Design, detailing, and analysis of short-grouted ductile reinforcing bar connections for special precast concrete shear walls, part 2: Short-grouted ductile reinforcing bar connection design examples

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- Five design examples are presented on precast concrete shear walls using new nonproprietary short-grouted ductile reinforcing bar connections.
- The examples are based on precast concrete shear wall details with conventional energy-dissipation (yielding flexural) reinforcing bar connections provided by precast concrete industry partners.
- The design examples focus on the connection length and the vertical, transverse, and longitudinal tie reinforcement areas around the connection ducts.

This paper contains five design examples for the paper titled "Design, Detailing, and Analysis of Short-Grouted Ductile Reinforcing Bar Connections for Special Precast Concrete Shear Walls, Part 1" by Baha'a Al-Khateeb, Jon Mohle, and Yahya C. Kurama,[1] which appears on pages 55 through 77 in this issue of *PCI Journal*. Equation numbers listed in the design examples refer to the numbering from the main body of the accompanying paper.

The examples demonstrate the design of the new nonproprietary short-grouted connections based on precast concrete shear wall details with conventional energy-dissipation (yielding flexural) reinforcing bar connections provided by precast concrete industry partners. The required inputs for these examples include the wall base cross-section geometry, layout of the energy-dissipation bars, and sizes and grades of these bars. The focus of the design examples is to demonstrate the calculations for the connection length and the vertical, transverse, and longitudinal tie reinforcement areas around the connection ducts. For each example, two design options are considered: one with the connections placed inside the foundation and the other with the connections placed in the wall panel, which could also represent a panel-to-panel connection. The design of shear reinforcement and special boundary confinement reinforcement for the walls is outside the scope of these examples. However, this reinforcement should be considered when placing the connection ducts and tie reinforcement in the wall cross section.

The longitudinal tie reinforcement designed for the connection should not be included in the shear reinforcement ratio when determining the nominal shear strength of the wall. The first shear reinforcement bar at the bottom of the wall should be placed above all of the connection longitudinal tie reinforcement or its area should be added to the longitudinal tie reinforcement area.

Example 1

Example 1 is a 20 in. (508 mm) thick wall with two no. 11 (36M) Grade 60 (414 MPa) energy-dissipation bars in each layer (across the wall thickness) spaced at 7 in. (178 mm) on center.

Connections in the foundation

Figure 1 shows the original wall cross section and the alternative design with short-grouted connections placed in the foundation.

The area of energy-dissipation bars in each layer across the wall thickness (from original wall design) A_{ED} = (2)(1.56 in.^{2}) = 3.12 in.^{2} (2013 mm^2).

Use Eq. (2) from "Design, Detailing, and Analysis of Short-Grouted Ductile Reinforcing Bar Connections for Special Precast Concrete Shear Walls, Part 1"[1] to calculate the area of vertical tie reinforcement $A_{vt} = A_{ED}$ = 3.12 in.^{2} (2013 mm^2).

Use one no. 8 (25M) U bar on each side of each connection layer (connecting two energy-dissipation bars), providing a total of four legs of vertical tie bars around each layer. Therefore, the total provided area of vertical tie reinforcement $A_{vt,provided}$ = (4)(0.79 in.^{2}) = 3.16 in.^{2} (2039 mm^2).

The area of transverse tie reinforcement is given in Eq. (3) from part 1.[1] Design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked due to the use of U bars as both vertical and transverse tie reinforcement.

Use Eq. (12) from part 1[1] to calculate the area of longitudinal tie reinforcement $A_{lt} = \left(0.32 \le \dfrac{0.75 \times X}{h_{wp} - S_{c,UL}} \le 1.5\right) \times A_{ED}$, where X is the horizontal distance between the center of the energy-dissipation reinforcing bar and the center of the vertical tie bar in the wall length direction, h_{wp} is the height of the strut-and-tie model work point measured from the center of the transverse tie pro-

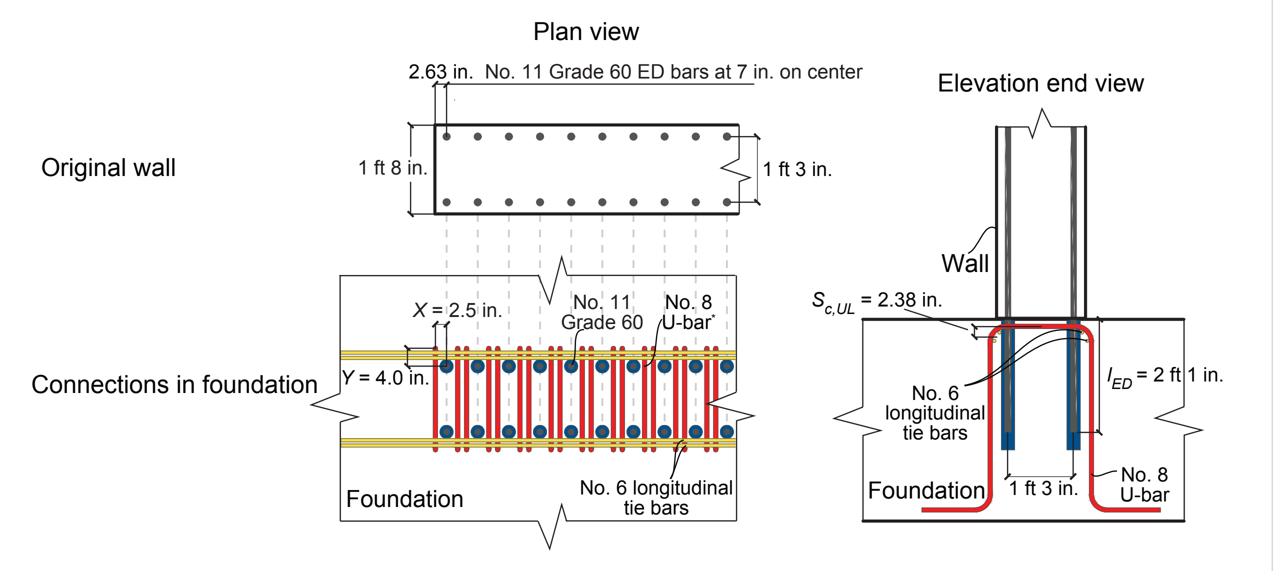

Figure 1. Example 1, connections in the foundation.
* Bottom hooks for U bars are not shown in plan view of foundation.
Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 6 = 19M; no. 8 = 25M; no. 11 = 36M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa.

jected onto the energy-dissipation bar, and $S_{c,UL}$ is the vertical distance between the center of the transverse tie bar and centroid of the longitudinal tie reinforcement.

To determine the area of longitudinal tie reinforcement, the values of X, the horizontal distance between the center of the energy-dissipation reinforcing bar and the center of the vertical tie bar in the wall thickness direction Y, and $S_{c,UL}$ must be selected for the connection layout, and the height of the work point h_{wp} must be calculated. The X dimension is governed by the spacing between the energy-dissipation bar layers, which is 7 in. (178 mm) for the wall. Within this spacing, two U bars are placed as the vertical and transverse tie reinforcement for adjacent connection layers while also meeting the minimum spacing requirement of ACI 318-19.[2] The X dimension is selected as 2.5 in. (64 mm) for this example (Fig. 1).

For connections placed in the foundation, the vertical legs of the U bars can be spaced farther apart than the wall thickness. However, increasing this distance between the vertical legs of the U bars increases the Y dimension, which in turn increases the connection length, making the design less efficient. The Y dimension is selected as 4.0 in. (102 mm) for this example, which satisfies the minimum bend diameter requirements for the U bars and longitudinal tie bars according to Table 25.3.2 of ACI 318-19.

The selection of $S_{c,UL}$ is an iterative process. An initial $S_{c,UL}$ value is chosen, and, after determining the area of longitudinal tie reinforcement and selecting the bar sizes and their locations, a revised $S_{c,UL}$ value is calculated. The longitudinal tie reinforcement area is then updated accordingly, as shown in the following calculations:

X = 2.5 in. (64 mm)

Y = 4.0 in. (102 mm)

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

Use Eq. (17) from part 1[1] to calculate the height of the work point h_{wp}.

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(4.0 in.) = 6 in. (152 mm) OK

$$h_{wp} = 1.5 \times Y \geq 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$$

$$h_{wp} = (1.5)(4.0 \text{ in.}) \geq 0.5\sqrt{2.5^2 + 4.0^2} \text{ in.} + 2.5 \text{ in.}$$

$$h_{wp} = 6.0 \text{ in.} \geq 4.9 \text{ in.}$$

therefore, h_{wp} = 6.0 in. (152 mm)

$$A_{lt} = \left(0.32 \leq \frac{0.75 \times 2.5}{6.0 - 2.5} \leq 1.5\right) \times 3.12 \text{ in.}^2 = (0.32 \leq 0.54 \leq 1.5)(3.12 \text{ in.}^2) = (0.54)(3.12 \text{ in.}^2) = 1.67 \text{ in.}^2 \ (1077 \text{ mm}^2)$$

Use two layers of no. 6 (19M) bars on each face of the wall, providing four longitudinal tie bars for each layer of energy-dissipation bars. Therefore, the total provided area of longitudinal tie reinforcement $A_{lt,provided}$ = (4)(0.44 in.^{2}) = 1.76 in.^{2} (1136 mm^2).

The centerlines of the first and second layers of the no. 6 (19M) longitudinal tie bars are placed at 2.75 and 4.5 in. (70 and 114 mm), respectively, from the top of the foundation, with a clear spacing of 1 in. (25 mm) between the two layers. The centroid of these two layers of longitudinal bars is 3.63 in. (92 mm) from the top of the foundation. The transverse (horizontal) legs of the U bars are placed with a minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.25 in. (32 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 8 [25M] U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 3.63 in. – 1.25 in. = 2.38 in. (61 mm)

Recalculate h_{wp} and A_{lt} as follows:

2.38 in. < (1.5)(4.0 in.) = 6 in. (152 mm) OK

h_{wp} = (1.5)(4.0 in.) ≥ $0.5\sqrt{2.5^2 + 4.0^2}$ in. + 2.38 in.

h_{wp} = 6.0 in. ≥ 4.74 in.

therefore, h_{wp} = 6.0 in. (152 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75 \times 2.5}{6.0 - 2.38} \le 1.5\right) \times 3.12 \text{ in.}^2 = (0.32 \le 0.52 \le 1.5)(3.12 \text{ in.}^2) = (0.52)(3.12 \text{ in.}^2) = 1.61 \text{ in.}^2 \ (1039 \text{ mm}^2)$$

The selection of two layers of no. 6 (19M) bars is valid. Therefore, $A_{lt,provided}$ = (4)(0.44 in.^{2}) = 1.76 in.^{2} (1136 mm^2).

