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APPENDIXA—SUMMARY OF STANDARD TEST METHODS

Table A provides a summary of test methods for the short- and long-term mechanical and durability testing of FRP rods and sheets.The recommended test methods are based on the knowledge gained from research results and literature worldwide and include those methods described in ACI 440.3R that have not yet been adopted by ASTM International.

Durability-related tests use the same test methods but require application-specific preconditioning of specimens. Acceptance of the data generated by the listed test methods can be the basis for FRP material system qualification and acceptance (for example,ACI 440.8).

Table A—Test methods for FRP systems

Property	ASTM test method(s)	ACI 440.3R test method	Summary of differences
Test methods for shets,prepreg.and laminates			
Surface hardness	D2538 D2240 D3418	—	No ACI methods developed
Coefficient of thermal expansion	D696	—	No ACI methods developed
Glass-transition temperature	E1640	—	No ACI methods developed
Volume fraction	D3171 D2584	—	NoACI methods developed
Sheet to concrete adhesion (direct tension pulloff)	D7522/D7522M	L.1*	ACI method provides specific requirements for specimen preparation not found in the ASTM method
Tensile strength and modulus	D7565/D7565M	L.2*	ACI method provides methods for calculating tensile strength and modulus on gross cross-sectional and effective fiber area basis.Section 3.3.1 is used to calculate design values.
Lap shear strength	D7616/D7616M	L.3	ACI method provides specific requirements for specimen preparation.
Test methods for FRP bars			
Cross-sectional area	D7205/D7205M	B.1'	Two options for bar area are provided in ASTM D7205/D7205M(nominal and actual),whereas only nominal area is used in ACI 440.3R Method B.1
Longitudinal tensile strength and modulus	D7205/D7205M	B.2°	Strain limits for calculation of modulus are different in the two methods.
Shear strength	D7617/D7617M	B.4*	The ACI method focuses on dowel action of bars and does not overlap with existing ASTM methods that focus mainly on beam shearing failure modes. Bar shear strength is of specific concern for applications where FRP rods are used to cross construction joints in concrete pavements.
Durability properties	—	B.6	No existing ASTM test methods available.
Fatigue properties	D3479/D3479M	B.7	ACI methods provide specific information on anchoring bars in the test fixtures and on attaching elongation measuring devices to the bar.The ACI methods also require specific calculations that are not provided in the ASTM methods.
Creep properties	D7337/D7337M	B.8°	
Relaxation properties	D2990 E328	B.9	
Flexural tensile properties	—	B.11	No existing ASTM test methods available.
Flexural properties	D790	—	No ACI methods developed.
Coefficient of thermal expansion	E831 D696	—	No ACI methods developed.
Glass-transition temperature	E1640 D648 E2092	—	No ACI methods developed.
Volume fraction	D3171	—	NoACI methods developed.
Test method inACI440.3R is replaced by reference to appropriate ASTM method.			

APPENDIX B—AREAS OF FUTURE RESEARCH

Future research is needed to provide information in areas that are still unclear or are in need of additional evidence to validate performance.The list of topics presented in this appendix provides a summary.

a)Materials

i.Durability of FRP-concrete bond for various exposure conditions

ii.Strength and stiffness degradation of FRP systems in harsh environments

iii.Creep-rupture behavior and endurance times of FRP systems

b)Flexure/axial force

i.Tensile strengthening of concrete members with FRP systems

ii.Anchorage of FRPsystems for flexural strengthening of concrete members

iii.Maximum crack width and deflection prediction and control of concrete reinforced with FRP systems

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iv.Long-term deflection behavior of concrete flexural members strengthened with FRP systems

v.Effects of high concrete strength on behavior ofFRP-strengthened members

vi.Effects of lightweight concrete on behavior ofFRP-strengthened members

c)Shear

i.Use ofFRP systems for strengthening deep beams

ii.Use of FRP systems for punching shear reinforcement in two-way systems

iii.Anchoring of FRP systems with anchorage techniques other than fiber anchors

d)Seismic strengthening

i.Use of FRP systems for strengthening diaphragms, including collectors

ii.Use ofFRP systems for strengthening shear walls

iii.Use of anchorage to control debonding of FRP systems for seismic strengthening

iv.Use of fiber anchors to provide load path continuity of longitudinal FRP for flexural strengthening of walls or columns through slabs.

v.Use of fiber anchors to provide anchorage of longitudinalFRP for flexural strengthening of walls or columns at foundations.

