S806-02
Design and Construction of Building Components with Fibre-Reinforced Polymers

(Reaffirmed 2007)

Update No. 5

CAN/CSA-S806-02

August 2009

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Revised	Clauses 8.4.5.2 and 10.6.2.3 and Table 14
New	None
Deleted	None

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May 2002	iii–x, 1–28, 31–38, 41–46, 49–64, 67–102, and 105–177
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May 2004	Cover, title page, and copyright page
November 2005	103 and 104
August 2009	29, 30, 39, 40, 65, and 66

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(v) other types of transverse FRP reinforcement possessing performance characteristics at least equal to those of the ties listed in Items (i) to (iv), as verified by sufficient experiments.
(b) The spacing of FRP ties shall not exceed the least of the following dimensions:
(i) 16 times the diameter of the smallest longitudinal bars or the smallest bar in a bundle;
(ii) 48 times the minimum cross-sectional dimension (or diameter) of FRP tie or grid;
(iii) the least dimension of the compression member; or
(iv) 300 mm in compression members containing bundled bars.
For specified concrete compressive strength in excess of 50 MPa, the tie or grid spacing determined above shall be multiplied by 0.75.
(c) Ties at column-slab, column-beam, and column-bracket connections shall be placed in accordance with Clauses 7.6.5.3 and 7.6.5.4 of CSA Standard A23.3.

8.4.3.4
All non-prestressed bars for tied compression members shall be enclosed by FRP ties having a minimum cross-sectional dimension (or diameter) of at least 30% of the diameter of the largest longitudinal bar when these are No. 30 or smaller, and a minimum cross-sectional dimension (or diameter) of at least 10 mm for No. 35, No. 45, No. 55, and bundled longitudinal bars.

8.4.4 Method for Design for Shear in Flexural Regions

8.4.4.1
The following method of design shall be used for shear of flexural members not subjected to significant axial tension.

8.4.4.2
Where the reaction force in the direction of the applied shear introduces compression into a support region, the following shall apply:
(a) for non-prestressed members, sections located less than a distance d from the face of the support may be designed for the same shear, V_f, as that computed at a distance d; and
(b) for prestressed members, sections located less than a distance h/2 from the face of the support may be designed for the same shear, V_f, as that computed at a distance h/2.

8.4.4.3
Members subjected to shear shall be proportioned so that $V_r \geq V_f$.

8.4.4.4
The factored shear resistance, V_r, shall be determined as follows:
(a) For FRP stirrups

$$V_r = V_c + V_{sF} \leq V_c + 0.6\lambda\phi_c\sqrt{f_c'}b_w d \quad \textbf{(8-8)}$$

(b) For steel stirrups

$$V_r = V_c + V_{ss} \leq V_c + 0.8\lambda\phi_c\sqrt{f_c'}b_w d \quad \textbf{(8-9)}$$

(c) For sections having either
(i) at least the minimum amount of transverse reinforcement given by Equation 8-14; or
(ii) an effective depth not exceeding 300 mm

$$V_c = 0.035\lambda\phi_c\left(f_c'\rho_w E_F \frac{V_f}{M_f} d\right)^{1/3} b_w d \quad \textbf{(8-10)}$$

but V_c need not be taken as less than $0.1\lambda\phi_c\sqrt{f'_c}b_w d$ nor shall it exceed $0.2\lambda\phi_c\sqrt{f'_c}b_w d$. The quantity $\frac{V_f d}{M_f}$ shall not be taken as greater than 1.0 where $V_f d/M_f$ is the value of factored shear divided by factored moment at the section under consideration corresponding to the load combination causing maximum moment to occur at the section.

8.4.4.5

For sections with an effective depth greater than 300 mm and with no transverse shear reinforcement or less transverse reinforcement than that required by Equation 8-14, the value of V_c shall be calculated from

$$V_c = \left(\frac{130}{1000 + d}\right)\lambda\phi_c\sqrt{f'_c}b_w d \geq 0.08\lambda\phi_c\sqrt{f'_c}b_w d \quad \textbf{(8-11)}$$

8.4.4.6

Transverse reinforcement shall be perpendicular to the longitudinal axis of the member.

