APPENDIX F: Guidelines for NDC Retrofits Using FRP

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1.0 INTRODUCTION

Fiber-Reinforced Polymer (FRP) is a composite material made up of a polymer matrix reinforced with fibers, such as resin epoxy and carbon, respectively. It may be used to strengthen and repair structural elements in existing buildings where a like-for-like replacement would otherwise be difficult to achieve.

The intent of this Appendix is to provide guidelines for the use of FRP in non-ductile concrete buildings subject to the City's Seismic Retrofit Ordinance No. 17-1011 and Chapter 13.36 of the West Hollywood Municipal Code. These guidelines outline the best practices that contribute to an effective retrofit utilizing FRP. In order to meet the intent and requirements of the City of West Hollywood Ordinance, an adequate retrofit scheme must be followed to ensure it is completed in accordance with the Seismic Design Guidelines, the Building Code, and applicable Codes, Standards, and References. FRP products utilized for a retrofit design shall have an approved agency testing document, such as an ICC-ES or IAPMO Evaluation Report or approved equivalent, to verify compliance with the applicable Building Codes and standards. For documents other than ICC-ES or IAPMO Evaluation Reports, the approval agency shall provide all information necessary for the Building Official to verify compliance with the requirements presented in Section 14.0 of this Appendix, Material Strengths and Pre-Production Qualifications.

The guidelines provided in this Appendix are intended only for the use of retrofits in non-ductile concrete buildings and shall not be used for any other purpose, unless approved by the Building Official. In the case of buildings with mixed structural systems that include masonry in addition to non-ductile concrete, the retrofit design shall adhere to Section 5.3, Alternative Methods of Compliance, of the Seismic Design Guidelines. The design principles presented in this Appendix may be used as a basis for such purposes.

2.0 CODES AND STANDARDS

2.1 ACI 318-19 (ACI 318), Building Code Requirements for Structural Concrete and Commentary.

2.2 ACI 369.1-22 (ACI 369.1), Standard Requirements for Seismic Evaluation and Retrofit of Existing Concrete Buildings and Commentary.

2.3 ASCE/SEI 41-17 (ASCE 41), Seismic Evaluation and Retrofit of Existing Buildings.

2.4 ASCE/SEI 41-23 (ASCE 41-23), Seismic Evaluation and Retrofit of Existing Buildings.

2.5 ANSI/AISC 360-10, Specification for Structural Steel Buildings, June 22, 2010.

2.6 2019 California Building Code, Title 24, Part 2 (Volumes 1 & 2).

3.0 REFERENCES

3.1 Ordinance No. 17-1011, An Ordinance of the city of West Hollywood Establishing Seismic Strengthening Requirements for Two Categories of Existing Buildings in the City and Amending Titles 13 and 9 of the West Hollywood Municipal Code, August 2017.

3.2 Seismic Design Guidelines, Mandatory Retrofit Program for Non-Ductile Concrete Buildings and Pre-Northridge Steel Moment Frame Buildings, November 2019,

3.3 IAPMO Uniform ES EC 038, Evaluation Criteria for Diaphragm Strengthening Using Fiber Reinforced Polymers, September 2019.

3.4 ICC Acceptance Criteria for Inspection and Verification of Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fiber-Reinforced Polymer (FRP) Composite Systems, AC178, June 2008, editorially revised December 2017.

3.5 ACI 440.2R-23 (ACI 440.2), Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, October 2008.

3.6 FEMA 306, Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, May 1999.

4.0 DEFINITIONS

Symbols

ε_{fe}	=	Effective strain in FRP reinforcement attained at failure, in./in.
κ	=	Knowledge factor per ASCE 41, Section 6.2.4
λ	=	Lightweight concrete reduction factor
λ_A	=	Dry fiber weight of an FRP anchor per unit length, oz./in.
π	=	Pi constant
ψ_f	=	FRP reduction factor, as defined in Table 8-1 of this Appendix
ρ_t	=	Ratio of area of distributed transverse reinforcement to gross concrete area perpendicular to that reinforcement, per ASCE 41
ϕ	=	Strength reduction factor per ASCE 41
ω_v	=	Dynamic shear amplification factor for evaluating maximum wall shear demand in linear analysis procedures
γ	=	Load factor from ASCE 41, Table 7-8
$\Upsilon_{s,Exp}$	=	Dry fiber weight of laminate per square surface area, oz./in.
χ	=	A factor for adjusting action caused by response for the selected performance level
A		
A_{Eqv}	=	Equivalent anchor laminate area, in^2
A_f	=	Area of FRP reinforcement, in^2
A_g	=	Gross area of column, in^2, per ASCE 41, Eq. (10-3)
A_v	=	Area of shear reinforcement within spacing, s, in^2
ACI 369.1^M	=	ACI 369.1-22 as modified by ASCE 41-23 Section 10.3
Anchor	=	Any anchor used to attach FRP to concrete: FRP Anchor, FRP splice anchor, or anchors *other than* embedded fiber anchors bonded through FRP adhesives, such as conventional post-installed anchors bonded to FRP through other means
B		
b	=	Width of compression face of member, in.
b_w	=	Web width or diameter of circular section, in.

C

c_{nl}	=	Parameter used to measure residual strength
c'_{nl}	=	Parameter used to measure maximum strength

D

d	=	Distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in.
d_{fv}	=	Effective depth of FRP shear reinforcement, in., per ACI 440.2
d_{nl}	=	Parameter used to measure deformation capacity
d'_{nl}	=	Parameter used to measure deformation capacity

E

E_f	=	Design tensile modulus of elasticity of FRP, ksi. Provided by the FRP vendor based on experimental testing, which can reliably be achieved in the field
E_s	=	Modulus of elasticity of reinforcement steel, ksi
e_{nl}	=	Parameter used to deformation capacity

F

F_y	=	Steel yield strength using expected or lower-bound material properties, as applicable for deformation-controlled or force-controlled actions, respectively, ksi
F_{yE}	=	Steel yield strength using expected material properties, ksi
F_{yL}	=	Steel yield strength using lower-bound material properties, ksi
f_{anc}	=	Ultimate design tensile strength of an anchor, kip
f'_c	=	Concrete compressive strength using expected or lower-bound material properties, as applicable for deformation-controlled or force-controlled actions, respectively, psi
f'_{cE}	=	Concrete compressive strength using expected material properties, psi
f'_{cL}	=	Concrete compressive strength using lower-bound material properties, psi
f_{fe}	=	Effective stress in FRP; stress attained at section failure, ksi
f_{fu}	=	Ultimate design tensile strength of FRP, ksi
Fiber Splice Anchor	=	An FRP anchor used to transfer the strength from one FRP laminate through an obstacle, such as walls, slabs, or beams, to another FRP laminate
FRP Anchor	=	Manufacturer-specific, fiber-reinforced polymer anchor designed to be partially or fully laminated with epoxy in the field

G

g_{nl}		Parameter used to measure deformation capacity

H

h_{FRP}	=	Effective depth of FRP, in.
h_n	=	Structural height from the base to the highest level of the seismic force-resisting system of the structure, ft, where the base level is the level at which the horizontal earthquake ground motions are considered to be imparted to the structure.
h_{wcs}	=	Height of entire structural wall above the critical section for flexural and axial loads, in.

I

$I_{gFlange}$	=	Gross moment of inertia of the concrete section bounded by the effective flange width defined in ACI 369 Section 3.1.3 about its centroidal axis, neglecting reinforcement, in.^{4}
I_{gRect}	=	Gross moment of inertia of the rectangular portion of the concrete section about its centroidal axis, neglecting reinforcement, in.^{4}

J

J	=	Force-delivery reduction factor, greater than or equal to 1.0, taken as the smallest demand-capacity ratio (DCR) of the components in the load path delivering force to the component in question, calculated in accordance with ASCE 41 Eq. (7-16).

K

k	=	Efficiency factor

L

l_w	=	Length of entire wall, or a segment of wall considered, in the direction of shear force, in.

M

M_{CultE}	=	Moment demand resulting in flexural yielding of the plastic hinges calculated using expected strengths of concrete and steel with applied axial load N_{UG}
m	=	Component demand modification factor to account for expected ductility associated with this action at the selected Structural Performance Level, per ASCE 41

N

N_{UD}	=	Member design axial force evaluated based on ASCE 41, Eq. (7-34)
N_{UG}	=	Member design axial force evaluated based on ASCE 41, Eq. (7-3); set to zero for tension force in Eq. (10-3)
n	=	Number of plies of FRP reinforcement

P

P_{uf}	=	Force-controlled demand for diaphragm tension or flexure, kip
P_{oL}	=	Lower-bound axial load strength at zero eccentricity in accordance with ASCE 41 Chapter 10

Q

Q_{CE}	=	Expected strength of component deformation-controlled action of an element at the deformation level under consideration, per ASCE 41
Q_{CL}	=	Lower-bound strength of a force-controlled action of an element at the deformation level under consideration
Q_G	=	Action caused gravity loads
Q_{UD}	=	Deformation-controlled action caused by gravity loads and earthquake forces, per ASCE 41
Q_{UF}	=	Force-controlled demand

S

S_n	=	Nominal strength of existing structural element, ksi
$S_{n,F}$	=	Additional nominal strength provided by FRP
s_{anc}	=	Center-to-center spacing of anchors, in.
s_f	=	Center-to-center spacing of FRP strips, in.

T

T_{chordL}	=	Tension capacity of diaphragm chord using lower-bound material properties, kip
$T_{collectL}$	=	Tension capacity of diaphragm collector using lower-bound material properties, kip
t_f	=	Nominal thickness of one ply of FRP reinforcement, in.