APPENDIX C—METHODOLOGY FOR COMPUTATION OF SIMPLIFIED P-M INTERACTION DIAGRAM FOR NONCIRCULAR COLUMNS

Axial load-moment(P-M)interaction diagrams may be developed by satisfying strain compatibility and force equilibrium using the model for the stress strain behavior for FRP-confined concrete presented in Eq.(12.1c)through (12.1e). For simplicity,the portion of the unconfined and confined P-M diagrams corresponding to compression-controlled failure can be reduced to twobilinear curves passing through the following points(Fig.12.2).(The following only makes reference to the confined case because the unconfined case is analogous):

a)Point A(pure compression)at a uniform axial compressive strain of confined concrete Eccu

b)Point B with a strain distribution corresponding to zero strain at the layer of longitudinal steel reinforcement nearest to the tensile face,and a compressive strain Ecu on the compression face

c)Point C with a strain distribution corresponding to balanced failure with a maximum compressive strain Eccuand a yielding tensile strain e,y at the layer of longitudinal steel reinforcement nearest to the tensile face

For confined concrete,the value of φP,corresponding to Point A(φM,equals zero)is given in Eq.(12.1a)and(12.1b), while the coordinates of Points B and C can be computed as:

$$\phi P_{n(B,C)} = \phi\begin{bmatrix} A(y_t)^3 + B(y_t)^2 + C(y_t) \\ +D + \sum A_{si} f_{si} \end{bmatrix} \quad \text{(C-1)}$$

$$\phi M_{n(B,C)} = \phi\begin{bmatrix} E(y_t)^4 + F(y_t)^3 + G(y_t)^2 \\ +H(y_t) + I + \sum A_{si} f_{si} d_i \end{bmatrix} \quad \text{(C-2)}$$

where

$$A = \frac{-b(E_c - E_2)^2}{12 f_c'}\left(\frac{\varepsilon_{ccu}}{c}\right)^2 \quad \text{(C-3a)}$$

$$B = \frac{b(E_c - E_2)}{2}\left(\frac{\varepsilon_{ccu}}{c}\right) \quad \text{(C-3b)}$$

$$C = -bf_c' \quad \text{(C-3c)}$$

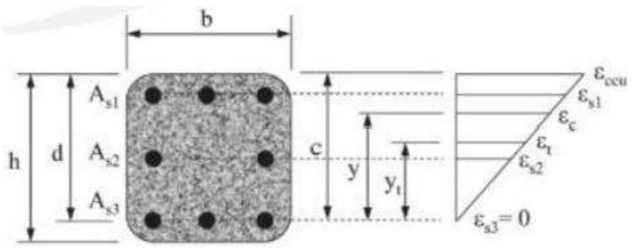
$$D = bcf_c' + \frac{bcE_2}{2}(\varepsilon_{ccu}) \quad \text{(C-3d)}$$

$$E = \frac{-b(E_c - E_2)^2}{16 f_c'}\left(\frac{\varepsilon_{ccu}}{c}\right)^2 \quad \text{(C-3e)}$$

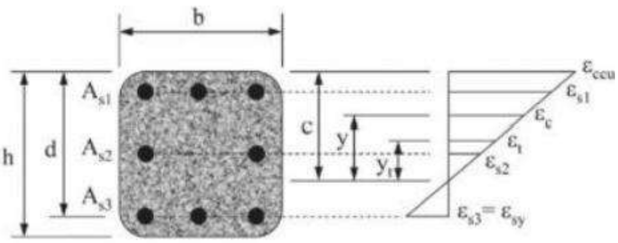
$$F = \begin{bmatrix} b\left(c - \dfrac{h}{2}\right)\dfrac{(E_c - E_2)^2}{12 f_c'}\left(\dfrac{\varepsilon_{ccu}}{c}\right)^2 \\ + \dfrac{b(E_c - E_2)}{3}\left(\dfrac{\varepsilon_{ccu}}{c}\right) \end{bmatrix} \quad \text{(C-3f)}$$

$$G = -\left(\frac{b}{2} f_c' + b(c - h/2)\frac{(E_c - E_2)}{2}\left(\frac{\varepsilon_{ccu}}{c}\right)\right) \quad \text{(C-3g)}$$

$$H = bf_c'\left(c - \frac{h}{2}\right) \quad \text{(C-3h)}$$



(a)Point B



(b)Point C

Fig.C1—Strain distributionsfor Points B and Cfor simplified interaction diagram.