For members with FRP flexural and shear reinforcement, the value of V_{sF} shall be calculated from

$$V_{sF} = \frac{0.4\phi_F A_v f_{Fu} d}{s} \quad \textbf{(8-12)}$$

For members with FRP flexural reinforcement and steel shear reinforcement, the value of V_{ss} shall be calculated from

$$V_{ss} = \frac{\phi_s A_v f_y d}{s} \quad \textbf{(8-13)}$$

8.4.5 Minimum Shear Reinforcement

8.4.5.1

A minimum area of shear reinforcement shall be provided in all regions of flexural members where the factored shear force, V_f, exceeds $0.5V_c + \phi_F V_p$ or the factored torsion, T_f, exceeds $0.25\ T_{cr}$. This requirement may be waived for

(a) slabs and footings;

(b) concrete joist construction;

(c) beams with a total depth not greater than 250 mm; and

(d) beams cast integrally with slabs where the overall depth is not greater than one-half the width of the web or 600 mm.

Δ 8.4.5.2

Where shear reinforcement is required by Clause 8.4.5.1 or by calculation, the minimum area of shear reinforcement shall be such that

$$A_v = \frac{0.2\sqrt{f'_c}b_w s}{f_{Fu}} \quad \textbf{(8-14)}$$

8.4.6 Types of Shear Reinforcement

Transverse reinforcement provided for shear may consist of

(a) stirrups or ties perpendicular to the axis of the member; or

(b) FRP two-dimensional grids or three-dimensional cages with ribs located perpendicular to the axis of the member.

(a) extreme fibre stress in compression due to sustained loads: $0.45f'_c$

(b) extreme fibre stress in compression due to total load: $0.60f'_c$

(c) extreme fibre stress in tension in precompressed tensile zone: $0.25\lambda\sqrt{f'_c}$

10.5 Permissible Stresses in Tendons

10.5.1 Permissible Stresses at Jacking and Transfer

Permissible stresses at jacking and transfer, as a function of $f_{Fpu,}$ shall be in accordance with Table 13. Special attention shall be given when jacking draped strands to avoid local failure at the bends.

Even when failure is initiated by the tensile rupture of the FRP strands and/or bars, the ultimate resistance moment of the section shall be based on the stresses given in Table 13.

10.5.2 Anchorage for FRP Tendons

Anchors shall be tested prior to application in order to check that they are capable of developing at least 90% of the specified tensile strength of FRP tendons. The number of samples required shall be specified on the plan and shall not be less than two.

10.5.3 Reinforcement of Disturbed Regions

Disturbed regions, such as the anchorage zone, anchor buttress, parts of beams around openings, and beams with dapped ends shall be reinforced against splitting and bursting.

10.6 Losses of Prestress

10.6.1 Effective Prestressing Force

Effective prestressing force shall be calculated according to

$$P(x) = P_i - \sum \Delta P_i(x) + \Delta P_T(x) \qquad \textbf{(10-1)}$$

10.6.2 Prestress Losses

10.6.2.1

To determine the effective prestress, $f_{Fpe,}$ allowance for the following sources of loss of prestress shall be considered:

(a) anchorage seating loss;
(b) elastic shortening of concrete;
(c) friction loss due to intended and unintended curvature in post-tensioning tendons;
(d) creep of concrete;
(e) shrinkage of concrete;
(f) relaxation of tendon stress; and
(g) temperature change.

10.6.2.2

When jacking is performed using steel strands connected to FRP tendons through steel couplers, the accumulation of setting loss due to anchorage of steel and FRP tendons shall be considered. For different anchoring systems, the amount of setting shall be provided by the manufacturer or determined by testing.

The loss due to anchor slip shall be computed using the formula

$$\Delta\sigma_{pAS} = (\Delta_{AS}\, E_F) / L \qquad \textbf{(10-2)}$$

where

L = length of tendon between anchorages

Δ **10.6.2.3**
Prestress loss due to elastic shortening shall be computed using the following formulas:

for pretensioned strands:

$$\Delta\sigma_{PES} = nf'_{cpg} \quad \textbf{(10-3)}$$

for post-tensioned strands:

$$\Delta\sigma_{PES} = 0.5nf'_{cpg}\left(\frac{N-1}{N}\right) \quad \textbf{(10-4)}$$

10.6.2.4
The effect of friction loss in post-tensioning tendons shall be computed by

$$P_x = P_i e^{-(\mu\alpha+\lambda x)} \quad \textbf{(10-5)}$$

The values of μ and λ shall be determined by testing, except that where the sheaths are used with CFRP, the values $\mu = 0.3$ and $\lambda = 0.004$/m may be used.

10.6.2.5
The loss of prestress due to creep and shrinkage shall be calculated as in steel prestressed concrete, taking into account the modulus of elasticity of FRP.

10.6.2.6
The amount of relaxation shall be evaluated appropriately for each type of FRP tendons used and shall be reflected in the design. In the absence of more specific information, the following values may be used:
(a) for CFRP: relaxation (%) = 0.231 + 0.345 log(t); and **(10-6)**
(b) for AFRP: relaxation (%) = 3.38 + 2.88 log(t). **(10-7)**

where
t = time in days.

