

$$= \left(\frac{460\ N/mm^2}{2}\right) \cdot \left(\frac{35E+3\ N/mm^2}{200E+3\ N/mm^2}\right) \cdot \left(\frac{(49\ mm)^2}{155\ mm - 49\ mm}\right) \cdot 4{,}000\ mm$$

$$= 3{,}647\ KN$$

Tension reinforcement actual stress

$$f_{s2} = f_y = 460\ N/mm^2$$

Tension reinforcement actual force

$$F_{s2} = A_{s2} \cdot f_{s2} = 5{,}626\ mm^2 \cdot 460\ N/mm^2 = 2{,}588\ KN$$

Compression reinforcement actual stress

$$f_{s2'} = f_y \cdot \frac{(c_{yld} - d_{c2})}{(d_{t2} - c_{yld})} = 460\ N/mm^2 \cdot \frac{(49\ mm - 45\ mm)}{(155\ mm - 49\ mm)}$$
$$= 17\ N/mm^2 \le f_y = 460\ N/mm^2$$

Compression reinforcement actual force

$$F_{s2'} = A_{s2'} \cdot f_{s2'} = 5{,}626\ mm^2 \cdot 17\ N/mm^2 = 96\ KN$$

Force unbalance

$$\text{Force Unbalance} = \frac{F_{c2} + F_{s2'} - F_{s2} - N_{Ed}}{F_{c2} + F_{s2'}}$$
$$= \frac{3{,}647\ KN + 96\ KN - 2{,}588\ KN - 1{,}131\ KN}{3{,}647\ KN + 96\ KN}$$
$$= -0.006 = -0.6\%$$

Rotational ductility about axis 2

Curvature at first yield

$$\phi_y = \frac{f_y}{E_s} \cdot \frac{1}{d_t - c_{yld}} = \frac{460\ N/mm^2}{200E+3\ N/mm^2} \cdot \frac{1}{155\ mm - 49\ mm} = 0.0000217$$

Ultimate curvature

$$\phi_u = \frac{\varepsilon_u}{c_{ult}} = \frac{0.0035}{40.4\ mm} = 0.0000866 \frac{1}{mm}$$

where c_{ult} is the neutral axis depth at ultimate resistance

Rotational ductility

$$\mu_\phi = \frac{\phi_u}{\phi_y} = \frac{0.0000866 \frac{1}{mm}}{0.0000217 \frac{1}{mm}} = 3.99$$

Neutral axis depth for bending about axis 3 at first yield

Neutral axis depth

$$c_{yld} = 1{,}049\ mm$$

Depth to tension reinforcement centre

$$d_{t3} = c_3 + \frac{(Length - c_3)}{2} = 1{,}049\ mm + \frac{(4{,}000\ mm - 1{,}049\ mm)}{2}$$
$$= 2{,}525\ mm$$

Depth to compression reinforcement centre

$$d_{c3} = \frac{c_3}{2} = \frac{1{,}049\ mm}{2} = 525\ mm$$

Depth to tension reinforcement edge

$$d_{t3edge} = Length - \text{cov}\,er - d_{rv} - d_{rL} = 4{,}000\ mm - 25\ mm - 12\ mm - \frac{16\ mm}{2}$$
$$= 3{,}955\ mm$$

Tension reinforcement area

$$A_{s3t} = A_s \cdot \frac{(Length - c_3)}{Length} = 11{,}253\,mm^2 \cdot \frac{(4{,}000\ mm - 1{,}049\ mm)}{4{,}000\ mm} = 8{,}302\,mm^2$$

Compression reinforcement area

$$A_{s3c} = A_s \cdot \frac{c_3}{Length} = 11{,}253\,mm^2 \cdot \frac{1{,}049\ mm}{4{,}000\ mm} = 2{,}951\,mm^2$$

Concrete strain and stress

$$\varepsilon_c = \frac{f_y}{E_s} \cdot \frac{d_{seg}}{(d_{t2} - c_{yld})} \le f_y$$

Concrete stress-block actual compressive force

Segment	Length (mm)	Distance from NA (mm)	ε_c	f_c (N/mm^2)	F_c (N)
1	262.25	131.125	0.0001	3.7212	195,177
2	262.25	393.375	0.0003	10.6088	556,434
3	262.25	655.625	0.0005	16.7604	879,085
4	262.25	917.875	0.0007	22.1804	1,163,363
				Total	2,794,059

