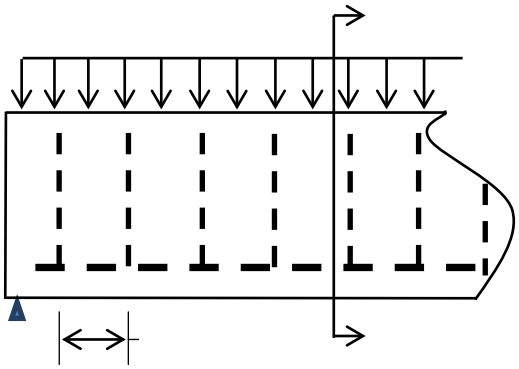
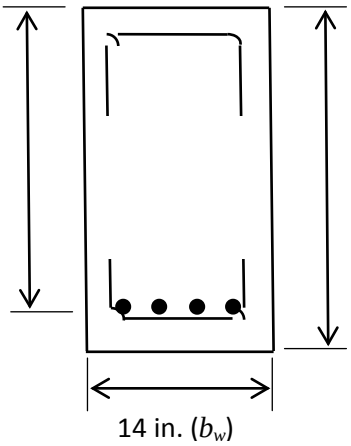
Reinforced concrete beam using externally-bonded carbon fabric





Beam Loading: ω_{DL} = 2.75 k/ft ; ω_{LL}^{e} = 1.0 k/ft; ω_{LL}^{n} = 1.60 k/ft; L = 25 ft.

Check Min. Shear Reinforcement: $A_{v,min} = 0.75 (f_c')^{1/2} b_w / f_y \geq 50 b_w s / f_y$ (ACI 318-14, Sec. 9.6.3.1 & 9.6.3.3)

$A_{v,min}$ = 50 (14 in.) 12 in. / 60,000 psi = 0.14 sq. in.

$A_{v,prov}$ = 2 (0.11 sq. in.) = 0.22 sq. in. ≥ $A_{v,min}$ = 0.14 sq. in. (Criteria satisfied)

Check Max. Stirrup Spacing: $s_{max} = d/2 \leq$ 24 in. (ACI 318-14, Sec. 9.7.6.2.2)

s_{max} = 24 in. / 2 = 12 in.

When….. $V_s \leq 4 (f_c')^{1/2} b_w d$

V_s = 26.4 k ≤ 4 (4000)$^{1/2}$ 14 in. (24 in.) / 1000 lbs./k = 85 k (Criteria satisfied)

Check Strengthening Limits:

Physical Damage: $\phi R_{n,\,exist.} \geq 1.1D + 0.75L$ (ACI 562-16, Sec. 5.5.2)

$(\phi R_{n,\,exist.} \geq 1.1D + 0.5L + 0.2S)$

$\phi R_{n,\,exist.} = \phi V_{n,\,exist.} = \phi (V_c + V_s)$; where $V_c = 2 (f_c')^{1/2} b_w d$; $V_s = A_v f_y d / s$

V_c = 2 (4000 psi)$^{1/2}$ 14 in. (24 in.) / 1000 lbs./k = 42.5 k

V_s = 0.22 sq. in.(60,000 psi) 24 in./ 12 in.(1000 lbs./k) = 26.4 k

$\phi V_{n,\,exist.}$ = 0.75 (42.5 k + 26.4 k) = 51.7 k

1.1 DL + 0.75 LL = 1.1 (2.75 k/ft.) + 0.75 (1.6 k/ft.) = ω_u = 4.23 k/ft.

$V_{u\ @\ x\,=\,d} = \omega_u (L) / 2 - \omega_u (x)$ (ACI 318-14, Sec. 9.4.3.2)

$V_{u\ @\ x\,=\,d}$ = (4.23 k/ft.) 25 ft./ 2 – (4.23 k/ft/) 2 ft. = 44.4 k

$\phi V_{n,\,exist.}$ = 51.7 k ≥ $V_{u\ @\ x\,=\,d}$ = 44.4 k (Criteria satisfied)

Fire Endurance: $\phi_{ex}\, R_{exist.} \geq (0.9 \text{ or } 1.2)D + 0.5L + 0.2S$; ϕ_{ex} = 1.0 (ACI 562-16, Sec. 5.5.3)

To account for potential performance issues during a fire event. Equation to be applied by Design Professional as required by the Project conditions.

FRP Properties for **C**ode-listed, **U**nidirectional, **C**arbon **F**abric: CSS – CUCF (11 oz./sq. yd.)

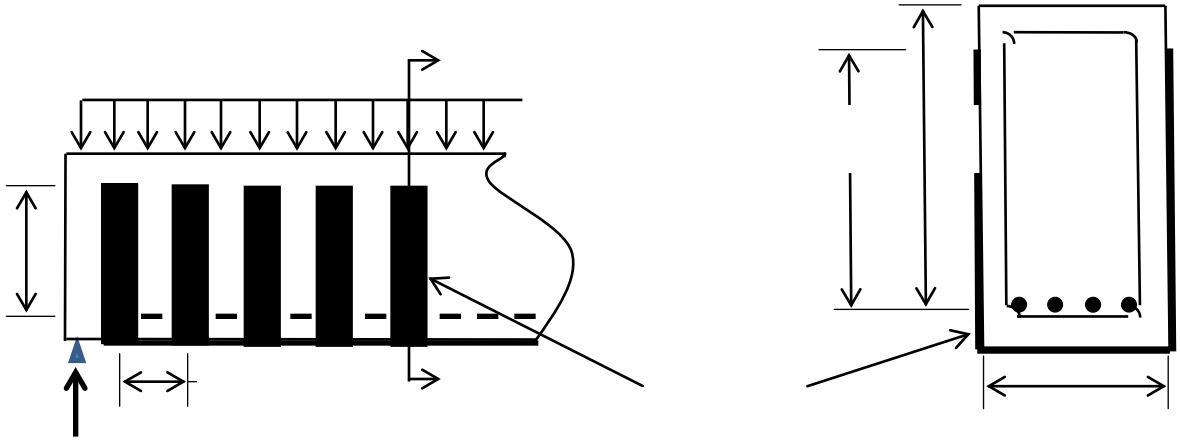
t_f = thickness per ply of FRP composite = 0.02 in./ply