Connection length is calculated using Eq. (18) from part 1[1] as follows:

l_{ED} = length of energy-dissipation bar inside connection duct = $C + 0.5 \times d_U + h_{wp} + l'_b$

C = clear vertical cover to U bars = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = diameter of U bar = 1.0 in. (25 mm) for no. 8 (25M) bars

h_{wp} = 6.0 in. (152 mm)

l'_b = prescribed minimum bond length extension (beyond work point) of 9 times bar diameter for no. 7, 8, and 9 (22M, 25M, and 29M) energy-dissipating bars and 12 times bar diameter for no. 10 and 11 (32M and 36M) bars = $12d_{ED}$ = (12)(1.41 in.) = 16.9 in. (429 mm) for no. 11 (36M) bars

d_{ED} = diameter of energy-dissipation bar

l_{ED} = 0.75 in. + (0.5)(1.0 in.) + 6.0 in. + 16.9 in.

l_{ED} = 24.2 in.

therefore, use l_{ED} = 25 in. (635 mm)

Connections in the wall panel

Unlike the placement of the connections inside the foundation, when the connections are placed inside the wall, the limited thickness of the wall must accommodate the connection ducts, tie reinforcement, shear reinforcement, and confinement hoops. Therefore, two adjustments are made to the original locations of the energy-dissipation bars (**Fig. 2**). First, all of the energy-dissipation bar layers are shifted inward along the length of the wall so that the center of the first layer is 5.0 in. (127 mm) from the wall end rather than the original distance of 2.63 in. (67 mm). This adjustment is made to facilitate the placement of the first layer of U-bar tie reinforcement for the connections. Second, the distance between the energy-dissipation bars across the wall thickness is reduced from 15.0 to 7.0 in. (381 to 178 mm). This change is necessary to allow the placement of the longitudinal tie reinforcement, U bars, shear reinforcement, and confinement hoops around the connection ducts with adequate clear cover, spacing, and bar bend diameter considerations within the wall thickness.

The area of energy-dissipation bars in each layer and the *X* value (2.5 in. [64 mm]) are the same as in the previous design with connections in the foundation. Furthermore, the large wall thickness of 20 in. (508 mm) allows the same *Y* value (4.0 in. [102 mm]) to be maintained, resulting in the same tie reinforcement design, $S_{c,UL}$, h_{wp}, and connection length.

The area of energy-dissipation bars in each layer across the wall thickness A_{ED} = 3.12 in.^{2} (2013 mm^2).

The area of vertical tie reinforcement can be calculated using Eq. (2). There is one no. 8 (25M) U bar on each side of each connection layer. Therefore, $A_{vt,provided}$ = 3.16 in.^{2} (2039 mm^2).

The area of transverse tie reinforcement can be calculated using Eq. (3). The design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked because of the use of U bars as both vertical and transverse tie reinforcement.

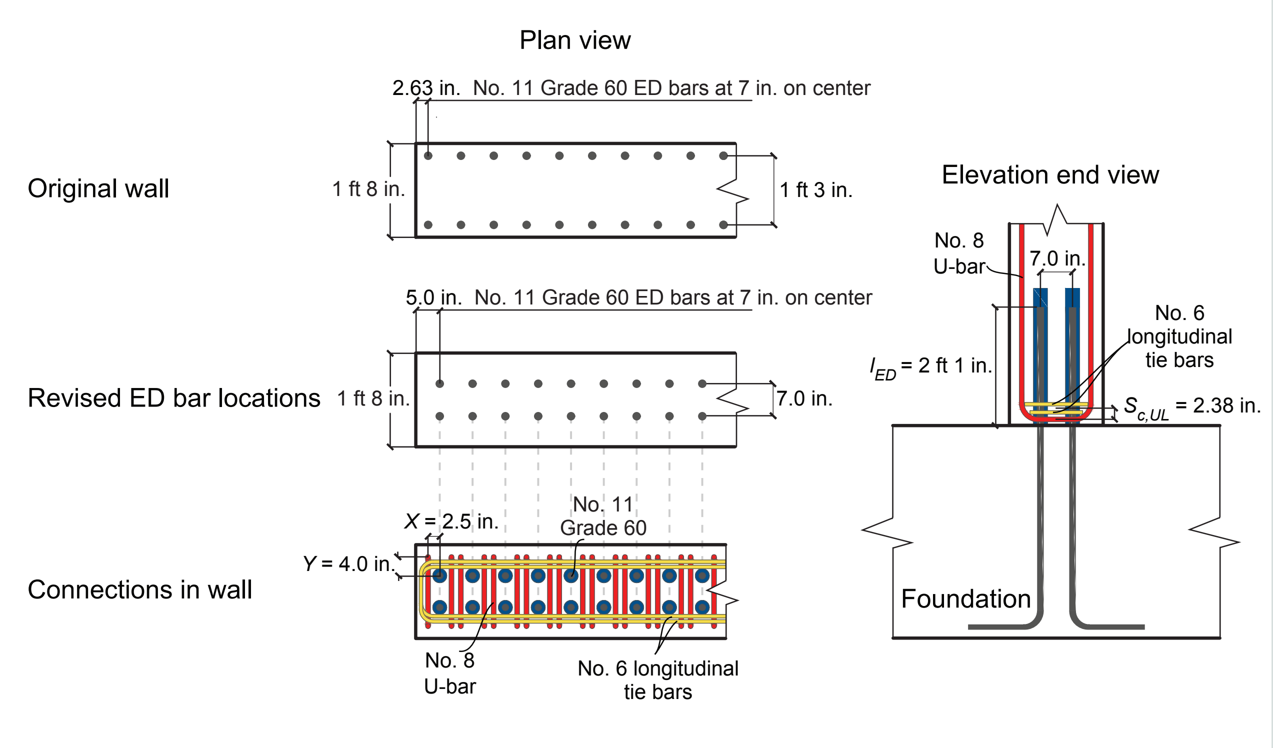

Figure 2. Example 1, connections in the wall panel. Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 6 = 19M; no. 8 = 25M; no. 11 = 36M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa.

The area of longitudinal tie reinforcement can be calculated using Eq. (12). There are two layers of no. 6 (19M) bars. Therefore, $A_{lt,provided}$ = 1.76 in.^{2} (1136 mm^2).

The connection length can be calculated using Eq. (18). Therefore, l_{ED} = 25 in. (635 mm).

Example 2

Example 2 is a 12 in. (305 mm) thick wall with two no. 8 (25M) Grade 80 (550 MPa) energy-dissipation bars in each layer (across the wall thickness) spaced at 12 in. (305 mm) on center. The experimental validation of the connections in this research is limited to Grade 60 (414 MPa) ASTM A706[3] steel for both the energy-dissipation bars and the tie reinforcement. Therefore, the energy-dissipation bars in the original wall design are replaced with Grade 60 bars and the spacing between the bar layers is reduced to 9.0 in. (229 mm), calculated as (12 in.)(60 ksi)/80 ksi = 9.0 in. These adjustments are made to ensure that the new layout of the energy-dissipation bars provides a section flexural strength equivalent to the original wall with no. 8 Grade 80 bars spaced at 12 in. Note that the lateral strength of the wall should be checked with the new bar layout, which is not done in this simple demonstration. Another option would be to change the no. 8 Grade 80 energy-dissipation bars to no. 9 (29M) Grade 60 bars while maintaining the same spacing of 12 in. However, this design option is less practical because the larger (no. 9) energy-dissipation bar size requires larger tie reinforcement bar sizes that would be more challenging to fit in the limited wall thickness. Placing the connections in the foundation would eliminate this limitation.

Connections in the foundation

Figure 3 shows the wall cross section and the design of the connections placed in the foundation. The design calculations are as follows.

The area of energy-dissipation bars in each layer across the wall thickness (from original wall design) A_{ED} = (2)(0.79 in.^{2}) = 1.58 in.^{2} (1019 mm^2).

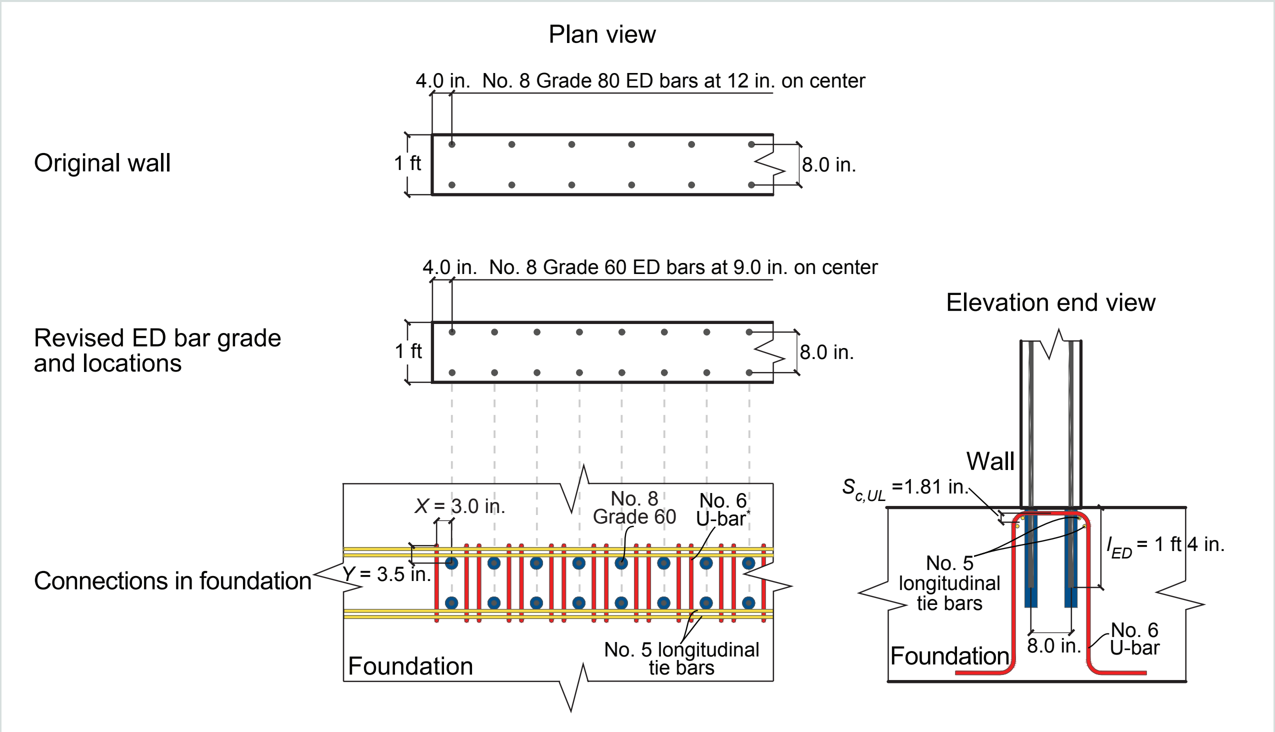

Figure 3. Example 2, connections in the foundation.
* Bottom hooks for U bars are not shown in plan view of foundation.
Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 5 = 16M; no. 6 = 19M; no. 8 = 25M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa; Grade 80 = 550 MPa.

Use Eq. (2) to calculate the area of vertical tie reinforcement $A_{vt} = A_{ED}$ = 1.58 in.^{2} (1019 mm^2). One no. 6 (19M) U bar is placed on each side of each connection layer. Therefore, $A_{vt,provided}$ = (4)(0.44 in.^{2}) = 1.76 in.^{2} (1136 mm^2).

The area of transverse tie reinforcement is calculated using Eq. (3). The design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked because of the use of U bars as both vertical and transverse tie reinforcement.

Using Eq. (12), calculate the area of longitudinal tie reinforcement $A_{lt} = \left(0.32 \le \dfrac{0.75 \times X}{h_{wp} - S_{c,UL}} \le 1.5\right) \times A_{ED}$.

X = 3.0 in. (76 mm)

Y = 3.5 in. (89 mm)

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

Use Eq. (17) to calculate the height of the work point h_{wp}.

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(3.5 in.) = 5.25 in. (133 mm) OK

$$h_{wp} = 1.5 \times Y \ge 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$$

$$h_{wp} = (1.5)(3.5 \text{ in.}) \ge 0.5\sqrt{3.0^2 + 3.5^2} \text{ in.} + 2.5 \text{ in.}$$

$$h_{wp} = 5.25 \text{ in.} \ge 4.80 \text{ in.}$$

therefore, h_{wp} = 5.25 in. (133 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75 \times 3.0}{5.25 - 2.5} \le 1.5\right) \times 1.58 \text{ in.}^2 = (0.32 \le 0.82 \le 1.5)(1.58 \text{ in.}^2) = (0.82)(1.58 \text{ in.}^2) = 1.29 \text{ in.}^2\ (832 \text{ mm}^2)$$

Two layers of no. 5 (16M) bars are used for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (4)(0.31 in.^{2}) = 1.24 in.^{2} (800 mm^2), which is insufficient but close. Continue iteration of $S_{c,UL}$.