U

U	=	Governing ultimate load, kip

V

V_c	=	Shear strength provided by concrete in accordance with ACI 369.1, kip
V_{cE}	=	Expected shear strength provided by concrete in accordance with ACI 369.1, kip
V_{cL}	=	Lower-bound shear strength provided by concrete in accordance with ACI 369.1, kip
V_{sE}	=	Expected shear strength provided by steel in accordance with ACI 369.1, kip
V_{sL}	=	Lower-bound shear strength provided by steel in accordance with ACI 369.1, kip
V_{Col0L}	=	Shear strength of existing column using lower-bound material properties (L), kip
V_{Col0E}	=	Shear strength of columns at a displacement ductility demand not exceeding 2.0, ASCE 41 Eq. (10-3); evaluated using expected material properties
V_{ColL}	=	Lower-bound shear strength of fully wrapped column, kip
$V_{CWall440E}$	=	Design shear strength of FRP-strengthened wall in accordance with ACI 440 where V_c and V_s are calculated using expected concrete and steel strengths in the wall, respectively, kip
$V_{CydWallE}$	=	Shear strength of wall using expected material properties (E) , kip
V_{DiaphE}	=	Design shear strength of FRP-strengthened diaphragm in accordance with ACI 440 where V_c and V_s are calculated using expected concrete and steel strengths in the diaphragm, respectively, kip
V_f	=	Lower-bound shear strength provided by FRP in accordance with ACI 440.2, kip
V_{fL}	=	Lower-bound shear strength provided by FRP for fully wrapped columns, kip
V_{MCultE}	=	Shear demand resulting in flexural yielding of the plastic hinges at a moment of $M_{CultE,}$ in accordance with ACI 369.1, kip
V_{MCyE}	=	Shear demand resulting in flexural yielding of the plastic hinges at a moment of $M_{CultE,}$ kip
V_s	=	Shear strength provided by steel using expected material properties (E) or lower-bound material properties (L), kip
V_{UD}	=	Deformation-controlled shear action as defined for deformation-controlled actions in ASCE 41, Section 7.5.2.1.1, kip
V_{UF}	=	Force-controlled shear action as defined for force-controlled actions in ASCE 41, Section 7.5.2.1.2, kip
V_{yE}	=	Shear demand resulting in flexural yielding of the plastic hinges, kip

W

w_f = Width of FRP reinforcing plies, in.

5.0 DEFERRED SUBMITTALS FOR PERFORMANCE-BASED FRP DRAWINGS

Deferred submittals for FRP retrofit designs are not permitted. Explicit FRP design drawings shall be included in the construction drawings at the time of plancheck submittal.

A minimum amount of information is required to verify basic structural information and the loading or performance criteria used for the proposed design when submitting a design to the City for review. Along with all other application documentation, such as retrofit drawings, the information in Table 5-1 and Table 5-2 shall be completed and included in the construction drawings.

The Structural Engineer of Record (SEOR) may submit the FRP retrofit design to the manufacturer for feedback. Any shop drawings and/or calculations received in return shall be stamped and signed by the SEOR.

It is the responsibility of the SEOR to ensure a retrofit design that meets the intent and requirements of the Ordinance.

Table 5-1: Basic Information for Performance-Based FRP Drawings[1]

Drawing Reference[2]	Reason for FRP Application: Strengthening/ Retrofit[3] or Repair[4]	Application Basic Information								
		Existing Concrete Structural Member		Existing Material Properties[7]		Accessible Surfaces to be Covered by FRP[8]	Bond- or Contact-Critical Application	Fiber Orientation[9]	Applicable Anchors[10]	Fire Rating Requirement[11]
		Type[5]	Dimensions[6]	f'_c	F_y					

1. This table shall be included in the construction drawings.
2. Detail and Sheet number.
3. If Strengthening/Retrofit, identify the nature of the loads (e.g., gravity, seismic, wind, blast).
4. If Repair, state the nature of damage (e.g., corrosion, impact, cut rebars/tendons, cracks).
5. Column, beam, wall, collector, slab, foundation, etc.
6. If V.I.F. (Verify In Field) since as-built dimensions are not available, identify if the task is delegated to the contractor or if the SEOR will establish and share with all the bidders. Use “N/A” if not applicable.
7. Properties are expected or lower-bound, as applicable for the component action being strengthened.
8. Indicate if one, two, three, or all sides are accessible to receive FRP. If all sides are not accessible, specify which sides are. In case of one-sided application of FRP for shear strengthening of walls, specify the size and spacing of existing wall reinforcement.
9. Relative to member’s longitudinal axis or any other fixed reference axis.
10. Through, embedded, precured, etc. Use “N/P” if not permitted or “N/A” if not applicable.
11. Use “N/A” for not applicable (e.g., in seismic applications). When fire resisting calculations are needed, reference applicable load combinations (e.g., Section 9.2, ACI 440.2).

Table 5-2: Loading or Performance Criteria for Performance-Based FRP Drawings[1]

Drawing Reference	Performance/Loading Criteria										Performance Criteria Related to Confinement or Detailing[8]		
	Existing Capacity[2]			Ultimate Demand				Added Capacity by FRP			Deficiency	Action Classification	Acceptance Criteria
	Φ[3]	Q_c[4]	Code/ Standard	Governing Load Combination	Q_u[5]	Code/ Standard	Action to be Strengthened	ψ_f[6]	Q_{cL}[7]	Code/ Standard			

1. This table shall be included in the construction drawings.
2. For shear capacity, total strength and breakdown of contributions from steel and concrete (Vs and Vc) must be reported.
3. Strength reduction factor per ASCE 41.
4. Existing component strength, expected or lower-bound, as applicable for the component action being strengthened.
5. Governing ultimate load, deformation-controlled or force-controlled, as applicable for the component action being strengthened.
6. FRP reduction factor per this Appendix.
7. Additional lower-bound strength provided by FRP.
8. Use in cases such as confinement or lap splice deficiency that are quantified in a different way than strengthening based on loads. However, fill out all the cells to the right that are applicable, including but not limited to the codes and standards that are basis of establishing the deficiency and retrofit.

6.0 TYPES OF COMPONENT ACTIONS TO BE STRENGTHENED

This Appendix is applicable to strengthening the building elements and their accompanying deficiencies per Table 6-1. It is noted that a complete, well-defined load path that includes structural elements and connections, shall either be verified or provided as part of the overall retrofit.

Table 6-1: FRP Element Applicability

Concrete Element Type	Component Action to be Strengthened	Section Number
Columns	Direct Shear	9.0
	Flexure-Axial Confinement	
Walls and Spandrels	In-Plane Shear	10.0
Diaphragms	In-Plane Shear	11.0
Diaphragm Chords and Collectors	Tension	11.0
Connections	Diaphragm-to-Wall Shear Transfer (Collector-to-Wall Tension Transfer, Wall-to-Foundation Shear Transfer)	12.0, 13.0

7.0 FRP REQUIREMENTS FOR EACH COMPONENT ACTION

The requirements for utilizing FRP in a retrofit design are listed in Table 7-1.

Table 7-1: FRP Utilization Requirements[1]

Component Action	Column	Wall and Spandrel Shear	Diaphragm Shear	Diaphragm Chord Tension, Collector Tension, Collector-to-Wall Tension	Diaphragm-to-Wall Shear Transfer, Wall-to-Foundation Shear Transfer
Design Category[2]	Secondary	Secondary	Secondary	Secondary	Secondary
Load Transfer	Contact / Bond[3]	Bond	Bond	Bond	Bond
Application	Wet Lay-Up	Wet Lay-Up	Wet Lay-Up	Wet Lay-Up	Wet Lay-Up
Type of FRP (with Resin Epoxy)[4]	Carbon	Carbon	Carbon	Carbon	Carbon
Are Anchors Required?[5]	Yes	Yes	Yes	Yes	Yes
Fabric Orientation	Parallel to the Applied Shear Force	Parallel to the Applied Shear Force	Parallel to the Applied Shear Force	Parallel to Axial Tension	± 45° to the Applied Shear Force

1. These requirements are subject to any and all additional FRP requirements as listed in this Appendix.

2. Primary structural member implies that the FRP is designed to take gravity loads. Secondary structural member implies that the FRP is designed to take seismic loads only.
3. Column seismic confinement shall be considered to be contact-critical. Column seismic shear strengthening shall be considered bond-critical, unless noted otherwise by the SEOR.
4. Glass FRP may be substituted in place of carbon FRP, provided testing results representative of the existing condition (i.e., reinforcement ratio, relative stiffness between elements, etc.) are submitted and approved by the SEOR prior to construction.
5. Along free edges of walls and diaphragms, one of the following shall be required:
    a. Anchors shall be provided.
    b. Corners shall be rounded to 0.5 inches minimum radius. The FRP shall wrap around the member thickness and extend on the opposite side with a minimum length of 12 inches.

8.0 DESIGN REQUIREMENTS FOR FRP STRENGTHENED MEMBERS

The following sections are intended to clarify the relationship between component action and acceptance criteria, provide guidance for linear analysis procedures, and provide guidance for nonlinear analysis procedures.

Means to allow moisture to escape from the existing structure shall be provided when the FRP system creates an impermeable layer and moisture vapor transmission is expected. Measures for post-earthquake structural observation in the FRP-strengthened component should be considered in the retrofit design, for example in spacing of FRP sheets, etc..

The FRP reduction factor, ψ_f, shall be selected from Table 8-1 and applied as applicable per this Appendix.

Table 8-1: FRP reduction factor, ψ_f, for different components

Element	Value
Columns	0.95 for bond-critical
	0.85 for contact-critical
Walls	0.75 for one-sided application
	0.85 for two-sided application
Diaphragms, Diaphragm Chords and Collectors	0.85

A knowledge factor, κ, from ASCE 41 shall be applied to existing materials, as applicable per this Appendix.

A strength reduction factor, ϕ, from ASCE 41 shall be applied to capacities, as applicable per this Appendix.

8.1 COMPONENT ACTION CLASSIFICATION AND ACCEPTANCE CRITERIA

Classification of force-controlled actions and deformation-controlled actions shall be in accordance with the provisions outlined in ASCE 41, Section 7.4. It is noted that unlike in ASCE 7, where a structural system receives a seismic force-reduction factor as a whole, ASCE 41 classifies each *component action* based on the expected load-deformation response of the relevant action. For example, a conventional concrete column can have both a force-controlled action from axial compression and a deformation-controlled action in flexure, i.e., the column as a whole is neither force-controlled nor deformation-controlled. As such, a column retrofitted with horizontal FRP for shear actions would have force-controlled actions in shear but would still be considered deformation-controlled in flexure. This is due to the flexural yielding action not being affected by an FRP failure mode.

Acceptance criteria for component actions in this Appendix shall be classified as either deformation-controlled or force-controlled in accordance with Table 8-2. The table illustrates the governing mode of failure (action) that dictates either a force-controlled or a deformation-controlled response in the element. Looking again at the column, while shear may have governed the failure of the column prior to a retrofit, sufficient horizontal FRP strengthening can be provided to ensure a deformation-controlled, flexure-governed response. The force-controlled shear action is akin to the capacity-based designed actions in new design. Additional guidance on component strengths and acceptance criteria is provided in later sections of this Appendix.

