STABL WALL Design Manual

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Address:
349 Highland Road
Macedonia, OH 44056

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1. INTRODUCTION

STABL WALL FRP composite systems can be used to strengthen unreinforced masonry wall for out of plane loads. The equations in this report are based on the minimum acceptable design criteria given in the Acceptance Criteria of Concrete and Reinforced and unreinforced Masonry Strengthening Using Externally Bonded Fiber Reinforced Polymer (FRP) Composite Systems (ICC-ES AC125).

2. Definition of Terms

Δ = displacement (in)
ε_f = strain in FRP (in/in)
ε_{fu} = ultimate strain of FRP (in/in)
ε_{fe} = effective strain in the FRP (in/in)
ε_{fd} = debonding strain of externally bonded FRP reinforcement (in/in)
ψ_f = FRP reduction factor
A_{fv} = area of FRP Shear reinforcement with spacing "s" (in^2)
A_n = net area of masonry wall (in^2)
C_E = environmental durability reduction factor
E_f = modulus of elasticity of FRP (ksi)
E_c = modulus of elasticity of concrete (psi)
f_{fe} = effective stress in the FRP (psi)
f'_m = masonry compressive strength (psi)
f_{fu} = guaranteed ultimate FRP stress (psi)
f_y = yield strength of steel reinforcement (ksi)

3. General Design Procedures

3.1. Material Properties

The tensile properties of STABL WALL FRP composite system are summarized in Table 1.

Table 1 Guaranteed Tensile Properties

Name	Description	FRP Composite Thickness (in.)	Guaranteed Tensile Strength f_{fu}^* (ksi)	Ultimate Tensile Strain (%)	Modulus of Elasticity (ksi)
STABL WALL FRP	Uniaxial Carbon Fiber Reinforced Polymer System	.040	152	1.36	11,170

3.2. Design Tensile Properties

The material properties of the FRP reinforcement reported by manufactures, such as the ultimate tensile strength, typically do not consider long-term exposure to environmental conditions, and should be considered as initial properties. FRP properties to be used in all design equations are given as follows (ACI 440.1R-15)

$$f_{fu} = C_E f_{fu}^* \quad (1)$$

$$\varepsilon_{fu} = C_E \varepsilon_{fu}^* \quad (2)$$

Where f_{fu} and ε_{fu} are the FRP design tensile strength and ultimate strain factored by the environmental reduction factor (C_E) as given in Table 2 below. (ACI 440.1R-15), and f_{fu}* and ε_{fu}* represent the FRP guaranteed tensile strength and ultimate strain as reported by STABL WALL.

Table 2 Environmental Reduction Factors

Exposure Conditions	Fiber Type	Environmental reduction factor, C_E
Interior Exposure	Carbon	.95
Exterior Exposure (including internal side of exterior walls)	Carbon	.85
Aggressive environment (basement walls)	Carbon	.85

3.3. Creep Rupture (AC125, Section 7.3.2.1.2)

Under sustained loads, a material may suddenly fail after a time period called the endurance time; this phenomenon is known as creep rupture. To prevent this type of failure the allowable sustained stress on the CFRP should be limited to 55% of its ultimate capacity (f_{fu}).

Table 3 Creep Rupture Reduction Factors

Stress Type	Fiber Type	Allowable Stress (%f_{fu})
Creep Rupture	Carbon	55

4. Masonry Wall Strengthening for Out-of-Plane Loading

4.1 Flexural Design

Fiber-reinforced polymer (FRP) composite materials boded to surfaces of masonry may be used to enhance the design flexural strength of sections by acting as additional tension reinforcement. The following design provisions can be followed to calculate the capacity of the existing masonry wall.

The following failure modes may be considered.

1. Crushing of the masonry in compression
2. FRP debonding
3. Rupture of the FRP

Checks must be done to ensure that the strain in the member is at least as high as what is assumed in design. Fibers shall not have a misalignment of more than 5 degrees.

Dependable flexural strengths shall be determined by multiplying the nominal flexural strength by the appropriate flexural strength reduction factor according to the IBC. Design moment capacity for flexure shall be calculated in accordance with Equation 3

$$\emptyset M_n = \emptyset\left(M_s + M_f\right) \qquad (3)$$

Where M_s is the strength of the existing reinforced wall (note that for unreinforced masonry M_s is 0) and M_f is the capacity of the wall strengthened with FRP.