The centerlines of the first and second layers of the no. 5 (16M) longitudinal tie bars are placed at 2.13 and 3.75 in. (54 and 95 mm), respectively, from the top of the foundation, with a clear spacing of 1 in. (25 mm) between the two layers. The centroid of these two layers of longitudinal bars is 2.94 in. (75 mm) from the top of the foundation. The transverse (horizontal) legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.13 in. (29 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 6 [19M] U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.94 in. – 1.13 in. = 1.81 in. (46 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.81 in. < (1.5)(3.5 in.) = 5.25 in. (133 mm) OK

$$h_{wp} = (1.5)(3.5 \text{ in.}) \ge 0.5\sqrt{3.0^2 + 3.5^2} \text{ in.} + 1.81 \text{ in.}$$

$$h_{wp} = 5.25 \text{ in.} \ge 4.11 \text{ in.}$$

therefore, h_{wp} = 5.25 in. (133 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75 \times 3.0}{5.25 - 1.81} \le 1.5\right) \times 1.58 \text{ in.}^2 = (0.32 \le 0.65 \le 1.5)(1.58 \text{ in.}^2) = (0.65)(1.58 \text{ in.}^2) = 1.03 \text{ in.}^2\ (665 \text{ mm}^2)$$

The selection of two layers of no. 5 (16M) bars is valid. Therefore, $A_{lt,provided}$ = (4)(0.31 in.^{2}) = 1.24 in.^{2} (800 mm^2).

Connection length is calculated using Eq. (18).

$$l_{ED} = C + 0.5 \times d_U + h_{wp} + l_b'$$

C = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = 0.75 in. (19 mm) for no. 6 (19M) bars

h_{wp} = 5.25 in. (133 mm)

l_b' = $9d_{ED}$ = (9)(1.0 in.) = 9.0 in. (229 mm) for no. 8 (25M) bars

$$l_{ED} = 0.75 \text{ in.} + (0.5)(0.75 \text{ in.}) + 5.25 \text{ in.} + 9.0 \text{ in.}$$

$$l_{ED} = 15.4 \text{ in.}$$

therefore, use l_{ED} = 16 in. (406 mm)

Connections in the wall panel

When placing the connections within the wall panel thickness, the energy-dissipation bars need to be relocated (**Fig. 4**) for the same reasons provided in the first example. Specifically, all of the energy-dissipation bar layers are shifted inward along the length of the wall so that the center of the first layer is 6.5 in. (165 mm) from the wall end rather than the original distance of 4.0 in. (102 mm). In addition, the distance between the energy-dissipation bars in each layer across the wall thickness is reduced from 8.0 to 3.0 in. (203 to 76 mm).

Because the area of the energy-dissipation bars in each layer is unchanged, the vertical and transverse tie areas also remain

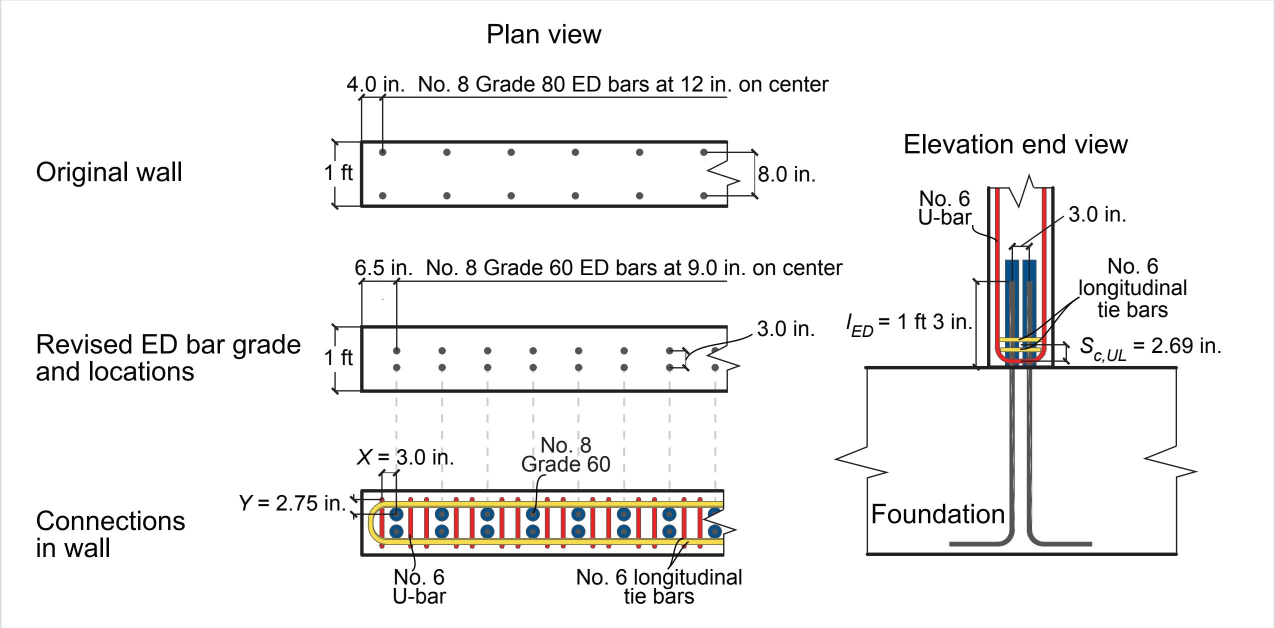

Figure 4. Example 2, connections in the wall panel. Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 6 = 19M; no. 8 = 25M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa; Grade 80 = 550 MPa.

unchanged as in the placement of the connections in the foundation.

The area of energy-dissipation bars in each layer across the wall thickness A_{ED} = 1.58 in.^{2} (1019 mm^2).

The area of vertical tie reinforcement can be calculated using Eq. (2). Use one no. 6 (19M) U bar on each side of each connection layer. Therefore, $A_{vt,provided}$ = 1.76 in.^{2} (1136 mm^2).

The area of transverse tie reinforcement can be calculated using Eq. (3). Design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked due to the use of U bars as both vertical and transverse tie reinforcement.

The area of longitudinal tie reinforcement is calculated using Eq. (12).

$$A_{lt} = \left(0.32 \le \frac{0.75 \times X}{h_{wp} - S_{c,UL}} \le 1.5\right) \times A_{ED}$$

To accommodate the placement of the connections inside the limited wall thickness, new Y and $S_{c,UL}$ values are selected. The X value is kept the same as the design with the connections placed in the foundation.

X = 3.0 in. (76 mm)

Y = 2.75 in. (70 mm)

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

Calculate the height of the work point h_{wp} using Eq. (17).

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(2.75 in.) = 4.13 in. (105 mm) OK

$h_{wp} = 1.5 \times Y \ge 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$

h_{wp} $= (1.5)(2.75 \text{ in.}) \geq 0.5\sqrt{3.0^2 + 2.75^2}$ in. + 2.5 in.

h_{wp} = 4.13 in. ≥ 4.53 in., NOT OK

therefore, h_{wp} = 4.53 in. (115 mm), the minimum value for the height of the work point governs

$$A_{lt} = \left(0.32 \leq \frac{0.75 \times 3.0}{4.53 - 2.5} \leq 1.5\right) \times 1.58 \text{ in.}^2 = (0.32 \leq 1.11 \leq 1.5)(1.58 \text{ in.}^2) = (1.11)(1.58 \text{ in.}^2) = 1.75 \text{ in.}^2 \text{ (1129 mm}^2\text{)}$$

Use two layers of no. 6 (19M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (4)(0.44 in.^{2}) = 1.76 in.^{2} (1136 mm^2).

The centerlines of the first and second layers of the no. 6 (19M) longitudinal tie bars are placed at 2.94 and 4.69 in. (75 and 119 mm), respectively, from the bottom of the wall, with a clear spacing of 1 in. (25 mm) between the two layers. The centroid of these two layers of longitudinal bars is 3.81 in. (97 mm) from the bottom of the wall. The transverse (horizontal) legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the bottom of the wall, resulting in a centroid location of 1.13 in. (29 mm) for these bars from the bottom of the wall (0.75 in. plus half the diameter of the no. 6 U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 3.81 in. – 1.13 in. = 2.69 in. (68 mm)

Recalculate h_{wp} and A_{lt} as follows:

2.69 in. < (1.5)(2.75 in.) = 4.13 in. (105 mm) OK

h_{wp} $= (1.5)(2.75 \text{ in.}) \geq 0.5\sqrt{3.0^2 + 2.75^2}$ in. + 2.69 in.

h_{wp} = 4.13 in. ≥ 4.72 in., NOT OK

therefore, h_{wp} = 4.72 in. (120 mm), the minimum value for the height of the work point governs

$$A_{lt} = \left(0.32 \leq \frac{0.75 \times 3.0}{4.72 - 2.69} \leq 1.5\right) \times 1.58 \text{ in.}^2 = (0.32 \leq 1.11 \leq 1.5)(1.58 \text{ in.}^2) = (1.11)(1.58 \text{ in.}^2) = 1.75 \text{ in.}^2 \text{ (1129 mm}^2\text{)}$$

Selection of two layers of no. 6 (19M) bars is valid. Therefore, $A_{lt,provided}$ = (4)(0.44 in.^{2}) = 1.76 in.^{2} (1136 mm^2).

Connection length is calculated using Eq. (18).

l_{ED} $= C + 0.5 \times d_U + h_{wp} + l'_b$

C = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = 0.75 in. (19 mm) for no. 6 (19M) bars

h_{wp} = 4.72 in. (120 mm)

l'_b $= 9d_{ED}$ = (9)(1.0 in.) = 9.0 in. (229 mm) for no. 8 (25M) bars

l_{ED} = 0.75 in. + (0.5)(0.75 in.) + 4.72 in. + 9.0 in.

l_{ED} = 14.8 in.

therefore, use l_{ED} = 15 in. (381 mm)

Example 3

Example 3 is a 10 in. (254 mm) thick wall with two no. 6 (19M) Grade 60 (414 MPa) energy-dissipation bars in each layer (across the wall thickness) spaced at 9 in. (229 mm) on center for the first five layers. Beyond these layers, the spacing is increased to 18 in. (457 mm).

Connections in the foundation

Figure 5 shows the wall cross section and the design of the connections placed inside the foundation. The design calculations are presented as follows. The area of energy-dissipation bars in each layer across the wall thickness (from original wall design) A_{ED} = (2)(0.44 in.^{2}) = 0.88 in.^{2} (568 mm^2).

Use Eq. (2) to calculate the area of vertical tie reinforcement $A_{vt} = A_{ED}$ = 0.88 in.^{2} (568 mm^2).

Use one no. 5 (16M) U bar on each side of each connection layer. Therefore, $A_{vt,provided}$ = (4)(0.31 in.^{2}) = 1.24 in.^{2} (800 mm^2).

Instead of providing one no. 5 (16M) U bar on each side of each connection layer, the required area of vertical tie reinforcement for two adjacent layers of energy-dissipation bars can be combined into one no. 6 (19M) U bar between the two adjacent layers of energy-dissipation bars. The spacing between the energy-dissipation bar layers varies in the cross section of the wall as 9 in. (229 mm) for the first five layers and 18 in. (458 mm) after the fifth layer (Fig. 5). As a result, the following U bar arrangements are used in this example. For the first and fifth layers of connection ducts, use one no. 5 (16M) U bar on the outer side of the connection layer and one no. 6 (19M) U bar on the inner side of the layer.