Table 8-2: Acceptance Criteria for Component Actions

Component	Deformation-Controlled Actions	Deformation-Controlled Relevant Provisions	Force-Controlled Actions	Force-Controlled Relevant Provisions
Columns	PMM (FRP Confinement)	Section 9.2 of this Appendix and/or ASCE 41, Tables 10-8, 10-9, 10-10a, and 10-10b		
	Moment (Existing Condition)	Acceptance criteria per ASCE 41, Tables 10-8, 10-9, 10-10a, and 10-10b	Moment (FRP Retrofitted)	Not covered by this Appendix
	Shear (Existing Condition)	Acceptance criteria per ASCE 41, Tables 10-8, 10-9, 10-10a, and 10-10b	Shear (FRP Retrofitted)	FRP shear strength per Section 9.0 of this Appendix, such that $V_{MCultE} < \Phi V_{ColL}$ and the retrofitted column is governed by flexure per Section 9.0. Acceptance criteria of flexural-controlled column per ASCE 41, Tables 10-8, 10-9, 10-10a, and 10-10b

Table 8-2: Acceptance Criteria for Component Actions (Continued)

Component	Deformation-Controlled Actions	Deformation-Controlled Relevant Provisions	Force-Controlled Actions	Force-Controlled Relevant Provisions
Walls	PMM (FRP Confinement)	Not covered by this Appendix		
	Moment (Existing Condition)	Acceptance criteria per ACI 369.1^{M}, Tables 7.3.2b, 7.4.1.1.1a, and 7.4.1.1.b	Moment (FRP Retrofitted)	Not covered by this Appendix
	Shear (Existing Condition)	Acceptance criteria per ACI 369.1^{M}, Tables 7.3.2b and 7.4.1.1.2		
	Shear (FRP Retrofitted with Anchorage Conforming to the Provisions of Section 10.0)	Design FRP shear strength per Section 10.0 of this Appendix. Acceptance criteria of shear-controlled wall per Table 8-3 or Table 8-4 and Table 8-5 of this Appendix		

Table 8-2: Acceptance Criteria for Component Actions (Continued)

Component	Deformation-Controlled Actions	Deformation-Controlled Relevant Provisions	Force-Controlled Actions	Force-Controlled Relevant Provisions
Diaphragms	Flexure (Existing Condition)	Acceptance criteria per ASCE 41, Tables 10-19 and 10-21	Flexure (Chords Retrofitted with FRP)	Design FRP strength per Section 11.0 of this Appendix, such that $P_{uf} < \Phi T_{chordL}$ where P_{uf} is defined based on ASCE 41, Section 7.5.2.1.2 and 7.5.3.2.3, and J is permitted to be taken as 2.0 or based on another limiting force in the load path where anchorage is provided in accordance with Section 13.0 of this Appendix
	Shear (Existing Condition)	Acceptance criteria per ASCE 41, Tables 10-20 and 10-22		
	Shear (FRP Retrofitted with Anchorage Conforming to the Provisions of Section 11.0)	Design FRP per Section 11.0 of this Appendix, and m = 3.0 for acceptance criteria		
			Shear Transfer to Wall	Determine number of plies of FRP reinforcement per Section 12.0 and FRP connection per Section 13.0 of this Appendix
	Tension (Mild Steel Collectors)	Acceptance criteria per ASCE 41, Section 10.10.2.4	Tension (FRP Collectors)	Design FRP strength per Section 11.0 of this Appendix, such that $P_{uf} < \Phi T_{collectL}$ where P_{uf} is defined based on ASCE 41, Section 7.5.2.1.2 and 7.5.3.2.3, and J is permitted to be taken as 2.0 or based on another limiting force in the load path where anchorage is provided in accordance with Section 13.0 of this Appendix

8.2 LINEAR ANALYSIS PROCEDURES

When calculating demands using ASCE 41 linear analysis procedures, the determination of forces and deformations shall be in accordance with the provisions outlined in ASCE 41, Sections 7.4.1 and 7.4.2. Acceptance criteria for linear procedures shall be in accordance with the provisions outlined in ASCE 41, Section 7.5.2.2.1 for deformation-controlled actions and Section 7.5.2.2.2 for force-controlled actions.

Where FRP is applied such that the governing inelastic action relates to the FRP (i.e., delamination), the component action shall be treated as force-controlled and the provisions of ASCE 41, Section 7.5.2.1.2 shall apply, except where specific strength equations and m-factors are provided in this Appendix.

Where FRP is applied such that the governing inelastic behavior is due to the structural component itself (i.e., not an FRP failure mode), and it involves ductile failure of the steel reinforcement, the component action shall be classified in accordance with ASCE 41. For example, if a column is strengthened for shear and becomes flexure-controlled, the flexural failure shall be treated as deformation-controlled, in accordance with ASCE 41, Section 7.5.2.2.1..

8.2.1 LINEAR ANALYSIS PROCEDURES FOR COLUMNS

The FRP retrofit of a nonductile column strengthened for shear actions should be provided over the entire height of the column, and the retrofit design shall satisfy both of the acceptance criteria items noted below. Columns controlled by inadequate development or splicing along their clear height shall continue to be based on m-factors for inadequate lap splices, unless the lap splices are retrofitted with FRP in accordance with ACI 440.2, Section 13.3.3.

The acceptance criteria for columns are as follows:

1. Column Shear Strengthening: The lower-bound shear strength of the retrofitted column, Q_{CL}, shall be greater than the shear force where the expected moment strength of the column is developed, Q_{UF}. In other words, the force-controlled acceptance criteria shall be satisfied for the shear demands based on limit state analysis;

$$\kappa Q_{CL} > Q_{UF} \qquad \text{(ASCE 41, Eq. (7-37))}$$

Where,

Q_{CL} shall be taken as V_{ColL} per Section 9.0 of this Appendix,

Q_{UF} shall be taken as V_{MCultE} per Section 9.0 of this Appendix.

2. Column Ductility Enhancement: Determination of the ASCE 41 m-factor shall use the quantity of materials necessary to satisfy the Column Shear Strengthening criteria in accordance with ASCE 41, Tables 10-10a and 10-10b. The deformation-controlled action acceptance criteria shall be satisfied for moment-axial interaction.

   To select the m-factor using the ASCE 41 tables:

   a. Replace V_{yE}/V_{Col0E} with V_{MCyE}/V_{ColL}, where the lower-bound shear strength, V_{ColL}, is calculated per Eq. (9-1) of this Appendix

   b. Calculate $\rho_t = \frac{A_v + A_f E_f / E_s}{b^* s}$

   c. Obtain $\frac{N_{UD}}{A_g f'_{cE}}$ from the linear analysis.

   d. It shall be permitted to consider the m-factor based on testing of columns strengthened with FRP per ASCE 41, Section 7.6.

   The following acceptance criteria for the deformation-controlled action shall be satisfied:

$$m\kappa Q_{CE} > Q_{UD} \qquad \text{(ASCE 41, Eq. (7-36))}$$

If the quantity of FRP materials required for the column shear strengthening does not satisfy the Column Ductility Enhancement criteria, the quantity of FRP should be increased until it is satisfied.

See Figure 8.1 for a flow chart of the procedure for an adequate FRP design.

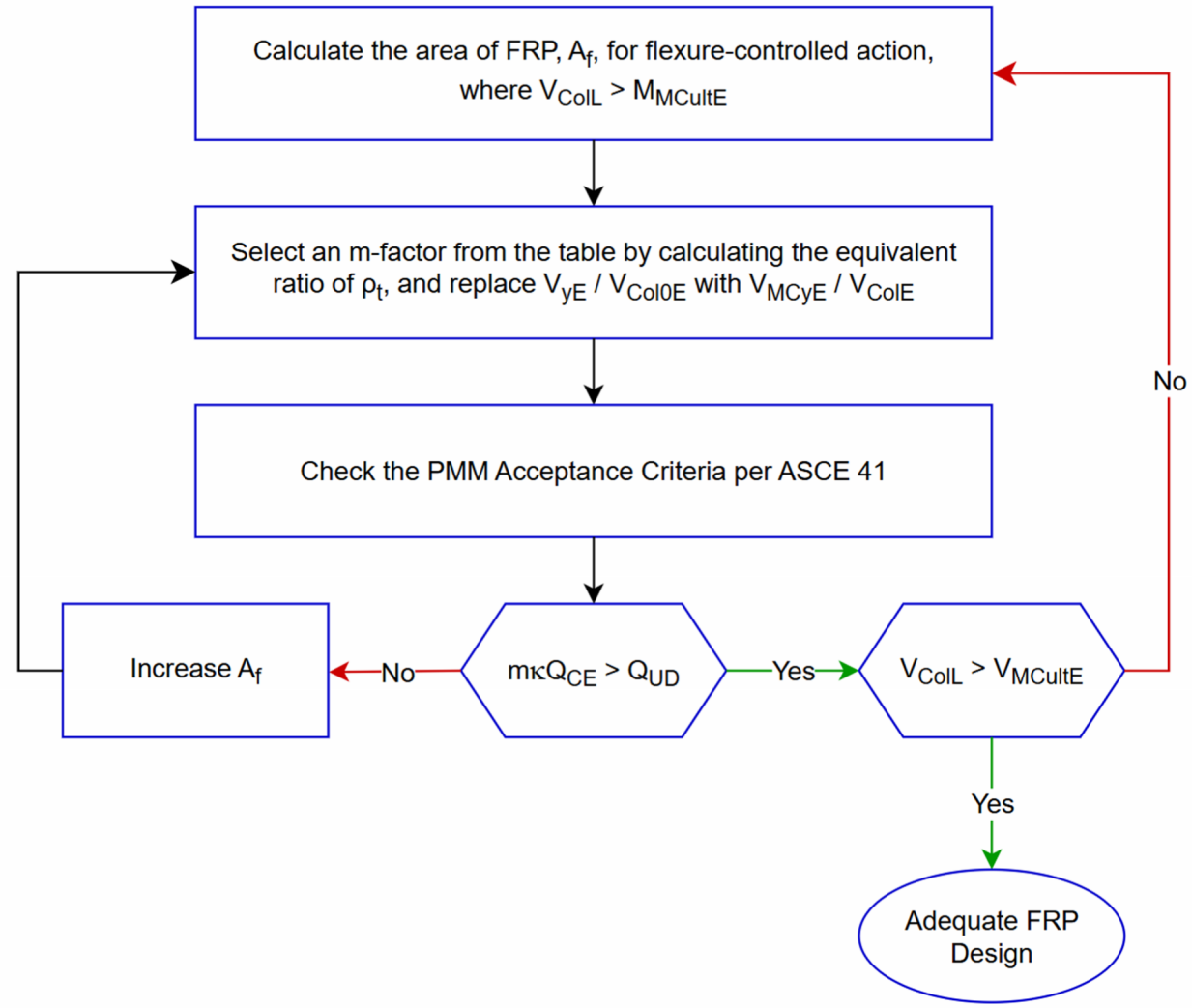

Figure 8.1: Linear Analysis Procedure Flow Chart

8.2.2 LINEAR ANALYSIS PROCEDURES FOR WALLS

Existing walls containing nonconforming transverse reinforcement and/or inadequate lap splices shall continue to be considered nonconforming after FRP is applied, unless the lap splice is explicitly addressed as part of the retrofit.