10.6.2.7
Special care shall be taken in estimating relaxation losses of FRP tendons when steam curing is used or when tendons of low-fibre volume are used.

10.6.2.8
The variation of prestress due to change of temperature shall be obtained using the formula

$$\Delta\sigma_{pT} = \Delta T(\alpha_F - \alpha_c)E_F \quad \textbf{(10-8)}$$

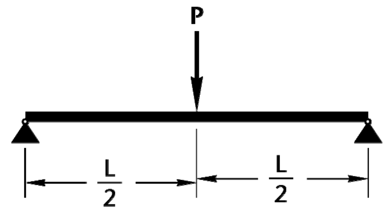
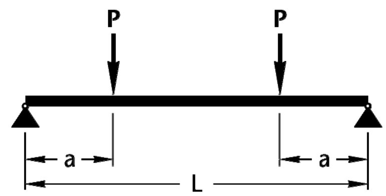
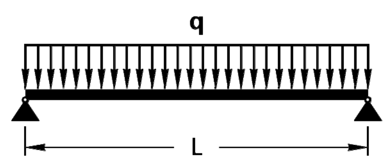
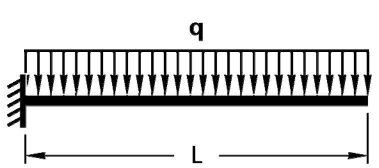
10.7 Flexural Resistance

10.7.1 Strain Compatibility Analysis
Strain compatibility analysis shall be based on the stress-strain curves of the FRP to be used and on the assumption of a perfect bond in the bonded tendons.

10.7.2 Bond Reduction Coefficient
The analysis of concrete elements prestressed with unbonded FRP tendons shall be based on the concept of bond reduction coefficient. The stress in unbonded FRP tendon at ultimate shall be calculated by solving Equations 10-9 and 10-10 simultaneously for f_{Fp}.

Table 12
Maximum Deflection Formulas for Typical FRP Reinforced Concrete Beams and One-Way Slabs

(See Clause 8.3.2.4.)

Beam type	Maximum deflection
	$\delta_{max} = \frac{PL^3}{48\,E_c I_{cr}}\left[1 - 8\eta\left(\frac{L_g}{L}\right)^3\right]$
	$\delta_{max} = \frac{PL^3}{24\,E_c I_{cr}}\left[3\left(\frac{a}{L}\right) - 4\left(\frac{a}{L}\right)^3 - 8\eta\left(\frac{L_g}{L}\right)^3\right]$
	$\delta_{max} = \frac{5qL^4}{384\,E_c I_{cr}}\left[1 - \frac{192}{5}\eta\left[\frac{1}{3}\left(\frac{L_g}{L}\right)^3 - \frac{1}{4}\left(\frac{L_g}{L}\right)^4\right]\right]$
	$\delta_{max} = \frac{PL^3}{3\,E_c I_{cr}}\left[1 - \eta\left(\frac{L_g}{L}\right)^3\right]$
	$\delta_{max} = \frac{qL^4}{8\,E_c I_{cr}}\left[1 - \eta\left(\frac{L_g}{L}\right)^4\right]$

Note: $\eta = \left(1 - \frac{I_{cr}}{I_g}\right)$

Table 13
Permissible Stresses in Tendons as a Function of f_{Fpu}

(See Clause 10.5.1.)

Tendon	Stresses at jacking		Stresses at transfer	
	Pretensioned	Post-tensioned	Pretensioned	Post-tensioned
AFRP	$0.40f_{Fpu}$	$0.40f_{Fpu}$	$0.38f_{Fpu}$	$0.35f_{Fpu}$
CFRP	$0.70f_{Fpu}$	$0.70f_{Fpu}$	$0.60f_{Fpu}$	$0.60f_{Fpu}$

Δ

Table 14
Minimum Area of Bonded Non-Prestressed Reinforcement

(See Clause 10.9.)

Type of member	Concrete tensile stress			
	$\leq 0.5\lambda\sqrt{f_c'}$		$< 0.5\lambda\sqrt{f_c'}$	
	Type of tendon			
	Bonded	Unbonded	Bonded	Unbonded
Beams				
CFRP	0	0.0044A	0.0033A	0.0055A
AFRP		0.0048A	0.0036A	0.0060A
One-way slabs				
CFRP	0	0.0033A	0.0022A	0.0044A
AFRP		0.0036A	0.0024A	0.0048A

Table 15
Development Length and Transfer Length for Certain Types of FRP

(See Clause 10.12.)