Therefore, $A_{vt,provided} = (2)(0.31\text{ in.}^2) + \dfrac{2}{2}(0.44\text{ in.}^2) = 1.06\text{ in.}^2$ (684 mm^2).

The total area of the two vertical legs of the no. 6 (19M) U bar is divided by 2 because the U bar is shared between two adjacent energy-dissipation bar layers.

For the second, third, and fourth connection layers, use one no. 6 (19M) U bar on each side of each layer. Therefore,

$A_{vt,provided} = \dfrac{4}{2}(0.44\text{ in.}^2) = 0.88\text{ in.}^2$ (568 mm^2).

Beyond the fifth connection layer, use one no. 5 (16M) U bar on each side of each layer. Therefore, $A_{vt,provided}$ = (4)(0.31 in.^{2}) = 1.24 in.^{2} (800 mm^2). The U bar areas are not combined at these locations because of the increased distance between the energy-dissipation bar layers.

The area of transverse tie reinforcement is calculated using Eq. (3). The design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked due to the use of U bars as both vertical and transverse tie reinforcement.

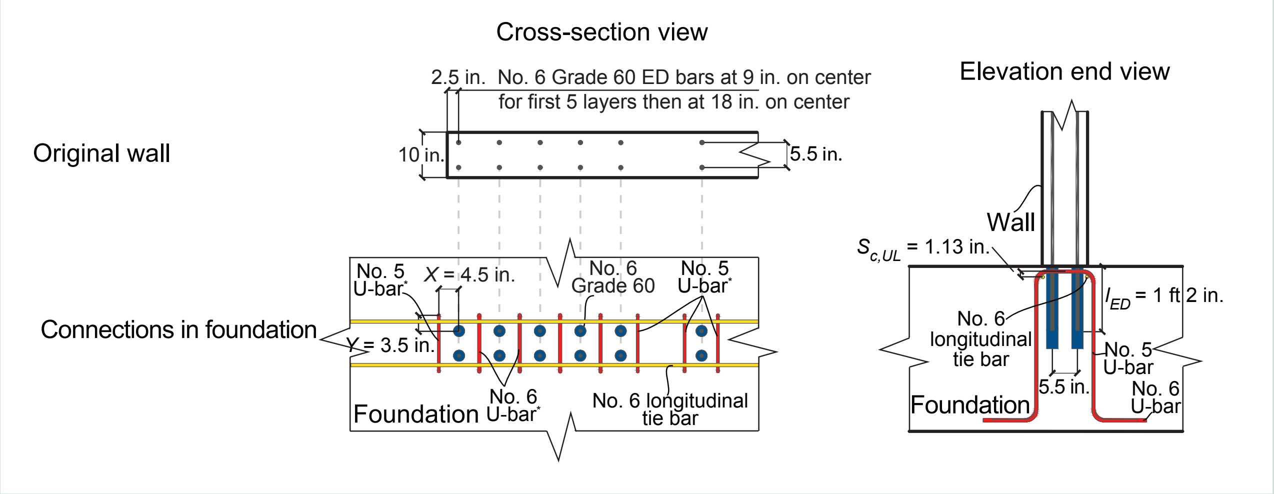

Figure 5. Example 3, connections in the foundation.
* Bottom hooks for U bars are not shown in plan view of foundation.
Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 5 = 16M; no. 6 = 19M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa.

Use Eq. (12) to calculate the area of longitudinal tie reinforcement $A_{lt} = \left(0.32 \le \frac{0.75 \times X}{h_{wp} - S_{c,UL}} \le 1.5\right) \times A_{ED}$.

X = 4.5 in. (114 mm)

Y = 3.5 in. (89 mm)

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

Use Eq. (17) to calculate the height of the work point h_{wp}.

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(3.5 in.) = 5.25 in. (133 mm) OK

$h_{wp} = 1.5 \times Y \ge 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$

h_{wp} = (1.5)(3.5 in.) ≥ $0.5\sqrt{4.5^2 + 3.5^2}$ in. + 2.5 in.

h_{wp} = 5.25 in. ≥ 5.35 in., NOT OK

therefore, h_{wp} = 5.35 in. (136 mm), the minimum value for the height of the work point governs

$A_{lt} = \left(0.32 \le \frac{0.75 \times 4.5}{5.35 - 2.5} \le 1.5\right) \times 0.88\text{ in.}^2 = (0.32 \le 1.18 \le 1.5)(0.88\text{ in.}^2) = (1.18)(0.88\text{ in.}^2) = 1.04\text{ in.}^2\ (671\text{ mm}^2)$

Use one layer of no. 7 (22M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided} = (2)(0.60\text{ in.}^2) = 1.20\text{ in.}^2$ (774 mm²).

The centerline of the no. 7 (22M) longitudinal tie bars is placed at 2.38 in. (61 mm) from the top of the foundation, satisfying the requirement that it not be placed closer to the transverse (horizontal) legs of the U bars than the center half of the U-bar bend. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.13 in. (29 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 6 U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.38 in. – 1.13 in. = 1.25 in. (32 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.25 in. < (1.5)(3.5 in.) = 5.25 in. (133 mm) OK

h_{wp} = (1.5)(3.5 in.) ≥ $0.5\sqrt{4.5^2 + 3.5^2}$ in. + 1.25 in.

h_{wp} = 5.25 in. ≥ 4.10 in.

therefore, h_{wp} = 5.25 in. (133 mm)

$A_{lt} = \left(0.32 \le \frac{0.75 \times 4.5}{5.25 - 1.25} \le 1.5\right) \times 0.88\text{ in.}^2 = (0.32 \le 0.84 \le 1.5)(0.88\text{ in.}^2) = (0.84)(0.88\text{ in.}^2) = 0.74\text{ in.}^2\ (477\text{ mm}^2)$

Use one layer of no. 6 (19M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided} = (2)(0.44\text{ in.}^2) = 0.88\text{ in.}^2$ (568 mm²).

The centerline of the no. 6 (19M) longitudinal tie bars is placed at 2.25 in. (57 mm) from the top of the foundation, satisfying the requirement that it not be placed closer to the transverse legs of the U bars than the center half of the U-bar bend. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.13 in. (29 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 6 U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement

$= 2.25$ in. – 1.13 in. = 1.13 in. (29 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.13 in. < (1.5)(3.5 in.) = 5.25 in. (133 mm) OK

h_{wp} $= (1.5)(3.5\text{ in.}) \geq 0.5\sqrt{4.5^2 + 3.5^2}$ in. + 1.13 in.

h_{wp} = 5.25 in. ≥ 3.98 in.

therefore, h_{wp} = 5.25 in. (133 mm)

$$A_{lt} = \left(0.32 \leq \frac{0.75 \times 4.5}{5.25 - 1.13} \leq 1.5\right) \times 0.88\text{ in.}^2 = (0.32 \leq 0.82 \leq 1.5)(0.88\text{ in.}^2) = (0.82)(0.88\text{ in.}^2) = 0.72\text{ in.}^2\ (465\text{ mm}^2)$$

Selection of one layer of no. 6 (19M) bars is valid. Therefore, $A_{lt,provided} = (2)(0.44\text{ in.}^2) = 0.88\text{ in.}^2$ (568 mm^2).

Connection length is calculated using Eq. (18).

l_{ED} $= C + 0.5 \times d_U + h_{wp} + l'_b$

C = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = 0.75 in. (19 mm) for no. 6 (19M) bars

h_{wp} = 5.25 in. (133 mm)

l'_b $= 9d_{ED}$ = (9)(0.75 in.) = 6.8 in. (173 mm) for no. 6 (19M) bars

l_{ED} = 0.75 in. + (0.5)(0.75 in.) + 5.25 in. + 6.8 in.

l_{ED} = 13.2 in.

therefore, use l_{ED} = 14 in. (356 mm)

Connections in the wall panel

Two options are provided for the design of the connections inside the wall panel. **Figure 6** shows the first option. For this example, all energy-dissipation bar layers are shifted inward along the length of the wall so that the center of the first layer is 6.0 in. (152 mm) from the wall end rather than the original distance of 2.5 in. (64 mm). In addition, the distance between the energy-dissipation bars in each layer across the wall thickness is reduced from 5.5 to 2.75 in. (140 to 70 mm).

The area of the energy-dissipation bars in each layer across the wall thickness (from the original wall design) $A_{ED} = (2)(0.44\text{ in.}^2) = 0.88\text{ in.}^2$ (568 mm^2).

Use Eq. (2) to calculate the area of vertical tie reinforcement $A_{vt} = A_{ED} = 0.88\text{ in.}^2$ (568 mm^2)

Use one no. 5 (16M) U bar on each side of each connection layer. Therefore, $A_{vt,provided} = (4)(0.31\text{ in.}^2) = 1.24\text{ in.}^2$ (800 mm^2).

The area of transverse tie reinforcement is calculated using Eq. (3). Design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked due to the use of U bars as both vertical and transverse tie reinforcement.

Use Eq. (12) to calculate the area of longitudinal tie reinforcement $A_{lt} = \left(0.32 \leq \frac{0.75 \times X}{h_{wp} - S_{c,UL}} \leq 1.5\right) \times A_{ED}$.

X = 3.5 in. (89 mm)

Y = 1.81 in. (46 mm)

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

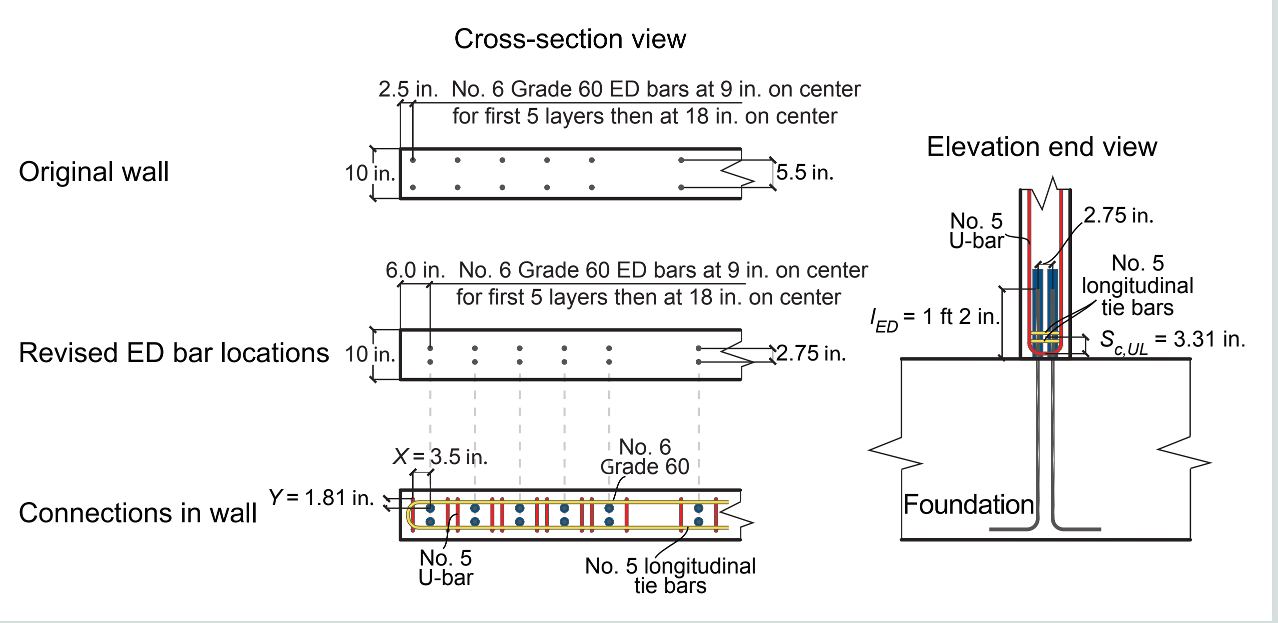

Figure 6. Example 3, connections in the wall panel, option 1. Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 5 = 16M; no. 6 = 19M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa.