Acceptance criteria for flexural actions of walls strengthened with horizontal FRP shall be in accordance with ACI 369.1[M], Tables 7.3.2b, 7.4.1.1.1a, and 7.4.1.1.1b.

Shear demands in walls shall be determined based on $\omega_v V_{McultE}$, the shear associated with flexural yielding, or another limiting state, in accordance with ASCE 41, Section 7.5.2.1.2. A dynamic shear amplification factor for maximum wall shear demand, ω_v, shall be in accordance with Equation 8-1.

$$\omega_v = 1.0 \quad \text{for} \quad h_{wcs}/l_w < 2.0$$
$$\omega_v = 0.8 + 0.09h_n^{1/3} \quad \text{for} \quad h_{wcs}/l_w \geq 2.0 \tag{8-1}$$

Shear actions in walls shall be considered deformation-controlled, and the provided anchorage shall satisfy the requirements of Section 13.0 of this Appendix. The acceptance criteria for shear actions shall be in accordance with Table 8-3 of this Appendix, for which the nonlinear parameters used are obtained from Table 8-5 of this Appendix. As an alternative to Table 8-3, it shall be permitted to use m-factors directly from Table 8-4, which employ an assumed yield deformation of 0.4%.

$$\omega_v V_{MCultE} \leq m\phi\kappa V_{CydWallE}$$

Table 8-3: Shear Action Acceptance Criteria for Walls Using Linear Analysis Procedures

Component Type	m-factors		
	Performance Level[1]		
	IO	LS	CP
Primary	$\frac{g_{nl} + 0.1(d_{nl} - g_{nl})}{g_{nl}}$	$\frac{1}{2}\left(\frac{e_{nl}}{g_{nl}}\right)$	$\frac{5}{8}\left(\frac{e_{nl}}{g_{nl}}\right)$
Secondary		$\frac{3}{5}\left(\frac{e_{nl}}{g_{nl}}\right)$	$\frac{4}{5}\left(\frac{e_{nl}}{g_{nl}}\right)$

1. The acceptance criteria for primary members shall not be taken as larger than those for secondary members.

Table 8-4: Alternative Shear Action Acceptance Criteria for Walls and Associated Components Using Linear Analysis Procedures

Conditions	m-factors[1]				
	Performance Level				
	IO	Primary		Secondary	
		LS	CP	LS	CP
≤ 0.075	1.0	2.5	3.1	3.0	4.0
≥ 0.150	1.0	1.3	1.6	1.5	2.0

1. Linear interpolation between values listed in this table shall be permitted.

8.2.3 LINEAR ANALYSIS PROCEDURES FOR DIAPHRAGMS

Diaphragm demands shall be determined in accordance with ASCE 41, Section 7.4.

Shear actions shall be considered as deformation-controlled, and the provided anchorage shall satisfy the requirements of Section 13.0 of this Appendix. The acceptance criteria for said shear actions shall be in accordance with Table 8-3 of this Appendix, for which the nonlinear parameters for use in the table are obtained from Table 8-5 of this Appendix. As an alternative to Table 8-3, it shall be permitted to use m-factors directly from Table 8-4 of this Appendix, which employ an assumed yield deformation of 0.4%. Component strengths shall be calculated in accordance with Section 10.0 of this Appendix.

$$V_{UD} \leq m\kappa V_{DiaphE}$$

Diaphragm tension component actions, i.e., tension demands in chords or collectors, strengthened with FRP shall be considered force-controlled and satisfy ASCE 41, Section 7.5.2.1.2. Lower-bound component strengths, $T_{collectL}$ and T_{chordL} for collectors and chords, respectively, shall be calculated in accordance with Section 11.0 of this Appendix.

Tension actions in collectors shall satisfy Equation 8-2:

$$T_{UF} \leq \phi\kappa T_{collectL} \quad (8\text{-}2)$$

Tension actions in chords shall satisfy Equation 8-3:

$$T_{UF} \leq \phi\kappa T_{chordL} \quad (8\text{-}3)$$

Anchors satisfying the requirements of Section 13.0 of this Appendix shall be provided.

8.3 NONLINEAR ANALYSIS PROCEDURES

When calculating demands using ASCE 41 nonlinear analysis procedures, the determination of forces and deformations shall be in accordance with the provisions outlined in ASCE 41, Sections 7.4.3 and 7.4.4. Acceptance criteria for nonlinear procedures shall be in accordance with the provisions outlined in ASCE 41, Section 7.5.3.2.2 for deformation-controlled actions and Section 7.5.3.2.3 for force-controlled actions.

Where FRP is applied such that the governing inelastic action relates to the FRP (i.e., delamination), the component action shall be treated as force-controlled and the provisions of ASCE 41, Section 7.5.3.2.3 shall apply, except where specific strength equations and nonlinear acceptance criteria are provided in this Appendix.

Where FRP is applied such that the governing inelastic action is in the structural component and not related to FRP failure modes, the action shall be classified in accordance with ASCE 41. For example, in a column strengthened for shear such that the column component is now flexure-controlled, the governing flexural mechanism shall be considered deformation-controlled and in accordance with ASCE 41, Section 7.5.3.2.2.

8.3.1 NONLINEAR ANALYSIS PROCEDURES FOR COLUMNS

The FRP retrofit of a nonductile column should be provided over the entire height of the column, and the design of the retrofit shall satisfy both of the acceptance criteria items noted below. Columns controlled by inadequate development or splicing along the clear height shall continue to be based on Modeling Parameters and acceptance criteria for inadequate lap splices unless the lap splices are retrofitted with FRP to achieve yielding of the steel reinforcement.

The acceptance criteria for columns are as follows:

1. Column Shear Strengthening: The lower-bound shear strength of retrofitted columns shall be greater than the shear force where the expected moment strength of the column is developed. In other words, the force-controlled acceptance criteria shall be satisfied for the shear demands based on limit state analysis and Exception 1 in ASCE 41, Section 7.5.3.2.3.

$$\gamma\chi(Q_{UF} - Q_G) + Q_G \leq Q_{CL} \qquad \text{(ASCE 41, Eq. 7-38)}$$

Where,

Q_{CL} shall be taken as V_{ColL} per Section 9.0,

$\gamma\chi(Q_{UF} - Q_G)$ shall be taken as V_{MCultE} per Section 9.0

2. Column Ductility Enhancement: Determination of ASCE 41 modeling parameters and acceptance criteria shall use the quantity of materials necessary to satisfy the Column Shear Strengthening criteria in accordance with ASCE 41, Tables 10-8 and 10-9. The deformation-controlled action acceptance criteria shall be satisfied for moment-axial interaction per ASCE 41, Section 7.5.3.2.2.

   To select the m-factor using the ASCE 41 tables:

   a. Replace V_{yE}/V_{Col0E} with V_{MCyE}/V_{ColL}, where the lower-bound shear strength, V_{ColL}, is calculated per Equation (9-1) of this Appendix

   b. Calculated $\rho_t = \frac{A_v + A_f E_f / E_s}{b^* s}$

   c. Obtain $\frac{N_{UD}}{A_g f'_{cE}}$ from the nonlinear analysis.

   d. It shall be permitted to consider modeling parameters and acceptance criteria based on testing of columns strengthened with FRP per ASCE 41, Section 7.6.

If the quantity of FRP materials required for the column shear strengthening does not satisfy the Column Ductility Enhancement criteria, the quantity of FRP should be increased until it is satisfied. See Figure 8.2 for a flow chart of the procedure for an adequate FRP design.