FRP tendon type	Diameter, mm	Development length	Transfer length
CFRP strand	N/A	$50d_b$	$20d_b$
CFRP rebar	N/A	$180d_b$	$60d_b$
AFRP	$8 \leq d_b < 12$	$120d_b$	$50d_b$
AFRP	$12 \leq d_b < 16$	$100d_b$	$40d_b$
AFRP	$16 \leq d_b$	$80d_b$	$35d_b$

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high-elongation (tough) adhesive system that will meet the temperature requirements of the test. The width of the tab shall be the same as the width of the specimen. The length of the tabs shall be determined by the shear strength of the adhesive, the specimen, or the tabs (whichever is lower), the thickness of the specimen, and the estimated strength of the composite. If a significant proportion of failures occur within one specimen width of the tab, there shall be a re-examination of the tab material and configuration, gripping method, and adhesive, and necessary adjustments shall be made in order to promote failure within the gauge section.

G8 Conditioning

G8.1 Standard Dry Specimens

The test specimens shall be stored in an enclosed space maintained at a temperature of 23 ± 5°C and a relative humidity of 50 ± 10%, and shall be tested in a room maintained at the same conditions.

G8.2 Other Than Standard Dry Specimens

The test specimens shall be stored in an enclosed space maintained at the specified conditions. All conditioning shall be reported.

G9 Test Procedure

G9.1 Number of Specimens

At least five specimens shall be tested for each test condition.

G9.2 Measurement

The width and thickness of the specimen shall be measured at several points. The average value of cross-sectional area shall be recorded.

Δ G9.3 Set-up and Speed

The specimen shall be placed in the grips of the testing machine, taking care to align the long axis of the specimen and the grips with an imaginary line joining the points of attachment of the grips to the machine. The speed of testing shall be set to give the strain rates in the specimen gauge section. Speed of testing shall be set to effect a constant strain rate in the gauge section, with standard strain rates between 166.7 and 333.4 micro strain/s being preferred. A constant cross-head speed may also be used. The cross-head speed shall be determined by multiplying the strain rate by the distance between tabs, in inches or millimetres. If strain is to be determined, the extension indicator or the strain-recording equipment (if strain gauges are used as primary transducers) shall be attached to the specimen.

G9.4 Recording

Load and strain (or deformation) shall be recorded continuously, if possible. Alternatively, load and deformation may be recorded at uniform intervals of strain. The maximum load sustained by the specimen during the test and the strain at rupture shall both be recorded.

G9.5 Calculations — Method 1

The tensile strength and modulus may be calculated using the following equations, with the results being reported to a precision of three significant figures:

$$f_u = \frac{p}{bd} \qquad \textbf{(G-1)}$$

$$E = \left(\frac{dP}{dl}\right)\left(\frac{l}{bd}\right) \qquad \textbf{(G-2)}$$

G9.6 Calculations — Method 2

An alternative method based on equivalent fibre area may be used, in which case the tensile strength and elastic modulus are found from the following equations and the results reported with a precision of three significant figures:

$$f'_u = \frac{P}{bd'} \qquad \textbf{(G-3)}$$

$$E' = \left(\frac{dP}{dl}\right)\left(\frac{l}{bd'}\right) \qquad \textbf{(G-4)}$$

G9.7

For each series of tests, the average value, standard deviation, and coefficient of variation for the tensile strength, failure strain, and elastic modulus shall be calculated.

G10 Report

The report shall include the following:
(a) identification of the material tested;
(b) description of fabrication method and stacking sequence;
(c) test specimen dimensions;
(d) the conditioning procedure used;
(e) the number of specimens tested;
(f) the speed of testing, if other than specified;
(g) the tensile strength, failure strain, and elastic modulus, including average value, standard deviation, and coefficient of variation;
(h) the date of test; and
(i) the test operator.

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shorter (b) section side dimension is not greater than 1.5, may have their axial compression capacity enhanced by the confining effect of FRP composite material placed with fibres running essentially perpendicular, $\theta \geq 75°$, to the longitudinal axis of the member.

For rectangular sections confined with transverse FRP composites, section corners shall be rounded to a radius not less than 20 mm before placing composite material. Axial compression capacity enhancement by fibre-reinforced composite material to rectangular sections with an aspect ratio h/b > 1.5 shall be subject to special analysis confirmed by test results.