Use Eq. (17) to calculate the height of the work point h_{wp}.

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(1.81 in.) = 2.72 in. (69 mm) OK

$$h_{wp} = 1.5 \times Y \geq 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$$

$$h_{wp} = (1.5)(1.81 \text{ in.}) \geq 0.5\sqrt{3.5^2 + 1.81^2} \text{ in.} + 2.5 \text{ in.}$$

$$h_{wp} = 2.72 \text{ in.} \geq 4.47 \text{ in., NOT OK}$$

therefore, h_{wp} = 4.47 in. (114 mm), the minimum value for the height of the work point governs

$$A_{lt} = \left(0.32 \leq \frac{0.75 \times 3.5}{4.47 - 2.5} \leq 1.5\right) \times 0.88 \text{ in.}^2 = (0.32 \leq 1.33 \leq 1.5)(0.88 \text{ in.}^2) = (1.33)(0.88 \text{ in.}^2) = 1.17 \text{ in.}^2 \text{ (755 mm}^2\text{)}$$

Use two layers of no. 5 (16M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (4)(0.31 in.^{2}) = 1.24 in.^{2} (800 mm^2).

The centerlines of the first and second layers of the no. 5 (16M) longitudinal tie bars are placed at 3.56 and 5.19 in. (90 and 132 mm), respectively, from the bottom of the wall, with a clear spacing of 1 in. (25 mm) between the two layers. The centroid of these two layers of longitudinal bars is 4.38 in. (111 mm) from the bottom of the wall. The transverse (horizontal) legs of the U bars are placed with a minimum concrete cover of 0.75 in. (19 mm) from the bottom of the wall, resulting in a centroid location of 1.06 in. (27 mm) for these bars from the bottom of the wall (0.75 in. plus half the diameter of the no. 5 U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 4.38 in. – 1.06 in. = 3.31 in. (84 mm)

Recalculate h_{wp} and A_{lt} as follows:

3.31 in. < (1.5)(1.81 in.) = 2.72 in. (69 mm) NOT OK

therefore, the minimum value for the height of the work point governs

h_{wp} $= 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$

h_{wp} $= 0.5\sqrt{3.5^2 + 1.81^2}$ in. + 3.31 in.

h_{wp} = 5.28 in. (134 mm)

A_{lt} $= \left(0.32 \le \frac{0.75 \times 3.5}{5.28 - 3.31} \le 1.5\right) \times 0.88$ in.^{2} = (0.32 ≤ 1.33 ≤ 1.5)(0.88 in.^{2}) = (1.33)(0.88 in.^{2}) = 1.17 in.^{2} (755 mm^2)

Selection of two layers of no. 5 (16M) bars is valid. Therefore, $A_{lt,provided}$ = (4)(0.31 in.^{2}) = 1.24 in.^{2} (800 mm^2).

Connection length is calculated using Eq. (18).

l_{ED} $= C + 0.5 \times d_U + h_{wp} + l'_b$

C = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = 0.63 in. (16 mm) for no. 5 (16M) bars

h_{wp} = 5.28 in. (134 mm)

l'_b $= 9d_{ED}$ = (9)(0.75 in.) = 6.8 in. (173 mm) for no. 6 (19M) bars

l_{ED} = 0.75 in. + (0.5)(0.63 in.) + 5.28 in. + 6.8 in.

l_{ED} = 13.1 in.

therefore, use l_{ED} = 14 in. (356 mm)

In this design option, the work point height h_{wp} is governed by its minimum value of $0.5\sqrt{X^2 + Y^2} + S_{c,UL}$ because of the limited thickness of the wall. Specifically, the width of the U bars is constrained by the wall thickness, the placement of no. 5 (16M) confinement hoops (from the original wall design), and the 1 in. (25 mm) concrete side clear cover used in the original design. This results in a small Y value (1.81 in. [46 mm]) and also requires the longitudinal tie bars to be placed farther from the transverse legs of the U bars ($S_{c,UL}$ of 3.31 in. [84 mm]) because the first layer of the longitudinal bars has to be moved up to the beginning of the vertical legs of the U bars.

Figure 7 shows a second design option where the two no. 6 (19M) energy-dissipation bars in each layer are replaced with a single no. 9 (29M) bar while maintaining the same spacing between the bar layers. In addition, all of the energy-dissipation bar layers are shifted inward along the length of the wall so that the center of the first layer is 6 in. (152 mm) from the wall end rather than the original distance of 2.5 in. (64 mm).

The area of energy-dissipation bar in each layer A_{ED} = (1)(1.0 in.^{2}) = 1.0 in.^{2} (645 mm^2).

Use Eq. (2) to calculate the area of vertical tie reinforcement $A_{vt} = A_{ED}$ = 1.0 in.^{2} (645 mm^2).

Use one no. 5 (16M) U bar on each side of each connection layer. Therefore, $A_{vt,provided}$ = (4)(0.31 in.^{2}) = 1.24 in.^{2} (800 mm^2).

The area of transverse tie reinforcement is calculated using Eq. (3). Design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked due to the use of U bars as both vertical and transverse tie reinforcement.

Use Eq. (12) to calculate the area of longitudinal tie reinforcement $A_{lt} = \left(0.32 \le \frac{0.75 \times X}{h_{wp} - S_{c,UL}} \le 1.5\right) \times A_{ED}$.

X = 3.5 in. (89 mm)

Y = 3.38 in. (86 mm)

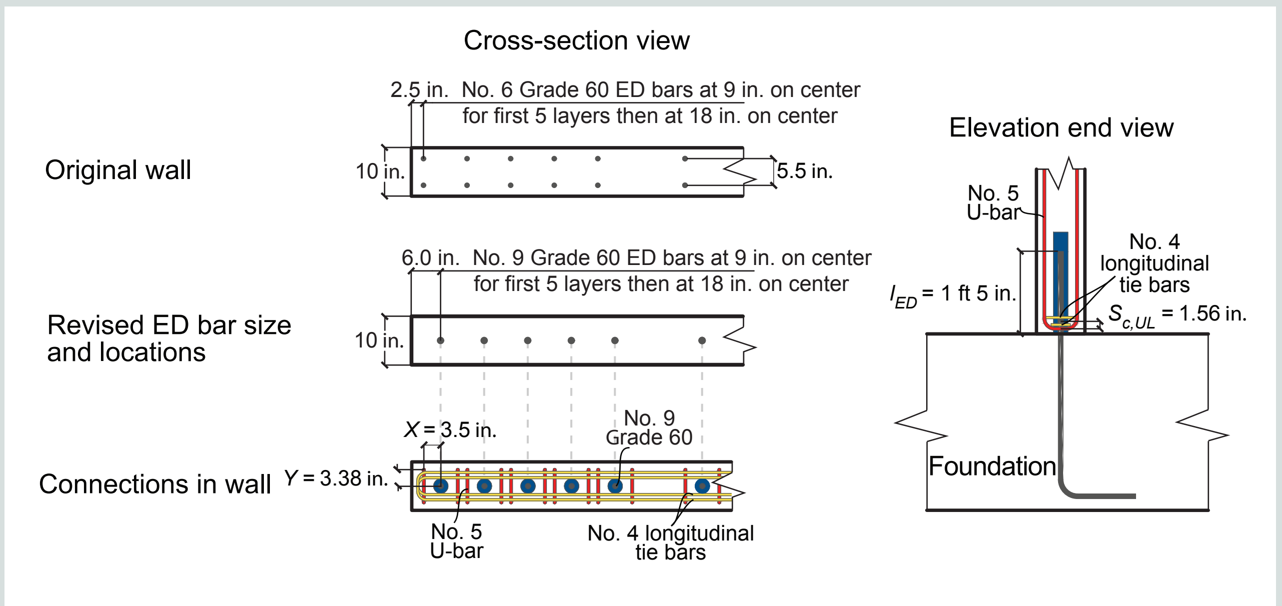

Figure 7. Example 3, connections in the wall panel, option 2. Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 4 = 13M; no. 5 = 16M; no. 6 = 19M; no. 9 = 29M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa.

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

Use Eq. (17) to calculate the height of the work point h_{wp}.

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(3.38 in.) = 5.06 in. (129 mm) OK

$$h_{wp} = 1.5 \times Y \geq 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$$

$$h_{wp} = (1.5)(3.38 \text{ in.}) \geq 0.5\sqrt{3.5^2 + 3.38^2} \text{ in.} + 2.5 \text{ in.}$$

$$h_{wp} = 5.06 \text{ in.} \geq 4.93 \text{ in.}$$

therefore, h_{wp} = 5.06 in. (129 mm)

$$A_{lt} = \left(0.32 \leq \frac{0.75 \times 3.5}{5.06 - 2.5} \leq 1.5\right) \times 1.0 \text{ in.}^2 = (0.32 \leq 1.0 \leq 1.5)(1.0 \text{ in.}^2) = (1.0)(1.0 \text{ in.}^2) = 1.0 \text{ in.}^2 \text{ (645 mm}^2\text{)}$$

Use two layers of no. 5 (16M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (4)(0.31 in.^{2}) = 1.24 in.^{2} (800 mm^2).

The centerlines of the first and second layers of the no. 5 (16M) longitudinal tie bars are placed at 2.0 and 3.63 in. (51 and 92 mm), respectively, from the bottom of the wall, with a clear spacing of 1 in. (25 mm) between the two layers. The centroid of these two layers of longitudinal bars is 2.81 in. (71 mm) from the bottom of the wall. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the bottom of the wall, resulting in a centroid location of 1.06 in. (27 mm) for these bars from the bottom of the wall (0.75 in. plus half the diameter of the no. 5 U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.81 in. – 1.06 in. = 1.75 in. (45 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.75 in. < (1.5)(3.38 in.) = 5.06 in. (129 mm) OK

h_{wp} = (1.5)(3.38 in.) ≥ $0.5\sqrt{3.5^2 + 3.38^2}$ in. + 1.75 in.

h_{wp} = 5.06 in. ≥ 4.18 in.

therefore, h_{wp} = 5.06 in. (129 mm)

A_{lt} = $\left(0.32 \leq \frac{0.75 \times 3.5}{5.06 - 1.75} \leq 1.5\right)$ × 1.0 in.^{2} = (0.32 ≤ 0.79 ≤ 1.5)(1.0 in.^{2}) = (0.79)(1.0 in.^{2}) = 0.79 in.^{2} (510 mm^2)

Use two layers of no. 4 (13M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (4)(0.2 in.^{2}) = 0.80 in.^{2} (516 mm^2).

The centerlines of the first and second layers of the no. 4 (13M) longitudinal tie bars are placed at 1.88 and 3.38 in. (48 and 86 mm), respectively, from the bottom of the wall, with a clear spacing of 1 in. (25 mm) between the two layers. The centroid of these two layers of longitudinal bars is 2.63 in. (67 mm) from the bottom of the wall. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the bottom of the wall, resulting in a centroid location of 1.06 in. (27 mm) for these bars from the bottom of the wall (0.75 in. plus half the diameter of the no. 5 [16M] U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.63 in. – 1.06 in. = 1.56 in. (40 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.56 in. < (1.5)(3.38 in.) = 5.06 in. (129 mm) OK

h_{wp} = (1.5)(3.38 in.) ≥ $0.5\sqrt{3.5^2 + 3.38^2}$ in. + 1.56 in.

h_{wp} = 5.06 in. ≥ 3.99 in.

therefore, h_{wp} = 5.06 in. (129 mm)

A_{lt} = $\left(0.32 \leq \frac{0.75 \times 3.5}{5.06 - 1.56} \leq 1.5\right)$ × 1.0 in.^{2} = (0.32 ≤ 0.75 ≤ 1.5)(1.0 in.^{2}) = (0.75)(1.0 in.^{2}) = 0.75 in.^{2} (484 mm^2)

Selection of two layers of no. 4 (13M) bars is valid. Therefore, $A_{lt,provided}$ = (4)(0.2 in.^{2}) = 0.80 in.^{2} (516 mm^2).