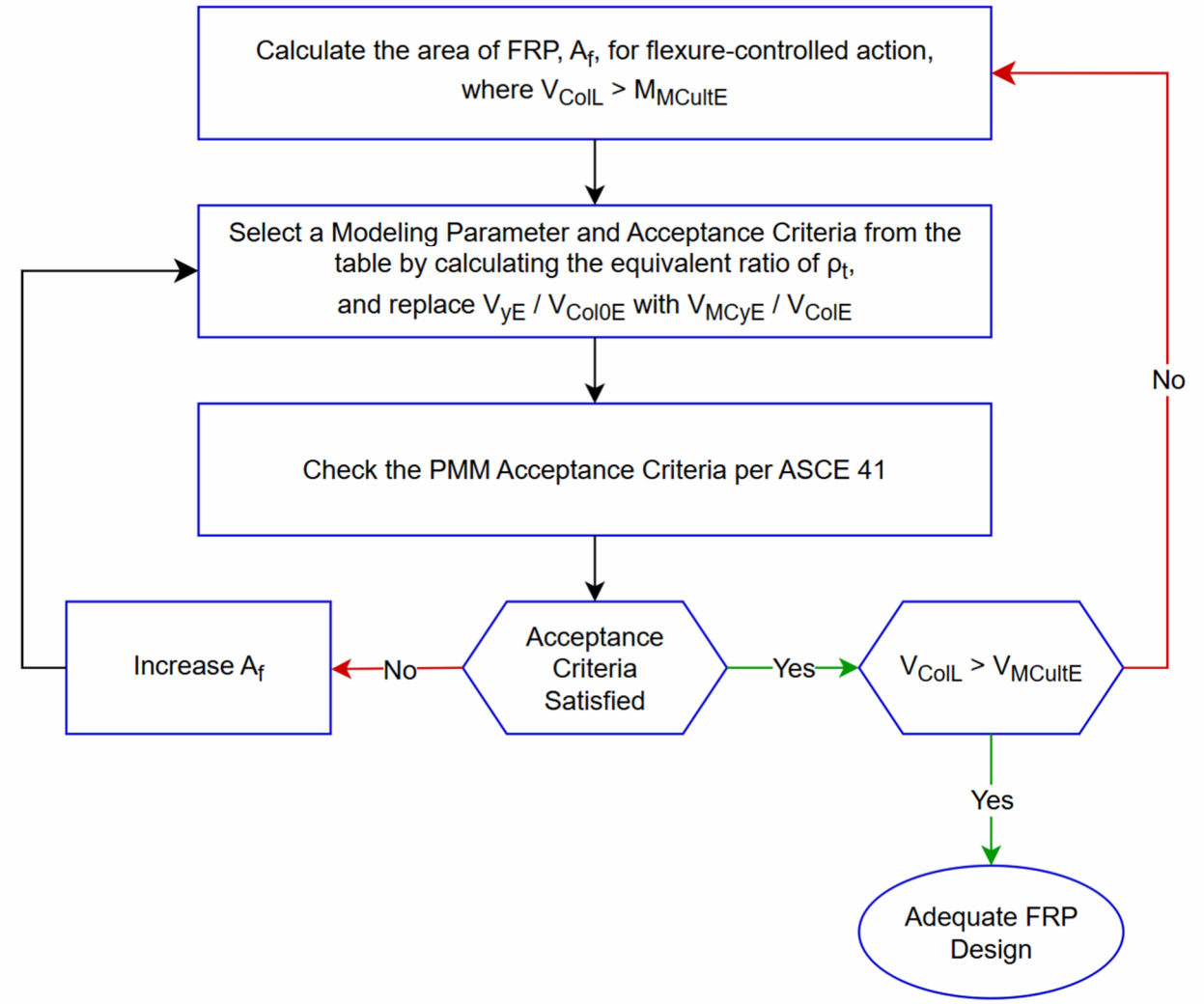

Figure 8.2: Nonlinear Analysis Procedure Flow Chart

8.3.2 NONLINEAR ANALYSIS PROCEDURES FOR WALLS

Existing walls containing nonconforming transverse reinforcement and/or inadequate lap splices shall continue to be considered nonconforming after FRP is applied, unless the lap splice is explicitly addressed as part of the retrofit.

Walls strengthened with horizontal FRP with conforming anchorage per Section 13.0 of this Appendix shall meet the deformation-controlled acceptance criteria for nonlinear analysis in accordance with ASCE 41, Section 7.5.3.

Shear actions in walls shall be considered deformation-controlled, and the provided anchorage shall satisfy the requirements of Section 13.0 of this Appendix. Shear actions shall be permitted to use load-deformation relationships and acceptance criteria based on Table 8-5 of this Appendix for nonlinear analysis procedures.

Table 8-5: Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures: Reinforced Concrete Structural Walls and Associated Components Controlled by Shear[1]

Condition		g_{nl}	d_{nl}[3]	**Acceptance Criteria Performance Objective**
Cross-section shape[2]	$\frac{N_{UD}}{A_g f'_{cE}}$			**IO**
Rectangular	0.005	0.004	0.006	$g_{nl}+0.1(d_{nl} - g_{nl})$
	0.5		θ_{yE}[4]	
Flanged	0.005		0.009	
	0.5		θ_{yE}	

Condition	d'_{nl}[5]	e_{nl}[5]	**Acceptance Criteria Performance Objective**	
$\frac{N_{UD}}{A_g f'_{cE}}$			**LS**	**CP**
≤ 0.075	0.015	0.020	0.65 e_{nl}	0.80 e_{nl}
≥ 0.150	0.010	0.010		

Condition		c_{nl}[6]	c'_{nl}
Cross-section shape[2]	$\frac{N_{UD}}{A_g f'_{cE}}$		
Rectangular	≤ 0.10	0.25	1.10
	≥ 0.15	0.00	
Flanged	≤ 0.15	0.40	
	≥ 0.20	0.00	

1. Linear interpolation between values listed in this table shall be permitted.
2. Linear interpolation between values listed in this table based on $I_{gFlange}/I_{gRect}$ shall be permitted for walls and wall segments between wall and flanged designations with $1.0 < I_{gFlange}/I_{gRect} < 1.5$.

3. d_{nl} shall be taken as the greater of 0.005 and θ_{yE} when ρ_t and ρ_l are less than 0.0015.
4. θ_{yE} shall be calculated using ASCE 41, Eq. 7.3.2f and Eq. 7.4.1.1.1 for linear and nonlinear procedures, respectively.
5. d'_{nl} and e_{nl} shall not be taken less than d_{nl}.
6. c_{nl} shall be taken as zero where ρ_t is less than 0.0015.

7.3.3 NONLINEAR ANALYSIS PROCEDURES FOR DIAPHRAGMS

Diaphragm demands shall be determined in accordance with ASCE 41, Section 7.4.

Shear actions in diaphragms shall be considered as deformation-controlled, and the anchorage provided shall satisfy the requirements of Section 13.0 of this Appendix. The acceptance criteria for said shear actions shall be in accordance with Table 8-5 of this Appendix in the condition the nonlinear behavior is captured in the analytical model and shear deformations are evaluated over the effective shear span of the diaphragm. Component strengths shall be calculated in accordance with Section 11.0 of this Appendix.

Diaphragm tension component actions, i.e., tension demands in chords or collectors, strengthened with FRP shall be considered force-controlled and satisfy ASCE 41, Section 7.5.2.1.2. Lower-bound component strengths, $T_{collectL}$ and T_{chordL} for collectors and chords, respectively, shall be calculated in accordance with Section 11.0 of this Appendix.

Tension actions in collectors shall satisfy Equation 8-4:

$$T_{UF} \leq \phi\kappa T_{collectL} \tag{8-4}$$

Tension actions in chords shall satisfy Equation 8-5:

$$T_{UF} \leq \phi\kappa T_{chordL} \tag{8-5}$$

Anchors satisfying the requirements of Section 13.0 of this Appendix shall be provided.

9.0 DESIGN FOR COLUMN ENHANCEMENT

The following sections are intended to provide guidance for direct shear strengthening, limit state analysis, and ductility enhancement.

9.1 DIRECT SHEAR STRENGTHENING FOR COLUMNS

Direct shear strength of columns can be enhanced by bonding FRP to their surface with the fibers oriented parallel to the applied shear force in the direction for which the column is to be strengthened.

Column shear strengthening is a bond-critical application per ACI 440.2. A contact-critical application per ACI 440.2 is permitted when the maximum column dimension is not greater than 12 inches. A building official may permit reduced surface preparation requirements on a project-specific basis.

The FRP jacket shall fully wrap the column. A minimum of 12 inches of overlap for the jacket shall be provided for carbon FRP. For glass FRP, a smaller overlap for the jacket is permitted, provided testing results representative of the existing condition are submitted.

Anchors shall be utilized, where required, to provide continuity of the FRP around the column and where continuous tension is required for confinement.

For retrofitted columns with FRP completely wrapping the perimeter, the lower-bound shear strength, V_{ColL}, shall be permitted to be calculated using Equation 9-1.

$$V_{ColL} = 0.75\left(V_{Col0L} + \psi_f V_{fL}\right) \leq 10\sqrt{f'_{cL}}\, b_w d \qquad (9\text{-}1)$$

Where,

$V_{fL} = A_{fv} f_{fe} (h_{FRP}/s_f)$,

$A_{fv} = 2 * n * t_f * w_f$,

n = Number of plies of FRP reinforcement,

t_f = Nominal thickness of one ply of FRP reinforcement,

w_f = Width of FRP reinforcing plies ($w_f = s_f$ for continuous jacket)

f_{fe} = Effective stress of FRP ($\varepsilon_{fe} * E_f$)

ε_{fe} = Effective strain of FRP; 0.004 for FRP wrapped completely around the section,

E_f = Design tensile modulus of elasticity of FRP, ksi,

h_{FRP} = Effective depth of the FRP,

s_f = Center to center spacing of FRP strips,

9.2 LIMIT STATE ANALYSIS FOR COLUMNS

V_{MCultE} shall be the shear demand resulting from flexural yielding of the plastic hinges at a moment of M_{CultE}, per ACI 369.1.

M_{CultE} shall be calculated using the expected strengths of concrete and steel materials, with applied axial load N_{UG}.

The increase of moment and axial strengths due to FRP confinement shall be considered. It is permitted to use ACI 440.2, Section 12.2 and the lower-bound strength of the FRP materials to calculate the effect.

9.3 COLUMN DUCTILITY ENHANCEMENT

Column ductility governed by longitudinal reinforcement can be enhanced by bonding FRP to their surface with the fibers oriented parallel to the applied shear force in the direction for which the column is to be strengthened. The process for designing a column FRP retrofit is shown for linear and nonlinear procedures in Figure 8.1 and Figure 8.2, respectively, with the following additional requirements.

Column strengthening is permitted to be a contact-critical application if the strengthening is only for ductility enhancement and is not utilized for shear strengthening. If the FRP is utilized for both shear and ductility enhancement, Section 1.0 of this Appendix shall be satisfied.

The FRP jacket shall fully horizontally wrap the column. A minimum of 12 inches of overlap for the jacket shall be provided for carbon FRP. For glass FRP, a smaller overlap for the jacket is permitted, provided testing results representative of the existing condition are submitted.

The corners of noncircular columns shall be rounded to a minimum of 0.5 inch radius, unless a larger radius is required by the SEOR.

Anchors shall be utilized where required to provide continuity of the FRP around the column and where continuous tension is required for confinement.

Means to allow moisture to escape from the existing structure shall be provided when the FRP system creates an impermeable layer and moisture vapor transmission is expected.

The expected shear demand, V_{McyE}, is associated with the yield moment of the column, based on moment-curvature analysis.

10.0 DESIGN FOR WALL AND SPANDREL IN-PLANE SHEAR STRENGTHENING

In-plane shear strength of walls can be enhanced by bonding FRP to their surface with the fibers oriented parallel to the applied shear force in the direction for which the wall is to be strengthened.

The bond strength of the FRP material to the concrete shall be a minimum of 200 psi. Bond stress shall be calculated based on the tension forces in the FRP that are to be developed over the bond area. All surfaces shall be prepared for bonding by abrasive blasting or an equivalent method, and all installation procedures must adhere to the manufacturer's specifications.

The FRP shall wrap around wall ends, where possible, to fully develop along that one side. Should this not be possible, anchorage shall be provided at the wall ends to fully develop the one-sided laminate.

FRP shall be installed on both sides of walls with thicknesses greater than or equal to 12 inches.

Means to allow moisture to escape from the existing structure shall be provided when the FRP system creates an impermeable layer and moisture vapor transmission is expected.

The efficiency factor, k, is 0.75 when the FRP is bonded to one face of a wall. A higher efficiency factor is allowed when justified by experimental testing results but shall not exceed a value of 0.9. The efficiency factor is permitted to be taken as 1.0 when the FRP is bonded to one face of a wall and carried around or anchored to the end of the element. For FRP bonded to two sides of a wall, the efficiency factor shall be taken as 2.0.