4.2 Flexural Strength Enhancement of Masonry Elements (AC125, Section 7.3.2.2)

The flexural strength of a masonry element strengthened with FRP shall be based on the assumptions presented in Section 4.1 of this document. The effective strain in the FRP reinforcement shall be limited to the strain level at which debonding may occur as defined in equation 4 below. Equation 5 the corresponding stress in the FRP.

$$\varepsilon_{fe} = .45\varepsilon_{fu} \qquad (4)$$

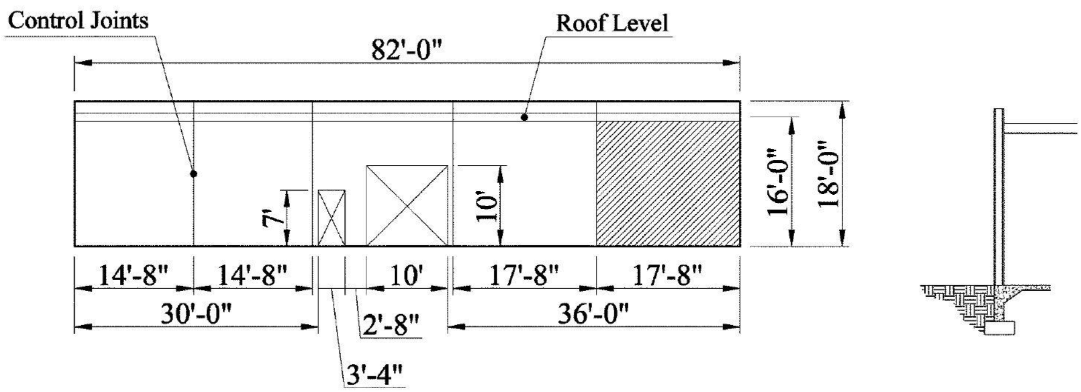
$$f_{fe} = E_f \varepsilon_{fe} \qquad (5)$$

The force per unit width provided by the FRP shall be determined from Equation 6 shown below.

$$\rho_{fm} = n t_f f_{fe} \leq 1500 lb/in \qquad (6)$$

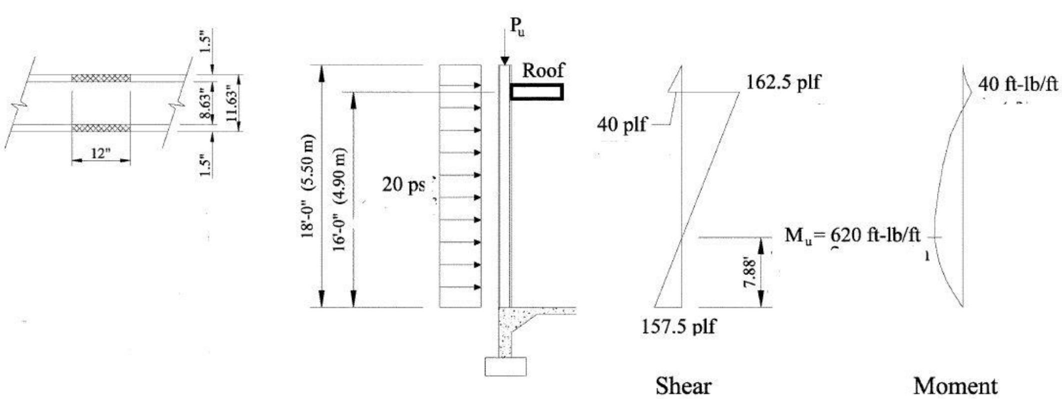
5. Design Example

The following design example has been taken from ACI 440.7R-10 and is applicable for the STABL WALL CFRP system. An 82’ long building with an 18’ height and 16’ tall roof level shall be strengthened to resist the applicable bending moment. Figure X below provides an illustration of the building and Figure X shows the wall dimensions and the shear and moment diagrams.



(a) Elevation view (b) Section

Figure 1 Building Illustration



(a) Wall thickness (b) Shear and bending moment diagrams

Figure 2 Wall Thickness and Shear and Moment Diagrams

The ungrotuted masonry wall is 12” nominally thick using Type N mortar. Table 4 below summarizes the geometrical and mechanical properties of the all and Table 5 Summarizes the mechanical properties of the STABL WALL system. For this example the axial loading will be ignored which is not uncommon and is conservative.

Table 4 Wall Properties

Height H	18'
Wall Thickness t	11.63"
Section area A_n	36 in^2/ft
Section Modulus S	160 in^3/ft
f'_m	1500 psi
ε_{mu}	.0025

Table 5 CFRP Properties

Ultimate Strength f_{fu}^*	152ksi
Modulus of Elasticity E_f	11,170ksi
Ultimate Strain ε_{fu}^*	.0136
Thickness t_f	.040"

Assume that a 6" wide strap will be used at 32" o.c. First check to see if reinforcing is required.