Connection length is calculated using Eq. (18).

l_{ED} = $C + 0.5 \times d_U + h_{wp} + l'_b$

C = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = 0.63 in. (16 mm) for no. 5 (16M) bars

h_{wp} = 5.06 in. (129 mm)

l'_b = $9d_{ED}$ = (9)(1.128 in.) = 10.2 in. (259 mm) for no. 9 (29M) bars

l_{ED} = 0.75 in. + (0.5)(0.63 in.) + 5.06 in. + 10.2 in.

l_{ED} = 16.3 in.

therefore, use l_{ED} = 17 in. (432 mm)

Example 4

Example 4 is a 12 in. (305 mm) thick wall with three layers of two no. 9 (29M) Grade 60 (414 MPa) energy-dissipation bars spaced at 6 in. (152 mm) on center.

Connections in the foundation

Figure 8 shows the wall cross section and the design of the connections placed in the foundation. The design calculations are presented as follows.

The area of energy-dissipation bars in each layer across the wall thickness (from original wall design)
A_{ED} = (2)(1.0 in.^{2}) = 2.0 in.^{2} (1290 mm^2)

Use Eq. (2) to calculate the area of vertical tie reinforcement $A_{vt} = A_{ED}$ = 2.0 in.^{2} (1290 mm^2).

Use one no. 7 (22M) U bar on each side of each connection layer. Therefore, $A_{vt,provided}$ = (4)(0.6 in.^{2}) = 2.4 in.^{2} (1548 mm^2).

Calculate the area of transverse tie reinforcement using Eq. (3). Design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked due to the use of U bars as both vertical and transverse tie reinforcement.

Use Eq. (12) to calculate the area of longitudinal tie reinforcement $A_{lt} = \left(0.32 \le \frac{0.75 \times X}{h_{wp} - S_{c,UL}} \le 1.5\right) \times A_{ED}$.

X = 2.0 in. (51 mm)

Y = 3.75 in. (95 mm)

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

Use Eq. (17) to calculate the height of the work point h_{wp}.

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(3.75 in.) = 5.63 in. (143 mm) OK

$h_{wp} = 1.5 \times Y \ge 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$

$h_{wp} = (1.5)(3.75 \text{ in.}) \ge 0.5\sqrt{2.0^2 + 3.75^2} \text{ in.} + 2.5 \text{ in.}$

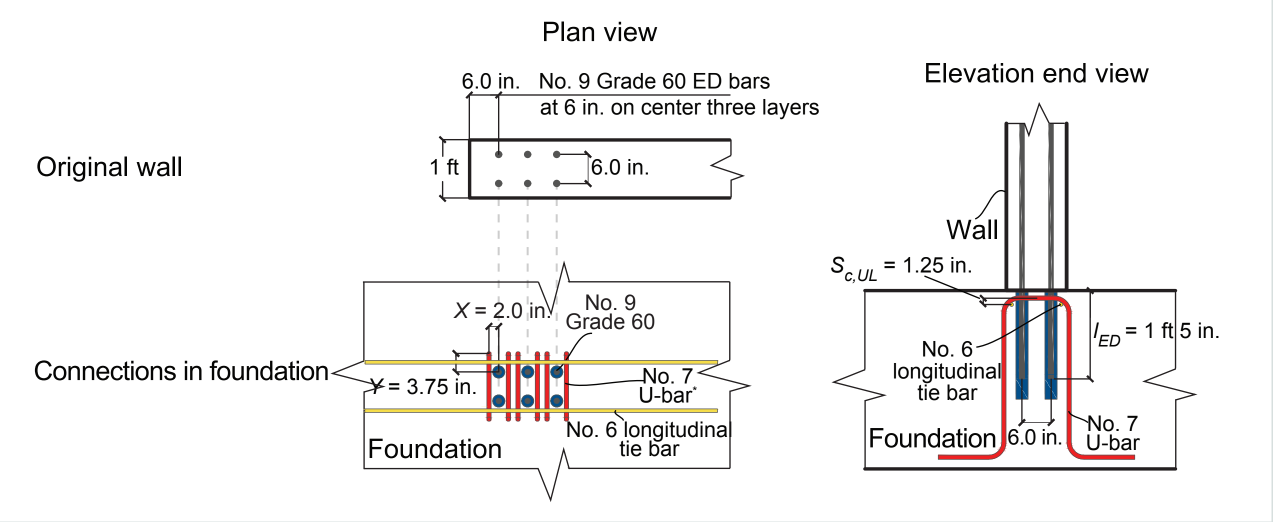

Figure 8. Example 4, connections in the foundation.
* Bottom hooks for U bars are not shown in plan view of foundation.
Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 6 = 19M; no. 7 = 22M; no. 9 = 29M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa.

h_{wp} = 5.63 in. ≥ 4.63 in.

therefore, h_{wp} = 5.63 in. (143 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75\times 2.0}{5.63-2.5} \le 1.5\right) \times 2.0 \text{ in.}^2 = (0.32 \le 0.48 \le 1.5)(2.0 \text{ in.}^2) = (0.48)(2.0 \text{ in.}^2) = 0.96 \text{ in.}^2 \ (619 \text{ mm}^2)$$

Use one layer of no. 7 (22M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (2)(0.60 in.^{2}) = 1.20 in.^{2} (774 mm^2).

The centerline of the no. 7 (22M) longitudinal tie bars is placed 2.5 in. (64 mm) from the top of the foundation, satisfying the requirement that it not be placed closer to the transverse (horizontal) legs of the U bars than the center half of the U-bar bend. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.19 in. (30 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 7 U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.5 in. – 1.19 in. = 1.31 in. (33 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.31 in. < (1.5)(3.75 in.) = 5.63 in. (143 mm) OK

$$h_{wp} = (1.5)(3.75 \text{ in.}) \ge 0.5\sqrt{2.0^2+3.75^2} \text{ in.} + 1.31 \text{ in.}$$

h_{wp} = 5.63 in. ≥ 3.44 in.

therefore, h_{wp} = 5.63 in. (143 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75\times 2.0}{5.63-1.31} \le 1.5\right) \times 2.0 \text{ in.}^2 = (0.32 \le 0.35 \le 1.5)(2.0 \text{ in.}^2) = (0.35)(2.0 \text{ in.}^2) = 0.70 \text{ in.}^2 \ (452 \text{ mm}^2)$$

Use one layer of no. 6 (19M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (2)(0.44 in.^{2}) = 0.88 in.^{2} (568 mm^2).

The centerline of the no. 6 (19M) longitudinal tie bars is placed 2.44 in. (62 mm) from the top of the foundation, satisfying the requirement that it not be placed closer to the transverse legs of the U bars than the center half of the U-bar bend. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.19 in. (30 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 7 [22M] U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.44 in. – 1.19 in. = 1.25 in. (32 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.25 in. < (1.5)(3.75 in.) = 5.63 in. (143 mm) OK

$$h_{wp} = (1.5)(3.75 \text{ in.}) \ge 0.5\sqrt{2.0^2+3.75^2} \text{ in.} + 1.25 \text{ in.}$$

h_{wp} = 5.63 in. ≥ 3.38 in.

therefore, h_{wp} = 5.63 in. (143 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75\times 2.0}{5.63-1.25} \le 1.5\right) \times 2.0 \text{ in.}^2 = (0.32 \le 0.34 \le 1.5)(2.0 \text{ in.}^2) = (0.34)(2.0 \text{ in.}^2) = 0.68 \text{ in.}^2 \ (439 \text{ mm}^2)$$

Selection of one layer of no. 6 (19M) bars is valid. Therefore, $A_{lt,provided}$ = (2)(0.44 in.^{2}) = 0.88 in.^{2} (568 mm^2).

Connection length is calculated using Eq. (18).

$l_{ED} = C + 0.5 \times d_U + h_{wp} + l'_b$

C = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = 0.88 in. (22 mm) for no. 7 (22M) bars

h_{wp} = 5.63 in. (143 mm)

$l'_b = 9d_{ED}$ = (9)(1.128 in.) = 10.2 in. (259 mm) for no. 9 (29M) bars

l_{ED} = 0.75 in. + (0.5)(0.88 in.) + 5.63 in. + 10.2 in.

l_{ED} = 17.0 in.

therefore, use l_{ED} = 17 in. (432 mm)

Connections in the wall panel

Figure 9 shows the design of the connections within the wall for example 4. In the original design of this wall, the first layer of energy-dissipation bars is placed 6 in. (152 mm) from the wall end, which is sufficient to accommodate the placement of the first layer of U bars. Therefore, the energy-dissipation bars do not need to be shifted inward along the wall length. However, the distance between the energy-dissipation bars within a single layer across the wall thickness is reduced from 6 to 3.5 in. (152 to 89 mm).

Because the area of the energy-dissipation bars in each layer is unchanged, the areas of vertical and transverse tie reinforcement also remain unchanged as in the placement of the connections in the foundation.

The area of energy-dissipation bars in each layer across the wall thickness A_{ED} = (2)(1.0 in.^{2}) = 2.0 in.^{2} (1290 mm^2).

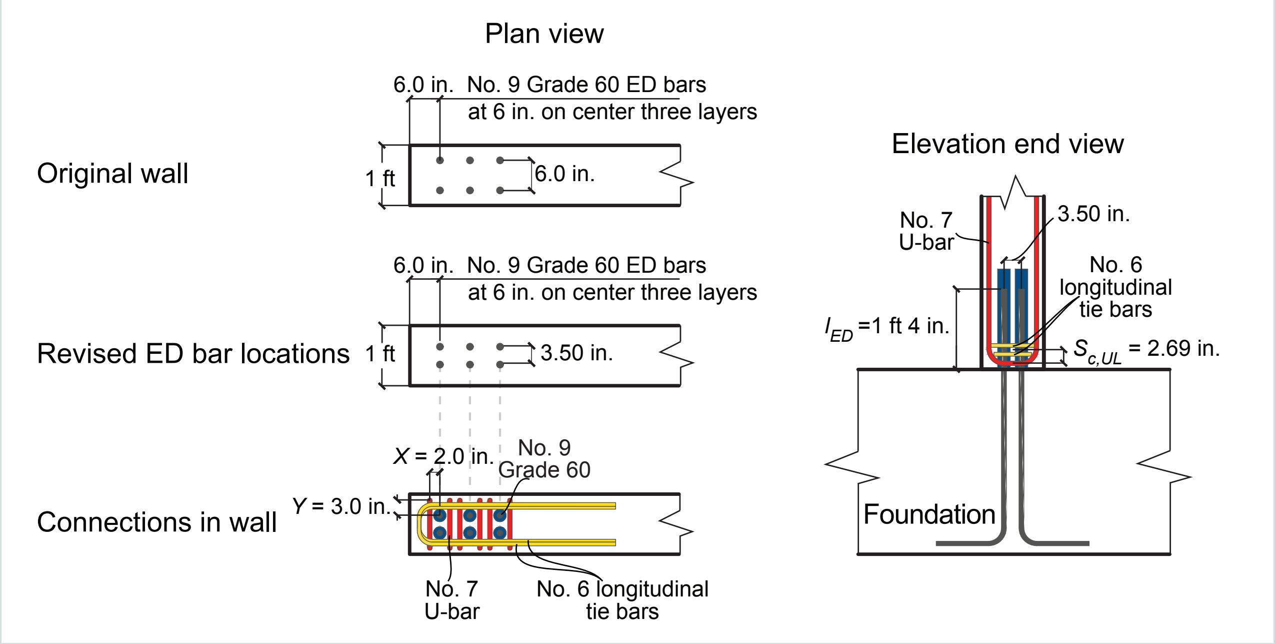

Figure 9. Example 4, connections in the wall panel. Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 6 = 19M; no. 7 = 22M; no. 9 = 29M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa.