Lower-bound shear strength for a wall or a segment of wall considered in the direction of shear, l_w, provided by FRP shall be calculated using Equation 10-1.

$$V_f = \phi * k * f_{fe} * t_f * n * l_w \quad (10\text{-}1)$$

Where,

f_{fe} shall not exceed 0.75 $f_{fu,}$

ε_{fe} = 0.0015 for FRP bonded to only one face of the wall, and anchored per requirements of Section 13.0 of this Appendix.

= 0.004 for FRP bonded to two sides of the wall, anchored per requirements of Section 13.0 of this Appendix and wrapped around the ends of the wall.

Alternatively, through FRP anchors may be provided to fully develop each side of the FRP, but the value shall not exceed $0.75\varepsilon_{fu}$.

[1]In regions where plastic hinging is not expected, the effective depth of the shear wall can be taken as $0.8l_w$.

[2]For shear strengthening in plastic hinge regions with boundary region confinement per ACI PRC-440.2-23 Section 13.7.3, the effective depth can be taken as $d_{fv} = l_w$. The transverse shear FRP should be extended to the wall ends with the confinement FRP installed over the transverse FRP.

[3]For shear strengthening in plastic hinge regions without boundary region confinement per ACI PRC-440.2-23 Section 13.7.3, d_{fv} should not exceed smaller of $0.8l_w$ (the distance between the anchored ends of the shear FRP) and the wall length less the length of the boundary elements. The transverse shear FRP should be anchored outside the boundary elements.

The expected shear strength for walls, $V_{CydWallE}$, shall be taken follows:

$$0.8\,V_{CWall440E} \le V_{CydWallE} = \left(1.65 - \frac{V_{CWall440E}}{\omega_v V_{MCultE}}\right) V_{CWall440E} \le 1.8\,V_{CWall440E} \qquad (10\text{-}3)$$

Where,

$$\phi V_{CWall440E} = \phi(V_{cE} + V_{sE} + \psi_f V_f) \qquad (10\text{-}4)$$

And,

$V_{CWall440E}$ = Design shear strength of FRP-strengthened wall in accordance with ACI 440 where V_{cE} and V_{sE} are calculated using expected concrete and steel strengths in the wall, respectively, kip

$V_{cE} = \alpha_c \lambda (f'_{cE})^{1/2}$ bd per ACI 318 using expected concrete material properties,

Where,

$\alpha_c = 3 \; for \; h_w/l_w \leq 1.5,$

$\alpha_c = 2 \; for \; h_w/l_w \geq 2.0,$

$(\alpha_c \; varies \; linearly \; between \; 3 \; and \; 2 \; for \; 1.5 < h_w/l_w < 2.0.)$

$\lambda = 0.75$ for lightweight concrete

$\phi V_{CWall440E}$ shall not be more than $10(f'_C)^{1/2}bd$ per ACI 318 using expected steel material properties.

The shear amplification factor ω_v shall not to be applied if V_{McultE} is obtained from nonlinear analyses procedures.

Alternatively, it shall be permitted to evaluate $V_{CydWallE}$ using Equation 10-5:

$$V_{CydWallE} = 0.8V_{CWall440E} \quad (10\text{-}5)$$

11.0 DESIGN FOR DIAPHRAGM IN-PLANE SHEAR AND DIAPHRAGM TENSION IN COLLECTORS AND CHORDS

The following sections are intended to provide guidance for in-plane shear strengthening of diaphragms and diaphragm tension in collectors and chords.

11.1 DIAPHRAGM IN-PLANE SHEAR

The expected shear strength for diaphragms shall be taken as follows:

$$\phi V_{DiaphE} = \phi(V_{cE} + V_{sE} + \psi_f V_f) \quad (11\text{-}1)$$

Where,

V_{DiaphE} = Design shear strength of FRP-strengthened diaphragm in accordance with ACI 440 where V_{cE} and V_{sE} are calculated using expected concrete and steel strengths in the diaphragm, respectively, kip,

$V_{cE} = 2\lambda(f'_{cE})^{1/2}$ bd per ACI 318, using expected concrete material properties,

$V_{sE} + \psi_f V_f$ shall not be more than $8(f'_C)^{1/2}bd$ per ACI 318, using expected steel material properties.

Lower-bound material strengths shall be used in Equation 11-1 for transfer diaphragms, in accordance with ASCE 41 Section 7.4.1.3.4.

11.2 DIAPHRAGM TENSION IN COLLECTORS AND CHORDS

When strengthening conventional, reinforced diaphragm members with fully developed or fully anchored FRP reinforcement, the lower-bound tension strength for chords and collectors shall be taken as follows:

$$\Phi T_{ChordL} = \phi T_{CollectL} = \phi(\psi_f * t_f * n * w_f * \varepsilon_{fe} * E_f) \quad (11\text{-}2)$$

Where,

$$\varepsilon_{fe} = 31.14\sqrt{\frac{\sqrt{f'c}}{n * t_f * E_f}} \leq 0.75\varepsilon_{fu} \quad (\%) \quad (11\text{-}3)$$

ε_{fe} shall not exceed 0.0015 where FRP is used to splice discontinuous existing reinforcement.

12.0 DESIGN FOR DIAPHRAGM-TO-WALL SHEAR TRANSFER

Shear-transfer strength between diaphragm and walls can be enhanced by bonding FRP to their surfaces with the fibers oriented diagonally to the shear plane.

In cases where the required strength is determined to be less than 5 klf, the necessary strength can be achieved exclusively through bonded, bi-axial FRP laminates with anchors omitted, or exclusively through properly detailed anchors.

When the required strength is equal to or exceeds 5 klf, anchors satisfying the requirements of Section 13.0 of this Appendix shall be provided. In such instances, the strength of the shear transfer mechanism shall be determined based on the provided anchors and their center-to-center spacing, s_{anc}, in accordance with manufacturer's specifications and Equation 12-1. Center-to-center spacing of the anchors shall be perpendicular to the fiber direction they anchor, with a minimum value of 4 inches and a maximum value of 10 inches.

$$\frac{12}{s_{anc}} * f_{anc} \geq \phi V_u \quad (12\text{-}1)$$

Additionally, the number of plies of FRP reinforcement required for shear transfer shall not be less than the maximum from Equation 12-2 and that which is specified in Table 12-1.

$$n \geq \frac{f_{anc}}{0.7 * t_f * s_{anc} * f_{fu}} \quad (12\text{-}2)$$

Where,

f_{fu} = Design ultimate tensile strength of FRP
f_{anc} = Design ultimate tensile strength of anchor

Table 12-1: Minimum Required Number of Plies of FRP Reinforcement for Shear Transfer

Demand[1]	Minimum number of plies
$V_u \leq 5$ klf	1
5 klf $< V_u <$ 15 klf	2
$V_u \geq 15$ klf	3

1. The design shear transfer demand shall not exceed the shear capacity of the diaphragm.

13.0 DESIGN OF CONNECTIONS

Anchorage shall be provided at all termination points of the bonded laminates. FRP anchors shall be made with the same fibers and resin as the FRP sheets they anchor.

Anchors other than embedded fiber anchors and fiber splice anchors bonded through FRP adhesives, such as conventional post-installed anchors bonded to FRP through other means, shall be acceptable only where specific applications and anchor spacing configurations are substantiated by testing.

Structural testing shall consist of at least 5 identical specimens, where the design strength is equal to the lesser of the mean minus one standard deviation, the mean multiplied by a factor of 0.7, or 15 klf. Tested configurations shall report the ultimate shear transfer obtained by the FRP alone (i.e., the contribution from existing steel and concrete friction shall be subtracted using control specimens).

The anchor failure modes shall be considered nonductile, force-controlled actions.

13.1 DEVELOPMENT INTO EXISTING CONCRETE

Anchors shall be designed to develop the full design tensile strength of the anchored FRP sheets. The following additional conditions shall be observed unless project-specific testing is provided to justify the design values of each unique condition, for which a testing plan shall be submitted and approved by the Building Official:

1. Embedded Fiber Anchor embedment shall be a minimum of 2 inches (50 mm) past the first layer of existing steel reinforcement in the concrete component, defined from the inside face of the outer reinforcement layer. The anchor shall be permitted to pass through the thickness of the concrete component and adhere to the far side of the concrete component where this embedment cannot be achieved. The total anchor embedment depth shall not be less than 4 inches, nor less than two thirds (2/3) the thickness for walls.
2. For the bond of FRP anchors into concrete, the embedded fiber anchors shall be embedded into concrete at an angle no less than 90 degrees from the primary orientation of the anchored fibers.
3. The orientation of FRP anchors shall be parallel to the fibers of the primary FRP reinforcement sheet being anchored. The splay of FRP anchor fans, w_{anc}, shall be equal to the width of the FRP sheet, w_f, plus 1 inch, where 0.5 inches of the anchor fan splay extends beyond the width of the FRP sheet on either side. At the end of primary reinforcement sheets, FRP anchors shall be located 2 inches interior of the sheet end. The FRP anchor splay shall be even, and the angle of the splay shall not exceed 60 degrees. For double-splay FRP anchors, fan splays shall be equal in the two directions. See Figure 13.4.
4. FRP anchor splays shall not overlap an adjacent FRP anchor hole.
5. FRP anchor holes shall not be placed less than the anchor embedment depth from an edge of concrete, measured normal to the anchor-hole axis.
6. In order to minimize stress concentrations around an FRP anchor bend and in the splay region, FRP patches, satisfying all the following, shall be applied over all FRP anchor splays:
    a. Two (2) FRP patches shall be applied over FRP anchors, unless the FRP anchor splay is placed between layers of the anchored FRP sheet. In this case, only one patch is required, with fibers oriented perpendicular to the sheet fibers.
    b. Where two patches are required, one patch shall have fibers oriented perpendicular to the anchored sheet fibers and the second patch shall have fibers oriented parallel to the anchored sheet fibers.

c. Patches shall be made of the same materials as the FRP anchors.

d. Patches shall extend at least the width of the sheet being anchored.

e. Patches shall extend at least two thirds (2/3) the length of each FRP anchor fan splay in the direction of the anchored sheet fibers.

f. Patches shall extend at least 1.5 inches past the anchor hole edge in all directions.

g. Patches shall be applied while the anchor and the FRP are still wet.