f_{fu}^{*} = ultimate tensile stress in FRP composite = 128 ksi

ε_{fu}^{*} = ultimate tensile strain at FRP rupture (elongation @ break) = 0.009 in./in.

E_f = tensile Modulus of Elasticity (MOE) of FRP composite = 14,200 ksi

FRP Environmental Reduction Factor: C_E = 0.85 (Carbon Fabric and Exterior Exp.) (ACI 440.2R-17, Table 9.4)



FRP Design Properties: (ACI 440.2R-17, Sec. 9.4)

$f_{fu} = C_E\, f_{fu}^{*}$ = (0.85) 128,000 psi = 108,800 psi

$\varepsilon_{fu} = C_E\, \varepsilon_{fu}^{*}$ = (0.85) 0.0090 in./in. = 0.0077 in./in.

$A_{fv} = 2\, n\ t_f\ w_f$ = 2 (1) 0.02 in. (6 in.) = 0.24 sq. in.

$\rho_f = A_f / b\, d$ = 0.96 sq. in. / 14 in. (24 in.) = 0.0029

Determine Max. FRP U-Wrap Spacing: $s_{max} = d/2 \le 24$ in.; when $V_s \le 4 (f_c')^{1/2} b_w d$ (ACI 318-14, Sec. 9.7.6.2.2)

s_{max} = (24 in. / 2) = 12 in.

Determine Max. Usable Effective FRP Strain (U-Wraps): $\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \le 0.004$ (ACI 440.2R-17, Sec. 11.4.1.2)

$\kappa_v = k_1 k_2 L_e / 468\, \varepsilon_{fu}$ (Bond-Reduction Coefficient)

$L_e = 2500 / (n\ t_f\ E_f)^{0.58}$ (Active Bond Length)

L_e = 2500 / [1 (0.02 in.) 14.2 x 10^6 psi] $^{0.58}$ = 1.72

$k_1 = (f_c'/4000)^{2/3}$ (Modification Factor)

$k_1 = (4000/4000)^{2/3}$ = 1

$k_2 = (d_{fv} - L_e) / d_{fv}$ (Modification Factor)

k_2 = (21 in. – 1.72) / 21 in. = 0.918

κ_v = 1 (0.918) 1.72 / 468 (0.0077) = 0.438

ε_{fe} = 0.438 (0.0077) = 0.0034 ≤ 0.004

Effective Stress in FRP: $f_{fe} = \varepsilon_{fe} E_f$ (ACI 440.2R-17, Sec. 11.4)

f_{fe} = 0.0034 (14,200 ksi) = 48.3 ksi

FRP Shear Strength Contribution: $V_f = \dfrac{A_{fv} f_{fe} (\sin\alpha + \cos\alpha) d_{fv}}{s_f}$ (ACI 440.2R-17, Sec. 11.4)

V_f = 0.24 sq. in. (48.3 ksi) 1 (21 in.) / 12 in. = 20.3 k

Calculate Shear Design Strength Including FRP: $\phi V_n^{w/FRP} = \phi (V_c + V_s + \Psi_f V_f)$ (ACI 440.2R-17, Sec. 11.3)

V_c = 42.5 k; V_s = 26.4 k V_f = 20.3 k

ϕ = 0.75 (ACI 318-14, Sec. 21.2.1)

Ψ_f = 0.85 (Additional reduction factor for FRP shear strengthening)

$\phi V_n^{w/FRP}$ = 0.75 (42.5 k + 26.4 k + [0.85] 20.3 k) = 64.6 k

Check Shear Design Strength against Max. Factored Shear Force:

1.2 DL + 1.6 LL = 1.2 (2.75 K/ft.) + 1.6 (1.6 K/ft.) = ω_u = 5.86 K/ft.

$V_{u\ @\ x = d} = \omega_u (L) / 2 - \omega_u (x)$ (ACI 318-14, Sec. 9.4.3.2)

$V_{u\ @\ x = d}$ = (5.86 k/ft.) 25 ft./ 2 – (5.86 k/ft/) 2 ft. = 61.5 k

$\phi V_n^{w/FRP}$ = 64.6 k ≥ V_u = 61.5 k (Criteria satisfied)

Shear Strengthening Limits: $V_s + V_f \leq 8 (f_c')^{1/2} b_w d$ (ACI 440.2R-17, Sec. 11.4.3)

26.4 k + 20.3 k = 46.7 k ≤ 8 (4000 psi)$^{1/2}$ 14 in. (24 in.)/1000 lbs./k = 170 k (Criteria satisfied)

Longitudinal Beam Length Requiring FRP U-Wrap Reinforcements: ≈ 48 in. (5 U-Wraps ea. end)