11.4.2.2

The confined compressive strength of concrete, f'_{cc}, in FRP wrapped columns shall be computed by

Δ $$f'_{cc} = 0.85 f'_c + k_l k_c f_l \qquad \textbf{(11-7)}$$

where

$$k_l = 6.7 (k_c f_l)^{-0.17} \qquad \textbf{(11-8)}$$

k_c = 1.0 for circular and oval jackets
= 0.25 for square and rectangular jackets

$$f_l = \frac{2 t_j f_{Fj}}{D} \qquad \textbf{(11-9)}$$

where

f_{Fj} = $0.004E_F$ or $\phi_F f_{Fu}$, whichever is less

11.4.3 Ductility Enhancement

FRP composites oriented essentially transversely to the axis of columns may be used to enhance the flexural ductility capacity of circular and rectangular sections where the ratio of longer to shorter section dimension does not exceed 1.5. The enhancement is provided by increasing the effective compression strain of the section and may be calculated in accordance with Clause 12.5.3.

11.4.4 Shear Strength Enhancement

11.4.4.1

Shear strength of circular and rectangular columns can be enhanced by FRP composites with fibre oriented essentially perpendicular, $\theta \geq 75°$, to the members' axis.

For rectangular sections with shear enhancement provided by transverse FRP composite material, section corners shall be rounded to a radius not less than 20 mm before placing composite material.

11.4.4.2

The shear resistance of a column strengthened by FRP composite with fibre oriented at angle $\theta \geq 75°$ to the longitudinal axis of the columns shall be determined by

$$V_r = V_c + V_s + V_F \leq V_c + 0.6\lambda\phi_c\sqrt{f'_c}A_{cv} \qquad \textbf{(11-10)}$$

where

$$V_c = 0.2\lambda\phi_c\sqrt{f'_c}A_{cv} \qquad \textbf{(11-11)}$$

For both circular and rectangular columns, the transverse steel reinforcement contribution, V_s, shall be determined by

$$V_s = \frac{\phi_s A_v f_y d}{s} \qquad \textbf{(11-12)}$$

For both circular and rectangular columns, the contribution from the FRP composites, V_F, shall be determined by

$$V_F = 2\phi_F f_{Fd} t_j D \qquad \textbf{(11-13)}$$

where

$$f_{Fd} = 0.004E_F \leq \phi_F f_{Fu} \qquad \textbf{(11-14)}$$

11.5 Design Requirements of Concrete and Masonry Wall Strengthening

11.5.1 Flexural Strength

11.5.1.1

FRP composites bonded to surfaces of concrete and masonry walls with $\theta \leq 15°$ may be used to enhance the design flexural strength of the walls. Only the tension FRP reinforcement shall be considered effective. Section analysis shall be based on normal assumptions and strain compatibility between concrete or masonry reinforcement and composite material. Unless the flexural strength is proven by tests, an extreme compression concrete strain of $\varepsilon_{cu} = 0.0035$, an extreme masonry compression strain of $\varepsilon = 0.003$, and the maximum FRP tensile strain of 0.007 shall be assumed in determining flexural strength. The enhancement of tensile force per unit width provided by a fibre element of effective thickness t_F, oriented at angle θ to the direction of member axis, shall be

$$\Delta F = t_j f_F \qquad \textbf{(11-15)}$$

where

$$f_F = E_F \varepsilon_F \cos^2\theta \leq \phi_F f_{FU}$$

where

ε_F = the strain in the concrete to which the fibre is bonded

If $\theta > 15°$, the fibre contribution to flexural strength shall be ignored, except if equal fibre quantities are provided with a mirror orientation of θ to the member axis thereby creating an overall symmetry of fibre orientation with respect to the column axis, the contribution of fibres with $\theta = 45°$ shall be considered.

11.5.1.2

Debonding or anchorage failure of the FRP flexural reinforcement shall be considered in the design.

11.5.1.3

Proven anchorage methods shall be used to ensure development of the strength of the FRP at the section considered.

11.5.2 Shear Strength Enhancement

11.5.2.1

The shear-resistant capacity of FRP reinforced concrete or masonry shear walls shall be determined from the following:

(a) For FRP reinforced concrete walls

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Preface

This is the first edition of CSA Standard S806, *Design and Construction of Building Components with Fibre-Reinforced Polymers*.

Because much of the content of this Standard is new, some overlap and duplication of requirements between clauses is deemed appropriate to foster clarity, to keep each clause a complete unit as much as possible, and to minimize cross-references.

This Standard contains provisions for building components composed of fibre-reinforced polymers (FRP) and also for building components reinforced with FRP. The fibres are of aramid, carbon, and glass. The polymers are resins that are rigid at room temperature; relevant provisions relate to thermosetting types of resin. The Standard covers general design requirements, limit states design, the properties of FRP components and reinforcing materials, the design of concrete components with FRP reinforcement, the design of concrete components prestressed with FRP, the design of components with surface-bonded FRP, the design of fibre-reinforced concrete (FRC)/FRP composite cladding, and seismic design and construction. Normative annexes provide test procedures that are integral to the Standard, while informative annexes describe best current practice.