7. **Anchor Size and Spacing**: Anchors shall be provided at termination points (e.g., wall ends and diaphragm ends) to develop the FRP tension capacity calculated using Equation 13-1. Multiple smaller anchors in series may be designed to share the load if substantiated by testing.

   a. **Wall Shear**: For walls strengthened for in-plane shear, intermediate anchors shall be provided along the length of the wall, with spacing parallel to the fiber direction not exceeding the effective shear span of the wall (moment demand divided by shear demand) nor 8 feet on center. These anchors must be capable of developing a tension capacity equal to half the value calculated using Equation 13-1. See Figure 13.1 for wall FRP anchor detailing summary.

      For walls where the effective height is less than the length, intermediate anchors are not required, as their intention is to accommodate having anchors either side of a 45-degree strut.

   b. **Diaphragm Shear**: For diaphragms strengthened for in-plane shear, intermediate anchors shall be required in the direction of shear action with a spacing not to exceed the effective diaphragm shear span, 0.4 times the distance between lines of lateral resistance, nor 8 feet on center. These anchors must be capable of developing a tension capacity equal to half the value calculated using Equation 13-1. See Figure 13.2 for diaphragm FRP anchor detailing summary.

   c. **Chords**: For chords, anchors shall be provided at a maximum anchor spacing of 8 feet on center in the direction of the FRP fibers. Beyond an FRP tension strain of 0.15%, the anchors shall be designed to transfer the diaphragm shear demand to the chord.

$$T_{Anchor,req} = 1.5 * t_f * n * s_{anc} * \varepsilon_{fe} * E_f \qquad (13\text{-}1)$$

d. **Collectors**: For collectors, anchors shall be provided at a maximum anchor spacing of 4 feet on center in the direction of the FRP fibers. Beyond an FRP tension strain of 0.15%, the anchors shall be designed to transfer the diaphragm shear demand to the collector element. This diaphragm shear is assumed to be transferred to the collector over the entirety of the collector length.

$$T_{Anchor,req} = 1.5 * t_f * n * s_{anc} * \varepsilon_{fe} * E_f \quad (13\text{-}2)$$

8. When developing FRP laminates through concrete obstacles, splice FRP anchors shall be designed to transfer the full design tensile strength of the FRP laminate from one termination point to another.

9. The center-to-center spacing of FRP anchors shall be 4 inches minimum and 10 inches maximum, measured perpendicular to the fiber direction they anchor.

10. For a surface level offset, the horizontal dimension shall not be less than four times the vertical offset.

11. In order to reduce stress concentrations at the edge of an FRP anchor hole, it shall be rounded with a minimum chamfer not less than 0.5 inch. The diameter of the FRP anchor hole shall be oversized relative to the diameter of the FRP anchor based on ACI 440.2 Section 14.1 requirements. The FRP anchor hole area shall be at least 1.4 times the equivalent laminate area of the FRP anchor, as defined by Equation 13-3.

$$A_{Eqv} = \frac{\lambda_A}{\Upsilon_{s,Exp}}(w_f * t_f * n) \quad (13\text{-}3)$$

Where,

λ_A = Dry fiber weight of an FRP anchor per unit length, oz./in.

$\Upsilon_{s,Exp}$ = Dry fiber weight of laminate per square surface area, oz./in.

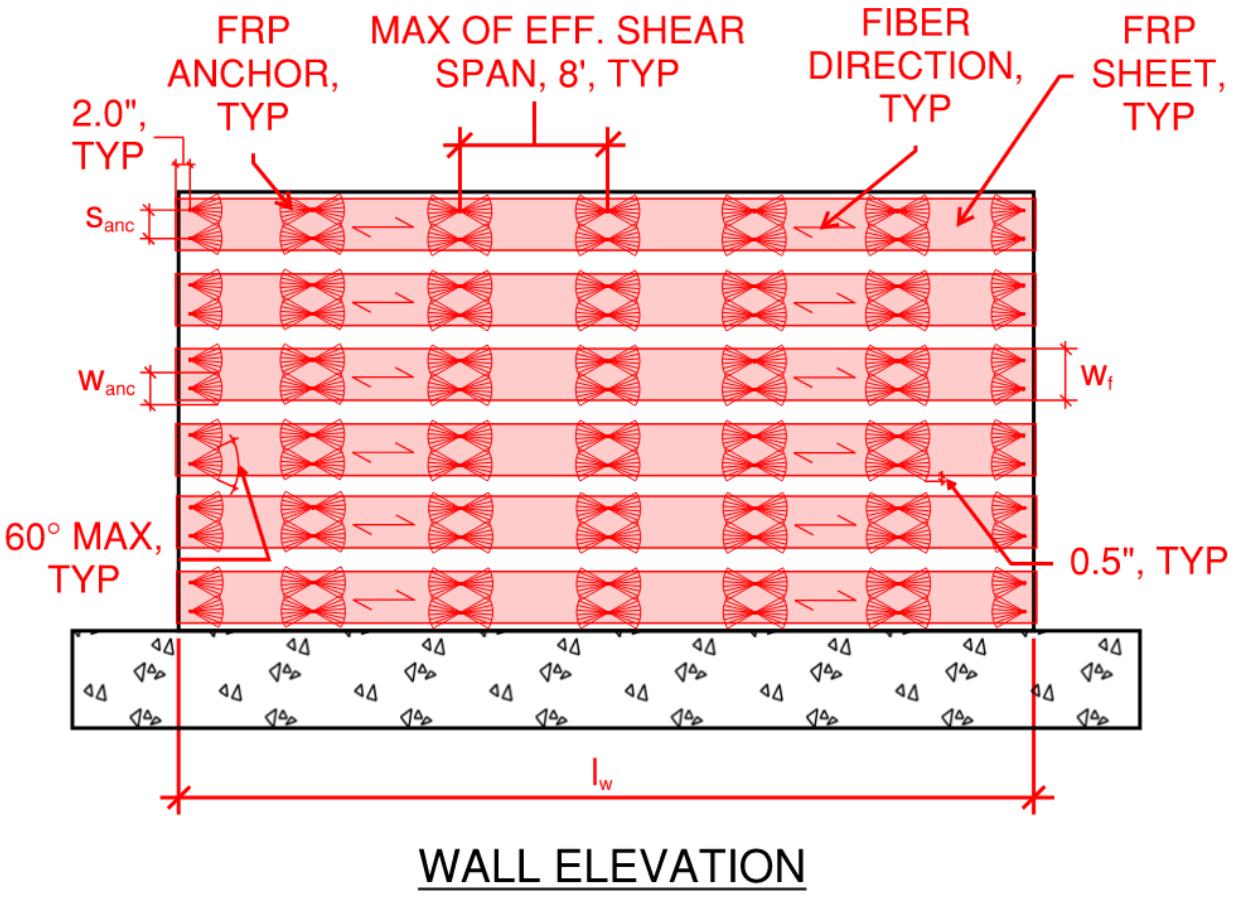

Figure 13.1: Wall FRP Anchor Detailing

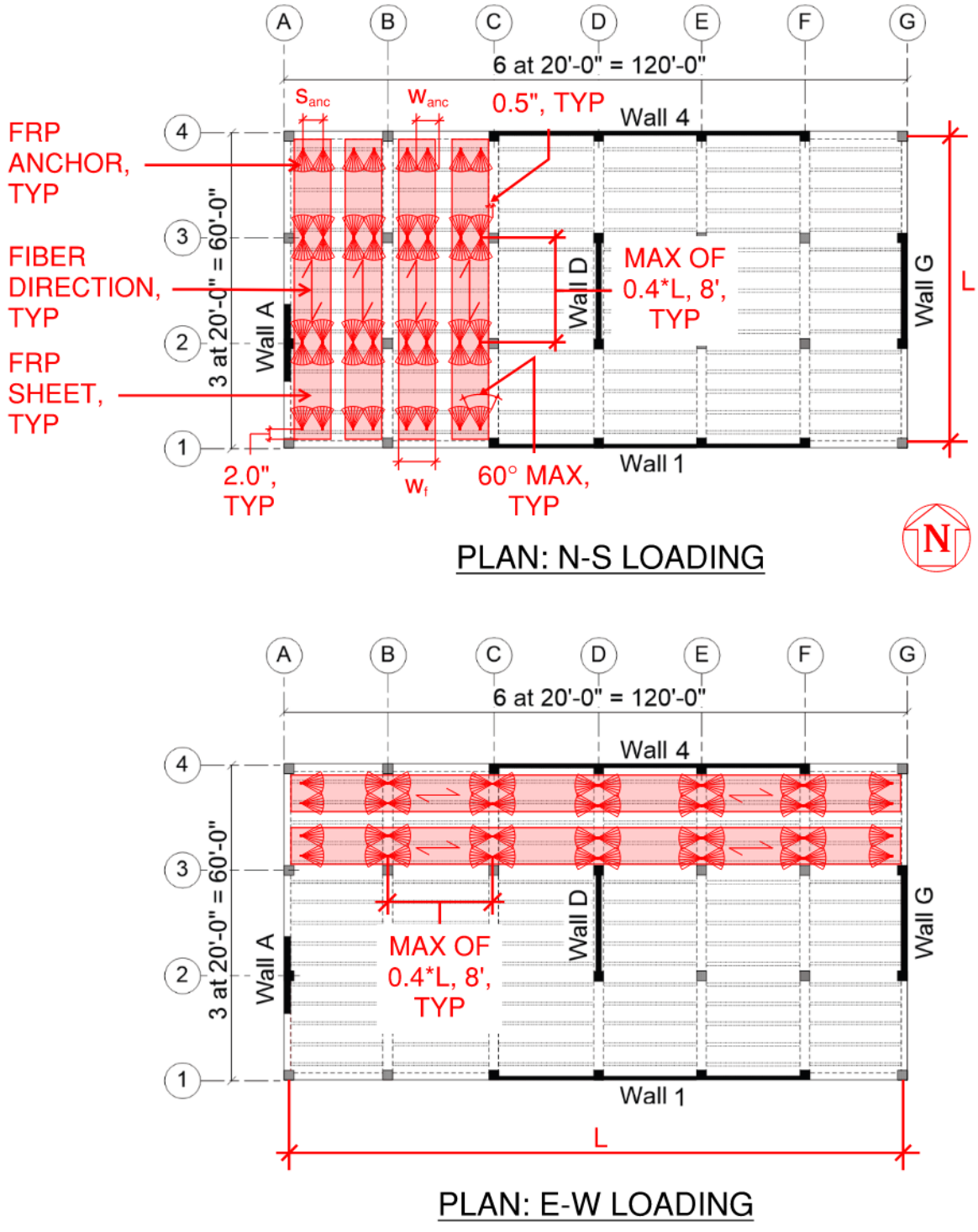

Figure 13.4: Diaphragm FRP Anchor Detailing

14.0 FRP MATERIAL STRENGTHS AND PRE-PRODUCTION QUALIFICATIONS

The FRP products used in the retrofit design shall have an approved agency testing document, such as an ICC-ES or IAPMO Evaluation Report, or approved equivalent, to verify compliance with the applicable Building Codes and standards. Testing documents other than ICC-ES or IAPMO Evaluation Reports require review and approval by the Building Official. The third party approval agency shall provide sufficient information and documentation to verify the following requirements:

1. The approval agency is objective, competent, and independent from the contractor responsible for the retrofit work, with disclosures provided to the Building Official and Structural Engineer of Record regarding possible conflicts of interest.
2. The approval agency shall have adequate equipment to perform any required tests, and said equipment shall be periodically calibrated.
3. The approval agency shall employ experienced personnel educated in conducting, supervising, and evaluating tests and special inspections.
4. The approval agency shall submit testing criteria, test setup, and approval methodology to the Building Official for approval.