Use Eq. (2) to calculate the area of vertical tie reinforcement $A_{vt} = A_{ED} = 2.0$ in.^{2} (1290 mm^2).

Use one no. 7 (22M) U bar on each side of each connection layer. Therefore, $A_{vt,provided} = (4)(0.6$ in.$^2) = 2.4$ in.^{2} (1548 mm^2).

The area of transverse tie reinforcement is calculated using Eq. (3). Design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked due to the use of U bars as both vertical and transverse tie reinforcement.

Use Eq. (12) to calculate the area of longitudinal tie reinforcement $A_{lt} = \left(0.32 \le \dfrac{0.75 \times X}{h_{wp} - S_{c,UL}} \le 1.5\right) \times A_{ED}$.

X = 2.0 in. (51 mm)

Y = 3.0 in. (76 mm)

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

Use Eq. (17) to calculate the height of the work point h_{wp}.

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(3.0 in.) = 4.5 in. (114 mm) OK

$$h_{wp} = 1.5 \times Y \ge 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$$

$$h_{wp} = (1.5)(3.0 \text{ in.}) \ge 0.5\sqrt{2.0^2 + 3.0^2} \text{ in.} + 2.5 \text{ in.}$$

$$h_{wp} = 4.5 \text{ in.} \ge 4.3 \text{ in.}$$

therefore, $h_{wp} = 4.5$ in. (114 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75 \times 2.0}{4.5 - 2.5} \le 1.5\right) \times 2.0 \text{ in.}^2 = (0.32 \le 0.75 \le 1.5)(2.0 \text{ in.}^2) = (0.75)(2.0 \text{ in.}^2) = 1.5 \text{ in.}^2 \text{ (968 mm}^2)$$

Use two layers of no. 6 (19M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided} = (4)(0.44$ in.$^2) = 1.76$ in.^{2} (1136 mm^2).

The centerlines of the first and second layers of the no. 6 (19M) longitudinal tie bars are placed 3.0 and 4.75 in. (76 and 121 mm), respectively, from the bottom of the wall, with a clear spacing of 1 in. (25 mm) between the two layers. The centroid of these two layers of longitudinal bars is 3.88 in. (99 mm) from the bottom of the wall. The transverse (horizontal) legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the bottom of the wall, resulting in a centroid location of 1.19 in. (30 mm) for these bars from the bottom of the wall (0.75 in. plus half the diameter of the no. 7 [22M] U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 3.88 in. – 1.19 in. = 2.69 in. (68 mm)

Recalculate h_{wp} and A_{lt} as follows:

2.69 in. < (1.5)(3.0 in.) = 4.5 in. (114 mm) OK

$$h_{wp} = (1.5)(3.0 \text{ in.}) \ge 0.5\sqrt{2.0^2 + 3.0^2} \text{ in.} + 2.69 \text{ in.}$$

$$h_{wp} = 4.5 \text{ in.} \ge 4.49 \text{ in.}$$

therefore, $h_{wp} = 4.5$ in. (114 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75 \times 2.0}{4.5 - 2.69} \le 1.5\right) \times 2.0 \text{ in.}^2 = (0.32 \le 0.83 \le 1.5)(2.0 \text{ in.}^2) = (0.83)(2.0 \text{ in.}^2) = 1.66 \text{ in.}^2 \text{ (1071 mm}^2)$$

Selection of two layers of no. 6 (19M) bars is valid. Therefore, $A_{lt,provided} = (4)(0.44$ in.$^2) = 1.76$ in.^{2} (1136 mm^2).

Connection length is calculated using Eq. (18).

l_{ED} $= C + 0.5 \times d_U + h_{wp} + l'_b$

C = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = 0.88 in. (22 mm) for no. 7 (22M) bars

h_{wp} = 4.5 in. (114 mm)

l'_b $= 9d_{ED}$ = (9)(1.128 in.) = 10.2 in. (259 mm) for no. 9 (29M) bars

l_{ED} = 0.75 in. + (0.5)(0.88 in.) + 4.5 in. + 10.2 in.

l_{ED} = 15.89 in.

therefore, use l_{ED} = 16 in. (406 mm)

Example 5

Example 5 is a 12 in. (305 mm) thick wall with one no. 11 (36M) Grade 60 (414 MPa) energy-dissipation bar in each layer (across the wall thickness) spaced at 36 in. (914 mm) on center.

Connections in the foundation

Figure 10 shows the wall cross section and the design of the connections placed in the foundation. The design calculations are presented as follows.

The area of energy-dissipation bar in each layer across the wall thickness (from original wall design)
A_{ED} = (1)(1.56 in.^{2}) = 1.56 in.^{2} (1007 mm^2)

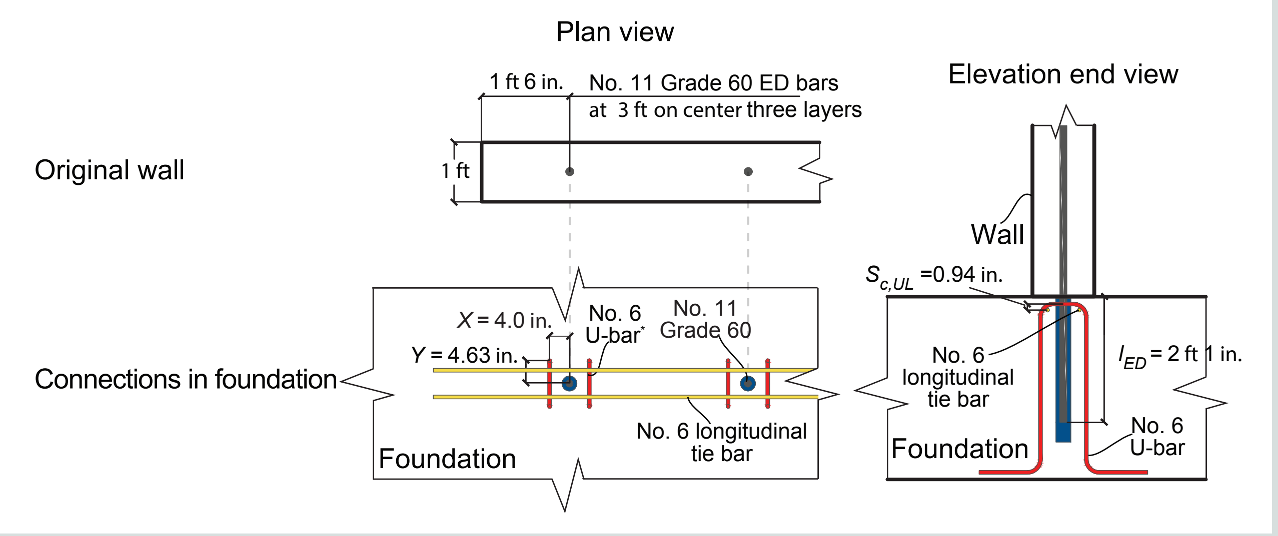

Figure 10. Example 5, connections in the foundation.
* Bottom hooks for U bars are not shown in plan view of foundation.
Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 6 = 19M; no. 11 = 36M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa.

Use Eq. (2) to calculate area of vertical tie reinforcement $A_{vt} = A_{ED}$ = 1.56 in.^{2} (1007 mm^2).

Use one no. 6 (19M) U bar on each side of each connection layer. Therefore, $A_{vt,provided}$ = (4)(0.44 in.^{2}) = 1.76 in.^{2} (1136 mm^2).

The area of transverse tie reinforcement is calculated using Eq. (3). Design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked due to the use of U bars as both vertical and transverse tie reinforcement.

Use Eq. (12) to calculate the area of longitudinal tie reinforcement $A_{lt} = \left(0.32 \le \dfrac{0.75 \times X}{h_{wp} - S_{c,UL}} \le 1.5\right) \times A_{ED}$.

X = 4.0 in. (102 mm)

Y = 4.63 in. (118 mm)

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

Use Eq. (17) to calculate the height of the work point h_{wp}.

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(4.63 in.) = 6.95 in. (177 mm) OK

$h_{wp} = 1.5 \times Y \ge 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$

h_{wp} = (1.5)(4.63 in.) ≥ $0.5\sqrt{4.0^2 + 4.63^2}$ in. + 2.5 in.

h_{wp} = 6.95 in. ≥ 5.56 in.

therefore, h_{wp} = 6.95 in. (177 mm)

$A_{lt} = \left(0.32 \le \dfrac{0.75 \times 4.0}{6.95 - 2.5} \le 1.5\right)$ × 1.56 in.^{2} = (0.32 ≤ 0.67 ≤ 1.5)(1.56 in.^{2}) = (0.67)(1.56 in.^{2}) = 1.05 in.^{2} (677 mm^2)

Use one layer of no. 7 (22M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (2)(0.60 in.^{2}) = 1.20 in.^{2} (774 mm^2).

The centerline of the no. 7 (22M) longitudinal tie bars is placed 2.13 in. (54 mm) from the top of the foundation, satisfying the requirement that it not be placed closer to the transverse (horizontal) legs of the U bars than the center half of the U-bar bend. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.13 in. (29 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 6 [19M] U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.13 in. – 1.13 in. = 1.0 in. (25 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.0 in. < (1.5)(4.63 in.) = 6.95 in. (177 mm) OK

h_{wp} = (1.5)(4.63 in.) ≥ $0.5\sqrt{4.0^2 + 4.63^2}$ in. + 1.0 in.

h_{wp} = 6.95 in. ≥ 4.06 in.

therefore, h_{wp} = 6.95 in. (177 mm)

$A_{lt} = \left(0.32 \le \dfrac{0.75 \times 4.0}{6.95 - 1.0} \le 1.5\right)$ × 1.56 in.^{2} = (0.32 ≤ 0.51 ≤ 1.5)(1.56 in.^{2}) = (0.51)(1.56 in.^{2}) = 0.79 in.^{2} (510 mm^2)

Use one layer of no. 6 (19M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (2)(0.44 in.^{2}) = 0.88 in.^{2} (568 mm^2).

The centerline of the no. 6 (19M) longitudinal tie bars is placed 2.06 in. (52 mm) from the top of the foundation, satisfying the requirement that it not be placed closer to the transverse legs of the U bars than the center half of the U-bar bend. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.13 in. (29 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 6 U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.06 in. – 1.13 in. = 0.94 in. (24 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.0 in. < (1.5)(4.63 in.) = 6.95 in. (177 mm) OK

$$h_{wp} = (1.5)(4.63\text{ in.}) \geq 0.5\sqrt{4.0^2 + 4.63^2}\text{ in.} + 0.94\text{ in.}$$

$$h_{wp} = 6.95\text{ in.} \geq 4.0\text{ in.}$$

therefore, h_{wp} = 6.95 in. (177 mm)

$$A_{lt} = \left(0.32 \leq \frac{0.75 \times 4.0}{6.95 - 0.94} \leq 1.5\right) \times 1.56\text{ in.}^2 = (0.32 \leq 0.5 \leq 1.5)(1.56\text{ in.}^2) = (0.5)(1.56\text{ in.}^2) = 0.78\text{ in.}^2\ (503\text{ mm}^2)$$

Selection of one layer of no. 6 (19M) bars is valid. Therefore, $A_{lt,provided}$ = (2)(0.44 in.^{2}) = 0.88 in.^{2} (568 mm^2).