This Standard was prepared by the Technical Committee on Design and Construction of Building Components with Fibre-Reinforced Polymers, under the jurisdiction of the Strategic Steering Committee on Structures (Design), and has been formally approved by the Technical Committee. It will be submitted to the Standards Council of Canada for approval as a National Standard of Canada.

May 2002

Notes:

(1) *Use of the singular does not exclude the plural (and vice versa) when the sense allows.*

(2) *Although the intended primary application of this Standard is stated in its Scope, it is important to note that it remains the responsibility of the users of the Standard to judge its suitability for their particular purpose.*

(3) *This publication was developed by consensus, which is defined by* CSA Policy governing standardization — Code of good practice for standardization *as "substantial agreement. Consensus implies much more than a simple majority, but not necessarily unanimity". It is consistent with this definition that a member may be included in the Technical Committee list and yet not be in full agreement with all clauses of this publication.*

(4) *CSA Standards are subject to periodic review, and suggestions for their improvement will be referred to the appropriate committee.*

(5) *All enquiries regarding this Standard, including requests for interpretation, should be addressed to Canadian Standards Association, 178 Rexdale Boulevard, Toronto, Ontario, Canada M9W 1R3.*

Requests for interpretation should

(a) define the problem, making reference to the specific clause, and, where appropriate, include an illustrative sketch;

(b) provide an explanation of circumstances surrounding the actual field condition; and

(c) be phrased where possible to permit a specific "yes" or "no" answer.

Committee interpretations are processed in accordance with the CSA Directives and guidelines governing standardization *and are published in CSA's periodical* Info Update. *For subscription details, write to CSA Sales Promotion,* Info Update, *at the address given above.*

S806-02
Design and Construction of Building Components with Fibre-Reinforced Polymers

1 Scope

1.1 General

This Standard provides requirements for the design and evaluation of building components of fibre-reinforced polymers (FRP) in buildings and of building components reinforced with FRP materials. It is based on limit states design principles and is consistent with the *National Building Code of Canada*.

This Standard does not apply to the design of fibre-reinforced concrete (FRC), except for FRC/FRP cladding as defined in Clause 7.3 and Clause 13.

Note: *Procedures, test methods, and specifications are provided in Annexes A to T.*

1.2 FRP Components

Requirements for the determination of engineering properties and design of self-supporting FRP components are covered by this Standard.

1.3 FRP Reinforced Components

Requirements for the determination of engineering properties and design of FRP reinforced building components are covered by this Standard. The FRP reinforcing elements covered include bars, tendons, mats, grids, roving, sheets, and laminates.

1.4 Exposure to Fire and Temperature Effects

This Standard requires the designer to consider the possible effects of exposure to fire or elevated temperatures on the performance of FRP components and FRP reinforced components.

2 Definitions, Acronyms, Subscripts and Symbols, and Units

2.1 Definitions

The following definitions apply in this Standard. Specialized definitions appear in individual clauses.

Aggregate, low density — aggregate conforming to the requirements of ASTM Standard C 330.

Aramid — organic material derived from polyamide incorporating aromatic ring structure.

Bar, FRP — resin-bound construction, made mostly of continuous fibres, in the shape of a bar, used to reinforce concrete.

Bonded tendon — a prestressing tendon that is bonded to concrete either directly or through grouting.

Braiding — intertwining of fibres in an organized fashion.

Column — member with a ratio of height to least lateral dimension of 3 or greater, used primarily to support axial compressive load.

Combustible — the property of a material that fails to meet the acceptance criteria of ULC Standard CAN4-S114.

Combustible construction — types of construction that do not meet the requirements for noncombustible construction.

Composite — a combination of one or more materials differing in form or composition on a macro scale. The constituents retain their identities, ie, they do not dissolve or merge completely into one another, although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

Composite concrete flexural members — flexural members of precast or cast-in-place concrete elements, or both, constructed in separate placements but interconnected so that all elements respond to loads as a unit.

Concrete clear cover — distance from the concrete surface to the nearest surface of reinforcement or prestressing tendon.

Concrete, structural low density — concrete having a 28 day compressive strength not less than 20 MPa and an air dry density not exceeding 1850 kg/m^3.

Concrete, structural semi-low density — concrete having a 28 day compressive strength not less than 20 MPa and an air dry density between 1850 and 2150 kg/m^3.

Cross tie — a reinforcing bar that passes through the core and ties together the opposite sides of a member.