If f_b is greater than ϕf_r then the wall will need to be strengthened. Where f_r is 20psi and ϕ is .6.

$$f_b = \frac{M_u}{S} - \frac{P_u}{A_n} = \frac{620 * 12}{160} - \frac{0}{A_n} = 46.5psi$$
$$\emptyset f_r = .6 * 20 = 12psi$$

f_b is greater than ϕf_r therefore the wall will need to be strengthened.

Assuming that the failure mode will be debonding the effective stress in the FRP will be 45% of the guaranteed strength.

$$f_{fe} = .45 f_{fu}{}^* = .45 * 152{,}000 = 68{,}400psi$$

f_{fe} cannot be larger than f_{fu}

$$f_{fu} = C_E f_{fu}{}^* = .95 * 152{,}000 = 144{,}400psi$$

f_{fe} is less than f_{fu} therefore the stress in the reinforcing (f_f) is equal to the effective stress.

The force per unit width must be less than 1500 lb/in and is defined below

$$\rho_{fm} = nt_f f_{fe} = 1 * .04 * 68{,}400 = \frac{2{,}736lb}{in}$$
$$\rho_{fm} > 1500 \xrightarrow{yields} f_{fe} \leq \frac{1500}{nt_f} = \frac{1500}{1 * .04} = 37{,}500psi$$

Using 6” wide straps with a thickness of .04” at 32” o.c. results in an FRP area of

$$A_f = 6"*.04" * \frac{12"}{32"} = .09\,in^2/ft$$

The maximum spacing shall not exceed 3 times the wall thickness (t) plus the width of the strap (b_f)

$$s_{f,max} < 3t + b_f = 3 * 11.63 + 6 = 40.9in$$

The chosen spacing is 32” which is less than $s_{f,max}$ so this is acceptable.

Using force equilibrium the tension from the FRP has to equal the compression in the masonry.

$$\sum F = 0 = T - C \xrightarrow{yields} T = C$$

$$T = A_f f_{fe} = .09\,in^2/ft * 37{,}500psi = 3{,}375lb$$

$$C = \gamma f_m{}' \beta_1 c b_w \xrightarrow{yields} c = \frac{C}{\gamma f_m{}' \beta_1 b_w}$$

With γ=.7, β_1=.7 and C=T=3,375lb

$$c = \frac{3{,}375}{.7 * 1500 * .7 * 12} = .383"$$

Summing forces around the compression force results in the following equation for the nominal Moment (M_n).

$$M_n = A_f f_f \left(d_f - \frac{\beta_1 c}{2}\right) + P_u \left(\frac{t}{2} - \frac{\beta_1 c}{2}\right)$$

With d_f equal to the thickness of the wall and P_u = 0, the nominal moment capacity of the wall is

$$M_n = .09 * 37{,}500 \left(11.63 - \frac{.7 * .383}{2}\right) = 38{,}799\ k - in = 3.233\ k - ft$$

The ϕ factor is set at .6 the reduced nominal capacity

$$\emptyset M_n = .6 * 3.233 = 1.94\ k - ft$$

Since ϕM_n is greater than the demand moment (M_u) the design is acceptable.

$$M_n = 1.94k - ft > .62k - ft = M_u$$

The assumption was made that the FRP debonding controlled the design and needs to be checked. In order for that to be true the strain in the masonry must be less than its’ ultimate strain (ε_{mu}) when the FRP achieves its' debonding strain (ε_{fe}). The debonding strain is defined below.

$$\varepsilon_{fe} = \frac{f_{fe}}{E_f} = \frac{37500}{11170000} = .00336$$

$$\varepsilon_m = \frac{\varepsilon_{fe}}{d_f - c} c = \frac{.00336}{11.63 - .383} .383 = .00011$$

The calculated strain in the masonry is much less than the ultimate strain

5. REFERENCES

ACI 440.7R-10 "Guide for the Design and Construction of Externally Bonded Fiber-Reinforced Polymer Systems for Strengthening Unreinforced Masonry Structures", Published by the American Concrete Institute, Farmington Hills, MI.

AC125 "Acceptance Criteria for Concrete and Reinforced and Unreinforced Masonry Strengthening Using Externally Bonded Fiber-Reinforced Polymer (FRP) Composite Systems", Published by ICC Evaluation Service, Brea, CA.