The FRP manufacturer shall provide the following material properties to the engineer of record for use in design and confirmation in quality control requirements in accordance with Section 15.0 of this document. The design tensile modulus of elasticity shall be provided by the FRP vendor based on experimental testing, which can reliably be achieved in the field. Example FRP properties are indicated in the tables below for illustrative purposes only.

Table 14-1: Example Unidirectional FRP Material Properties

Property	[Product Name] Unidirectional Carbon FRP System Requirement	Pre-Production Certification (ASTM Test Method)
Corresponding design thickness per layer	(0.02/0.04/0.08) in.	N/A
Ultimate Design Tensile Strength, min., in primary fiber direction[1]	125,000 psi	D3039
Ultimate Breaking Load, min., in primary fiber direction	(2,500/5,000/10,00) lb/in. Width	D3039
Elongation at break	0.9%	D3039
Design Tensile Modulus	13,000 ksi	D3039
Stiffness in primary fiber direction based on the unit width of one layer of cured FRP system. (Modulus times measured area; E x A)	(300/600/1,200) kips/in.	D3039

1. Ultimate Design Tensile Strength, f_{fu}, is at the typical design strength of the material. Most designs are governed by strain limitations.

Table 14-2: Example FRP Anchor Material Properties

Property	¼" to 1" Diameter [Product Name] FRP Anchors Requirement	Pre-Production Certification (ASTM Test Method)
Ultimate Design Tensile Strength, min., in primary fiber direction[1]	100,000 psi	D3039
Ultimate Breaking Load, min., in primary fiber direction	6,000 lb per ¼" dia. FRP anchor	D3039
Elongation at break	0.9%	D3039
Design Tensile Modulus	13,000 ksi	D3039
Stiffness in primary fiber direction based on the unit width of one layer of cured FRP system. (Modulus times measured area; E x A)	600 kip per ¼" dia. FRP anchor	D3039
Shear Capacity per FRP anchor	50,000 psi	EC 038

1. Ultimate Design Tensile Strength, f_{fu}, is at the typical design strength of the material. Most designs are governed by strain limitations.

Table 14-3: Example FRP Anchor Design Capacities

Diameter (in.)	[Product Name] Design Capacity (k)	Pre-Production Certification (Test Method)
3/8	5	AC557
1/2	10	AC557
5/8	15	AC557
3/4	20	AC557

15.0 POST-PRODUCTION QUALITY ASSURANCE CRITERIA AND ENVIRONMENTAL EXPOSURE

The quality control shall comply with the submitted, this Section, and ICC AC178.

Field testing of fiber shall include pull-off adhesion testing, per ASTM C1583/C1583M, and cured material tensile tests, per ASTM D3039, as per the project specifications and ICC AC178. Field tension testing for FRP anchors shall be per ASTM D7522/D7522M.

Exterior applications shall be protected with a 10-15 mil thick coat of epoxy. All seams and edges must be feathered. Apply paint to match existing condition.

All interior applications shall be protected with a fire resistive coating finish to provide a Class 1 rating per ASTM E84.

The following requirements shall be noted in the structural drawings:

GENERAL NOTES:

FIBER REINFORCED POLYMER (FRP)

1. CARBON FIBER REINFORCED POLYMER (FRP): [PRODUCT NAME] FRP COMPOSITE USING [PRODUCT NAME] EPOXY BY [MANUFACTURER], ICC-ESR-[NUMBER] OR IAPMO-UES-[NUMBER] (*OR EQUIVALENT*).
2. CLEAN AND PREPARE CONCRETE SURFACE FOR “BOND-CRITICAL APPLICATIONS” PER ACI 440.2R-17, SECTION 6 AND MANUFACTURER’S RECOMMENDATIONS.
3. MITGATION OF CRACKS WIDER THAN 0.010 INCH MUST BE PERFORMED PRIOR TO INSTALLATION OF FRP. NOTIFY SEOR IF CRACKS WIDER THAN 0.010 INCH ARE OBSERVED AT FRP INSTALLATION LOCATIONS.
4. MORTAR RAMP FOR FRP: SELECT MORTAR AND INSTALL RAMP PER MANUFACTURER’S SPECIFICATIONS.
5. INSTALL FRP COMPOSITE PER ACI 440.2R-17, SECTION 6 AND MANUFACTURER’S RECOMMENDED PROCEDURE. INSTALLATION OF FRP SYSTEM SHALL BE PERFORMED BY CERTIFIED APPLICATORS ONLY.
6. INSTALL FIRE AND UV PROTECTIVE COATING OVER THE ENTIRE FRP COMPOSITE PER MANUFACTURER’S RECOMMENDATIONS.

7. IF PENETRATIONS THROUGH FRP ARE REQUIRED FOR INSTALLATION OF MECHANICAL ANCHORS, ADHESIVE ANCHORS AND/OR POWDER-DRIVEN FASTENSERS (SHOT-PINS), SUBMIT PROPOSED PENETRATION LAYOUT FOR SEOR'S REVIEW.
8. FLAME-SPREAD COATING TO ACHIEVE CLASS I FLAME-SPREAD CLASSIFICATION AND A SMOKE-DENSITY CLASSIFICATION IN ACCORDANCE WITH CBC, SECTION 803.1.
9. THE ONSITE SUPERVISOR, FORMAN, AND SATURATION/MIXING TECHNICIAN SHALL PROVIDE WRITTEN VERIFICATION FROM THE MATERIAL MANUFATURER AS BEING FULLY TRAINED AND CERTIFIED TO INSTALL THE PROPOSED SYSTEMS.
10. THE CONTRACTOR SHALL HAVE A MINIUM OF TWENTY STRENGTHENING PROJECT REFERENCES USING FRP REINFORCEMENT SYSTEMS FOR SIMILAR PROJECTS AND APPLICATIONS IN THE LAST TWO YEARS.

STRUCTURAL TESTS, INSPECTIONS, AND OBSERVATIONS

1. AN INDEPENDENT TESTING AGENCY AND SPECIAL INSPECTORS SHALL BE RETAINED BY THE OWNER TO PERFORM TESTS AND INSPECTIONS.
2. THE FOLLOWING ITEMS REQUIRE TESTS AND INSPECTIONS IN ACCORDANCE WITH THE REQUIREMENTS OF THE CHAPTER "STRUCTURAL TESTS AND INSPECTIONS" OF THE APPLICABLE CODE. REQUIREMENTS FOR TESTS AND INSPECTIONS ARE IDENTIFIED IN THE SPECIFICATIONS.
    a. FIBER REINFORCED POLYMER (FRP)
    b. SEISMIC FORCE RESISTING SYSTEM (SFRS)
    c. [ENGINEER TO SPECIFY ADDITIONAL APPROPRIATE ELEMENTS PER DESIGN SCOPE, SUCH AS: SOILS AND EXCAVATIONS, CAST-IN-PLACE CONCRETE, STRUCTURAL STEEL, ETC.]
3. PROVIDE SPECIAL INSPECTION AND TESTING OF FIBER REINFORCED POLYMER (FRP) AS FOLLOWS. SUBMIT RESULTS FOR SEOR'S REVIEW.
    a. INSPECT AND EVALUATE INSTALLATION PER ACI 440.2R-17, SECTION 7.

b. ADHESION STRENGTH OF FRP COMPOSITE WILL BE TESTED PER ASTM D7522.

   i. INSTALL (3) 12”x12” SAMPLES OF SACRIFICAL (3) PLIES OF FRP COMPOSITE DUMMIES FOR ADHESION TEST FOR EACH BATCH MIX BUT NOT LESS THAN (3) DUMMIES PER FLOOR. THE DUMMY FRP COMPOSITES ARE TO BE INSTALLED AT THE TIME OR PROJECT FRP INSTALLATION USING THE SAME PROCEDURE AND MATERIALS. LOCATION OF DUMMIES ARE SHOWN ON DRAWINGS.

   ii. PERFORM (4) MINIMUM ADHESION STRENGTH TESTS ON EACH DUMMY. TENSION ADHESION STRENGTH SHOULD EXCEED 200 PSI AND SHOULD EXHIBIT FAILURE OF THE CONCRETE SUBSTRATE, FAILURE MODE “G,” PER ASTM D7522.

c. TENSION TEST FRP COMPOSITE PER ASTM D7565. PREPARE A SINGLE 12”x12” SAMPLE PER BATCH MIX AND PERFORM (3) TENSILE TESTS PER SAMPLE.

d. PERFORM FRP ANCHOR TESTS PER ASTM D7522/D7522M.

4. PROVIDE TESTS AND INSPECTIONS IN ACCORDANCE WITH THE CITY TESTING AND INSPECTION FORM. REQUIREMENTS FOR TESTS AND INSPECTIONS ARE IDENTIFIED IN THE SPECIFICATIONS.

5. NOTIFY THE SEOR AT SIGNIFICANT CONSTRUCTION STAGES (72) HOURS IN ADVANCE, AND PROVIDE ACCESS FOR THE FOLLOWING STRUCTURAL OBSERVATIONS:

   a. FIBER REINFORCED POLYMER (FRP)

      i. SURFACE PREPARATION

      ii. INSTALLATION OF FRP

      iii. INSTALLATION OF FRP ANCHORS

   b. [ENGINEER TO SPECIFY ADDITIONAL APPROPRIATE ELEMENTS PER DESIGN SCOPE, SUCH AS: STEEL FRAMING, CONCRETE, ETC.]