Curvature friction — friction resulting from bends or curves in the specified prestressing tendon profile.

Deformability — the ratio of energy absorption (area under the moment curvature curve) at the ultimate limit state to that at a defined service level.

Designer — person responsible for the design.

Development length — length of embedded reinforcement required to develop the design strength of reinforcement.

Effective depth of section — distance measured from the extreme compression fibre to the tension force.

Effective prestress — stress remaining in prestressing tendons after all losses have occurred.

E-glass — a family of glass with a calcium alumina borosilicate composition and a maximum alkali content of 2.0%; a general-purpose fibre that is used in reinforced polymers.

Embedment length — length of embedded reinforcement provided beyond a critical section.

Fibre — any fine threadlike object of mineral or organic origin, natural or synthetic.

Fibre, aramid — a highly oriented organic fibre derived from polyamide incorporating aromatic ring structure.

Fibre, carbon — fibre produced by the heating of organic precursor materials containing a substantial amount of carbon, such as rayon, polyacrylonitrile (PAN), or pitch, in an inert environment.

Fibre content — the amount of fibre present in a composite. This is usually expressed as a percentage volume fraction or weight fraction of the composite.

Fibre, glass — fibre drawn from an inorganic product of fusion that has cooled without crystallizing.

Fibre-reinforced concrete (FRC) — for the purposes of this Standard, concrete reinforced by randomly distributed short fibres.

Fibre-reinforced polymers (FRP) — composite material formed from continuous fibres impregnated with a fibre-binding polymer, then hardened and moulded in the form of reinforcement for concrete.

Fibre volume fraction — the ratio of the volume of fibres to the volume of the composite.

Fibre weight fraction — the ratio of the weight of fibres to the weight of the composite.

Fire endurance — a measure of the elapsed time during which a building material or assemblage continues to exhibit fire resistance. As applied to elements of buildings, it is measured by the methods and criteria defined in ULC Standard CAN/ULC-S101.

Fire resistance — the property of a material or assemblage to withstand or give protection from fire. As applied to buildings, it is characterized by the ability to confine fire or to continue to perform a given structural function, or both, as defined in ULC Standard CAN/ULC-S101.

Fire-resistance rating — the time in hours or fraction thereof during which a material or assembly of materials will withstand the passage of flame and the transmission of heat, determined by exposure to fire under specified conditions of test and performance criteria or as determined by extension or interpretation of information derived from those conditions and criteria as prescribed in the *National Building Code of Canada*.

Flame-spread rating — an index or classification indicating the extent of spread-of-flame on the surface of a material or assembly of materials as determined in a standard fire test as prescribed in the *National Building Code of Canada*.

Glass transition temperature — the temperature at which the elastic modulus of the polymers is significantly reduced due to its molecular structure.

Grid — a two-dimensional (planar) or three-dimensional (spatial) rigid array of interconnected FRP bars that form a contiguous lattice, which can be used to reinforce concrete. The lattice may be manufactured with integrally connected bars or may be made of mechanically connected individual bars.

Helical tie — a continuously wound reinforcement in the form of a cylindrical helix enclosing longitudinal reinforcement.

Jacking force — temporary force exerted by the device that introduces tension into prestressing tendons.

Limit states — the conditions in which a structure ceases to fulfil the relevant function for which it was designed.

Load, dead — specified dead load as defined in the *National Building Code of Canada*.

Load factor — a factor applied to a specified load that, for the limit state under consideration, takes into account the variability of the loads and load patterns and the analysis of their effects.

Load, factored — a product of a specified load and its load factor.

Load, live — specified live load as defined in the *National Building Code of Canada*.

Load, specified — load specified by the *National Building Code of Canada* without load factors.

Load, sustained — specified dead load plus that portion of the specified live load expected to act over a period of time sufficient to cause significant long-time deflection.

Matrix — in the case of fibre-reinforced polymers, the materials that serve to bind the fibres together, transfer loads to the fibres, and protect fibres against environmental attack and damage due to handling.

Noncombustible — the property of a material that meets the acceptance criteria of ULC Standard CAN4-S114.

Noncombustible construction — types of construction in which a degree of fire safety is attained by the use of noncombustible materials for structural members and other building assemblies.

Partial prestressing — prestressing such that the calculated tensile stresses under specified loads exceed the limits specified in Clause 10.4.2.

Pedestal — upright compression member with a ratio of unsupported height to least lateral dimension of less than 3.

Plain concrete — concrete containing no reinforcing or prestressing steel or with less than the specified minimum for reinforced concrete.

Plain reinforcement — reinforcement that does not conform to the definition of deformed reinforcement.