Tension reinforcement actual stress

$$f_{s3t} = f_y = 460\ N/mm^2$$

$$f_{s3t} = f_y \cdot \frac{(d_{t3} - c_{yld})}{(d_{t3edge} - c_{yld})} = 460\ N/mm^2 \cdot \frac{(2{,}525\ mm - 1{,}049\ mm)}{(3{,}955\ mm - 1{,}049\ mm)}$$
$$= 233\ N/mm^2 \leq f_y = 460\ N/mm^2$$

Tension reinforcement actual force

$$F_{s3t} = A_{s3t} \cdot f_{s3t} = 8{,}302\ mm^2 \cdot 233\ N/mm^2 = 1{,}935\ KN$$

Compression reinforcement actual stress

$$f_{s3c} = f_y \cdot \frac{(c_{yld} - d_{c3})}{(d_{t3edge} - c_{yld})} = 460\ N/mm^2 \cdot \frac{(1{,}049\ mm - 525\ mm)}{(3{,}955\ mm - 1{,}049\ mm)}$$
$$= 83\ N/mm^2 \leq f_y = 460\ N/mm^2$$

Compression reinforcement actual force

$$F_{s3c} = A_{s3c} \cdot f_{s3c} = 2{,}951\ mm^2 \cdot 83\ N/mm^2 = 245\ KN$$

Force unbalance

$$\text{Force Unbalance } = \frac{F_{c3} + F_{s3c} - F_{s3t} - N_{Ed}}{F_{c3} + F_{s3c}}$$
$$= \frac{2{,}794\ KN + 245\ KN - 1{,}935\ KN - 1{,}131\ KN}{2{,}794\ KN + 245\ KN}$$
$$= 0.009 = 0.9\%$$

Rotational ductility about axis 3

Curvature at first yield

$$\phi_y = \frac{f_y}{E_s} \cdot \frac{1}{d_{t3} - c_{yld}} = \frac{460\ N/mm^2}{200E+3\ N/mm^2} \cdot \frac{1}{3{,}955\ mm - 1{,}049\ mm} = 0.00000079$$

Ultimate curvature

$$\phi_u = \frac{\varepsilon_u}{c_{ult}} = \frac{0.0035}{840\ mm} = 0.00000417 \frac{1}{mm}$$

where c_{ult} is the neutral axis depth at ultimate resistance

Rotational ductility

$$\mu_\phi = \frac{\phi_u}{\phi_y} = \frac{0.00000417 \frac{1}{mm}}{0.00000079 \frac{1}{mm}} = 5.28$$

Design shear resistance in direction 2

Lever arm

$$z_3 = Length - cover - d_{rv} - \frac{d_{rL}}{2}$$
$$= 4{,}000\ mm - 25\ mm - 12\ mm - \frac{16\ mm}{2}$$
$$= 3{,}955\ m$$

Design shear resistance contribution of reinforcement

$$V_{s2} = \frac{A_{v2} \cdot z_3 \cdot f_{yd}}{s_{rv}} = \frac{226\ mm^2 \cdot 3{,}955\ mm \cdot 400\ N/mm^2}{100\ mm} = 3{,}575\ KN$$

Total design shear resistance

$$V_{t2} = V_{s2} = 3{,}575\ KN$$

Maximum shear resistance

$$V_{max,2} = \frac{Thickness \cdot z_3 \cdot 0.6 \cdot f_{cd}}{2} = \frac{200\ mm \cdot 3{,}955\ mm \cdot 0.6 \cdot 20\ N/mm^2}{2}$$
$$= 4{,}746\ KN$$

Maximum design shear force in direction 2

Design bending moment resistance about axis 3

$$M_{Rd3} = 8{,}605\ KNm$$

Design bending moment about axis 3

$$M_{Ed3} = 1{,}532\ KNm$$

Design shear force in the direction of axis 2

$$V_{Ed} = 726\ KN$$

Design overstrength factor for wall

$$\gamma_{Rd,wall} = 1.1$$

Behaviour factor of structure

$$q = 3.5$$

Maximum shear force that can develop on the wall is the maximum of the following

$$V_{Ed1,max} = \gamma_{Rd,wall\cdot} \left(\frac{M_{Rd}}{M_{Ed}} \right) \cdot V_{Ed} = 1.1 \cdot \left(\frac{8{,}605\ KNm}{1{,}532\ KNm} \right) \cdot 726\ KN = 4{,}485\ KN$$

$$V_{Ed2,max} = q \cdot V_{Ed} = 3.5 \cdot 726\ KN = 2{,}541\ KN$$

$V_{Ed1,max}$ dominates