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$$I = \begin{bmatrix} \frac{bc^2}{2} f_c' - bcf_c'\left(c - \frac{h}{2}\right) + \frac{bc^2 E_2}{3}(\varepsilon_{ccu}) \\ -\frac{bcE_2}{2}\left(c - \frac{h}{2}\right)(\varepsilon_{ccu}) \end{bmatrix} \quad \text{(C-3i)}$$

In Eq.(C-3a)through (C-3i),c is the distance from the extreme compression fiber to the neutral axis(Fig C.1 given by Eq.(C-4):

$$c = \begin{cases} d & \text{for Point B} \\ d\dfrac{\varepsilon_{ccu}}{\varepsilon_{sy} + \varepsilon_{ccu}} & \text{for Point C} \end{cases} \quad \text{(C-4)}$$

The parameter y,represents the vertical coordinate within the compression region measured from the neutral axis position and corresponds to the transition strain e!(Eq.(C-5) [refer to Fig.C.1]).

$$y_t = c\frac{\varepsilon_t'}{\varepsilon_{ccu}} \quad \text{(C-5)}$$

wherefsi is the stress in the i-th layer of longitudinal steel reinforcement.The values are calculated by similar triangles from the strain distribution corresponding to Points B and C.Depending on the neutral axis position c,the sign of fi will be positive for compression and negative for tension.A flowchart illustrating the application of the proposed methodology is shown in Fig.C.2.

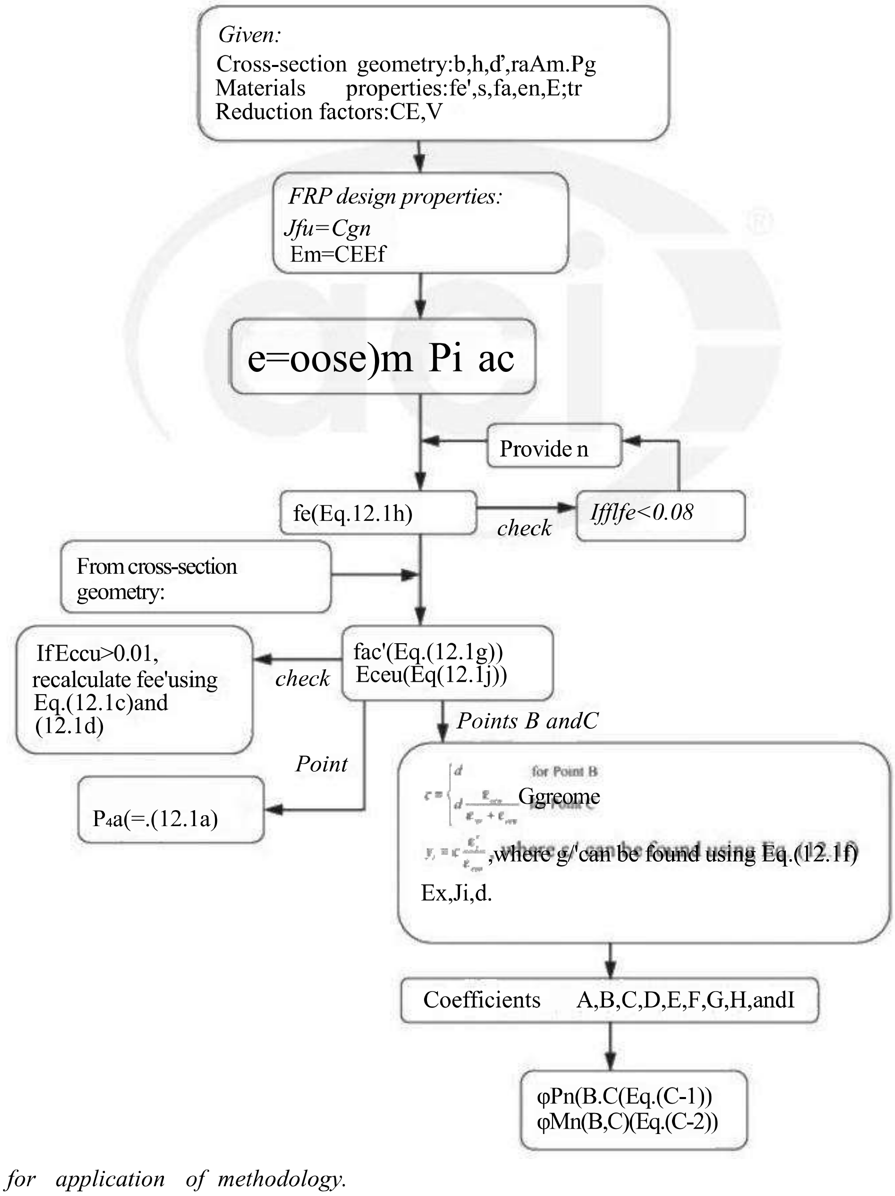

Fig.C.2—Flowchart for application of methodology.

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