Connection length is calculated using Eq. (18).

$$l_{ED} = C + 0.5 \times d_U + h_{wp} + l'_b$$

C = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = 0.75 in. (19 mm) for no. 6 (19M) bars

h_{wp} = 6.95 in. (177 mm)

l'_b = $12d_{ED}$ = (12)(1.41 in.) = 16.9 in. (429 mm) for no. 11 (36M) bars

$$l_{ED} = 0.75\text{ in.} + (0.5)(0.75\text{ in.}) + 6.95\text{ in.} + 16.9\text{ in.}$$

$$l_{ED} = 25.0\text{ in.}$$

therefore, use l_{ED} = 25 in. (635 mm)

Connections in the wall panel

The design of the connections in the wall panel (**Fig. 11**) is similar to the design of the connections in the foundation.

The area of energy-dissipation bars in each layer across the wall thickness (from original wall design) A_{ED} = (1)(1.56 in.^{2}) = 1.56 in.^{2} (1007 mm^2).

Use Eq. (2) to calculate the area of vertical tie reinforcement $A_{vt} = A_{ED}$ = 1.56 in.^{2} (1007 mm^2).

Use one no. 6 (19M) U bar on each side of each connection layer. Therefore, $A_{vt,provided}$ = (4)(0.44 in.^{2}) = 1.76 in.^{2} (1136 mm^2).

The area of transverse tie reinforcement is calculated using Eq. (3). Design of transverse tie reinforcement is automatically satisfied and thus does not need to be checked due to the use of U bars as both vertical and transverse tie reinforcement.

Use Eq. (12) to calculate the area of longitudinal tie reinforcement $A_{lt} = \left(0.32 \leq \frac{0.75 \times X}{h_{wp} - S_{c,UL}} \leq 1.5\right) \times A_{ED}$.

X = 4.0 in. (102 mm)

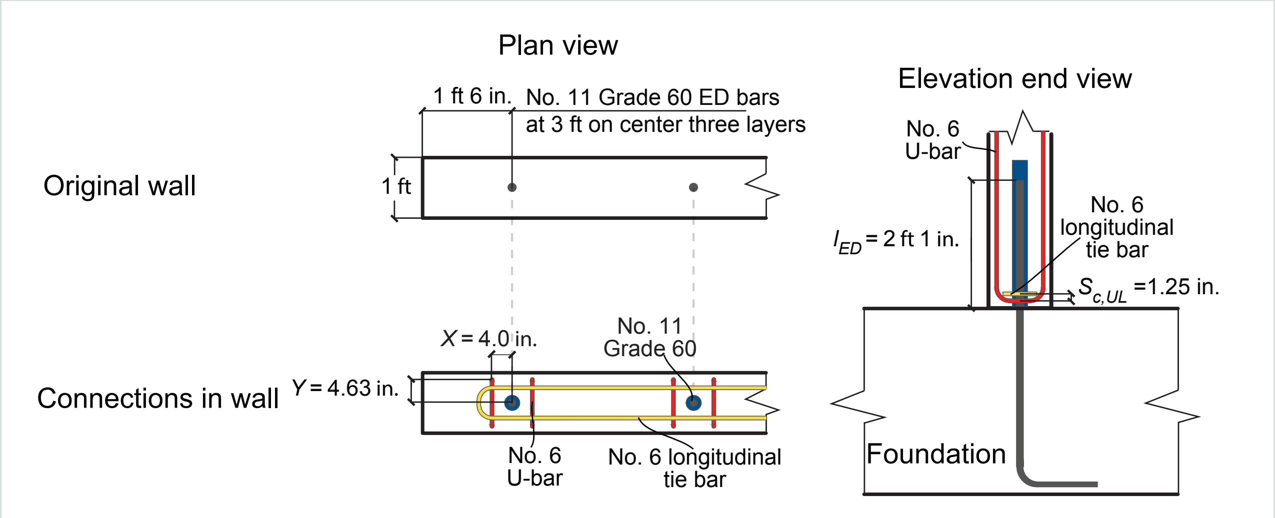

Figure 11. Example 5, connections in the wall panel. Note: ED = energy dissipation; l_{ED} = length of energy-dissipation bar inside connection duct; $S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement; X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction; Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction. No. 6 = 19M; no. 11 = 36M. 1 in. = 25.4 mm; 1 ft = 0.305 m; Grade 60 = 414 MPa.

Y = 4.63 in. (118 mm)

$S_{c,UL}$ = 2.5 in. (64 mm), first iteration

Use Eq. (17) to calculate the height of the work point h_{wp}.

check constraint: $S_{c,UL} < 1.5 \times Y$

2.5 in. < (1.5)(4.63 in.) = 6.95 in. (177 mm) OK

$$h_{wp} = 1.5 \times Y \geq 0.5\sqrt{X^2 + Y^2} + S_{c,UL}$$

$$h_{wp} = (1.5)(4.63 \text{ in.}) \geq 0.5\sqrt{4.0^2 + 4.63^2} \text{ in.} + 2.5 \text{ in.}$$

$$h_{wp} = 6.95 \text{ in.} \geq 5.56 \text{ in.}$$

therefore, h_{wp} = 6.95 in. (177 mm)

$$A_{lt} = \left(0.32 \leq \frac{0.75 \times 4.0}{6.95 - 2.5} \leq 1.5\right) \times 1.56 \text{ in.}^2 = (0.32 \leq 0.67 \leq 1.5)(1.56 \text{ in.}^2) = (0.67)(1.56 \text{ in.}^2) = 1.05 \text{ in.}^2 \text{ (677 mm}^2\text{)}$$

Use one layer of no. 7 (22M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (2)(0.6 in.^{2}) = 1.2 in.^{2} (774 mm^2).

The centerline of the no. 7 (22M) longitudinal tie bars is placed 2.56 in. (65 mm) from the top of the foundation, satisfying the requirement that it not be placed closer to the transverse (horizontal) legs of the U bars than the center half of the U-bar bend. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.13 in. (29 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 6 [19M] U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.56 in. – 1.13 in. = 1.44 in. (37 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.0 in. < (1.5)(4.63 in.) = 6.95 in. (177 mm) OK

h_{wp} = (1.5)(4.63 in.) ≥ $0.5\sqrt{4.0^2+4.63^2}$ in. + 1.44 in.

h_{wp} = 6.95 in. ≥ 4.5 in.

therefore, h_{wp} = 6.95 in. (177 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75\times 4.0}{6.95-1.44} \le 1.5\right) \times 1.56\text{ in.}^2 = (0.32 \le 0.55 \le 1.5)(1.56\text{ in.}^2) = (0.55)(1.56\text{ in.}^2) = 0.85\text{ in.}^2\ (548\text{ mm}^2)$$

Use one layer of no. 6 (19M) bars for the longitudinal tie reinforcement. Therefore, $A_{lt,provided}$ = (2)(0.44 in.^{2}) = 0.88 in.^{2} (568 mm^2).

The centerline of the no. 6 (19M) longitudinal tie bars is placed 2.38 in. (61 mm) from the top of the foundation, satisfying the requirement that it not be placed closer to the transverse legs of the U bars than the center half of the U-bar bend. The transverse legs of the U bars are placed with minimum concrete cover of 0.75 in. (19 mm) from the top of the foundation, resulting in a centroid location of 1.13 in. (29 mm) for these bars from the top of the foundation (0.75 in. plus half the diameter of the no. 6 U bar). Then, $S_{c,UL}$ can be updated as follows:

$S_{c,UL}$ = centroid of the longitudinal tie reinforcement – centroid of the transverse tie reinforcement
= 2.38 in. – 1.13 in. = 1.25 in. (32 mm)

Recalculate h_{wp} and A_{lt} as follows:

1.0 in. < (1.5)(4.63 in.) = 6.95 in. (177 mm) OK

h_{wp} = (1.5)(4.63 in.) ≥ $0.5\sqrt{4.0^2+4.63^2}$ in. + 1.25 in.

h_{wp} = 6.95 in. ≥ 4.31 in.

therefore, h_{wp} = 6.95 in. (177 mm)

$$A_{lt} = \left(0.32 \le \frac{0.75\times 4.0}{6.95-1.25} \le 1.5\right) \times 1.56\text{ in.}^2 = (0.32 \le 0.53 \le 1.5)(1.56\text{ in.}^2) = (0.53)(1.56\text{ in.}^2) = 0.82\text{ in.}^2\ (529\text{ mm}^2)$$

Selection of one layer of no. 6 (19M) bars is valid. Therefore, $A_{lt,provided}$ = (2)(0.44 in.^{2}) = 0.88 in.^{2} (568 mm^2).

Connection length is calculated using Eq. (18).

l_{ED} = $C + 0.5 \times d_U + h_{wp} + l'_b$

C = 0.75 in. (19 mm), assuming minimum concrete cover

d_U = 0.75 in. (19 mm) for no. 6 (19M) bars

h_{wp} = 6.95 in. (177 mm)

l'_b = $12d_{ED}$ = (12)(1.41 in.) = 16.9 in. (429 mm) for no. 11 (36M) bars

l_{ED} = 0.75 in. + (0.5)(0.75 in.) + 6.95 in. + 16.9 in.

l_{ED} = 25.0 in. ≥ 22.1 in.

therefore, use l_{ED} = 25 in. (635 mm)

References

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2. ACI (American Concrete Institute) Committee 318. 2019. *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)*. Farmington Hills, MI: ACI.

3. ASTM Subcommittee A01.05. 2016. *Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement*. ASTM A706/A706M. West Conshohocken, PA: ASTM International.

Notation

A_{ED} = total area of energy-dissipation bar or bars in one layer across thickness of wall cross section

A_{lt} = total required area of longitudinal tie reinforcement to transfer tension force in A_{ED}

$A_{lt,provided}$ = total provided area of longitudinal tie reinforcement

A_{tt} = total required area of transverse tie reinforcement to transfer tension force in A_{ED}

A_{vt} = total required area of vertical tie reinforcement to transfer tension force in A_{ED}

$A_{vt,provided}$ = total provided area of vertical tie reinforcement

C = clear vertical cover to U bars

d_{ED} = diameter of energy-dissipation bar

d_U = diameter of U bar

h_{wp} = height of strut-and-tie model work point measured from center of transverse tie (horizontal leg of U bar) projected onto energy-dissipation bar

l'_b = prescribed minimum grouted bond length extension (beyond strut-and-tie model work point) of 9 times bar diameter for no. 7, 8, and 9 (22M, 25M, and 29M) energy-dissipating bars and 12 times bar diameter for no. 10 and 11 (32M and 36M) bars

l_{ED} = length of energy-dissipation bar inside connection duct

$S_{c,UL}$ = vertical distance between center of transverse tie bar (horizontal leg of U bar) and centroid of longitudinal tie reinforcement

X = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall length direction

Y = horizontal distance between center of energy-dissipation reinforcing bar and center of vertical tie bar (vertical leg of U bar) in wall thickness direction

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Abstract

This paper presents five worked-out examples on the design of precast concrete shear walls using new non-proprietary short-grouted ductile reinforcing bar connections. The examples are based on precast concrete shear wall details with conventional energy-dissipation (yielding flexural) reinforcing bar connections provided by precast concrete industry partners. The focus of the design examples is to demonstrate the calculations for the connection length and the vertical, transverse, and longitudinal tie reinforcement areas around the connection ducts.

Keywords

Energy-dissipation bar, mechanical grouted connection, reinforcing bar connector, special shear wall, strut-and-tie design model.

Review policy

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