Polymer — a high molecular weight organic compound, natural or synthetic, containing repeating units.

Precast concrete — concrete elements cast in a location other than their final position in service.

Prestressed concrete — concrete in which internal stresses have been initially introduced so that the subsequent stresses resulting from dead load and superimposed loads are counteracted to a desired degree. This may be accomplished by the following methods:
(a) **Post-tensioning** — a method of prestressing in which the tendons are tensioned after the concrete has hardened; or
(b) **Pretensioning** — a method of prestressing in which the tendons are tensioned before the concrete is placed.

Pultrusion — a continuous process for manufacturing composites that have a uniform cross-sectional shape. The process consists of pulling a fibre-reinforcing material through a resin impregnation bath and then through a shaping die where the resin is subsequently cured.

Reinforced concrete — concrete reinforced with no less than the minimum amount of reinforcement required by the relevant clauses of this Standard and designed on the assumption that the two materials act together in resisting forces.

Resin — polymeric material that is rigid or semi-rigid at room temperature, usually with a melting point or glass transition temperature above room temperature.

Resistance factor — the factor specified in Clause 6.5, applied to a specified material property or to the resistance of a member for the limit state under consideration, that takes into account the variability of dimensions, material properties, quality of work, type of failure, and uncertainty in the prediction of resistance.

Resistance, factored — resistance of a member, connection, or cross-section calculated in accordance with the provisions and assumptions of this Standard including the application of appropriate resistance factors.

Resistance, nominal — resistance of a member, connection, or cross-section calculated in accordance with the provisions and assumptions of this Standard without the inclusion of any resistance factors.

Spiral column — a column in which the longitudinal reinforcement is enclosed by a helical tie.

Splitting tensile strength — tensile strength of concrete determined by a splitting test.

Stirrup — reinforcement used to resist shear and torsion stresses in a structural member.

Strength of concrete, specified — compressive strength of concrete used in the design and evaluated in accordance with the provisions of Clause 8.5.1.

Tendon — a steel or FRP element, such as wire, bar, strand, or a bundle of such elements, used to impart prestress to concrete.

Thermoset — resin that is formed by cross-linking polymer chains and that cannot be melted and recycled because the polymer chains form a three-dimensional network.

Tie — a loop of reinforcing bar or wire enclosing longitudinal reinforcement. See also **Stirrup**.

Tilt-up wall panels — reinforced concrete panels that are site-cast on a horizontal surface and subsequently tilted to a vertical orientation to form vertical and lateral load-resisting building elements.

Transfer — the act of transferring force in prestressing tendons from jacks or the pretensioning anchorage to the concrete member.

Vinyl esters — a class of thermosetting resins containing ester of acrylic and/or methacrylic acids.

Wall — a vertical panel element, which may or may not be required to carry superimposed in-plane loads.

Wobble friction — friction caused by unintended deviation of prestressing sheath or duct from its specified profile.

Yield strength — specified minimum yield strength of steel reinforcement in accordance with Clause 8.6.1.

2.2 Acronyms

The following acronyms are used in this Standard:
AFRP — aramid fibre-reinforced polymer
CFRM — continuous fibre-reinforced material
CFRP — carbon fibre-reinforced polymer
FRC — fibre-reinforced concrete
FRP — fibre-reinforced polymer
GFRP — glass fibre-reinforced polymer

2.3 Subscripts and Symbols

Throughout this Standard the subscript "f" applied to a symbol denotes a load effect based on factored loads and the subscript "r" denotes a resistance calculated using factored material strengths.

Symbols are defined in the notation portions of the various clauses of this Standard.

2.4 Units of Measure

The following units of measurement are used in the equations in this Standard:
(a) force: N (newtons);
(b) length: mm (millimetres);
(c) moment: N•mm; and
(d) stress: MPa (megapascals).

Whenever the square root of the concrete strength is determined, the units of both the concrete strength and the square root of the concrete strength are to be in megapascals.

Other dimensionally consistent combinations of units may be used provided that appropriate adjustments are made to constants in non-homogeneous equations.

3 Reference Publications

This Standard refers to the following publications and where such reference is made it shall be to the edition listed below.

Note: *New or amended editions of these referenced publications may exist. The user may find it more appropriate to refer to such editions.*

CSA Standards

CAN/CSA-A23.1-00/A23.2-00,
Concrete Materials and Methods of Concrete Construction/Methods of Test for Concrete;

A23.3-94 (R2000),
Design of Concrete Structures;

A23.4-00/A251-00,
Precast Concrete — Materials and Construction/Qualification Code for Architectural and Structural Precast Concrete Products;

CAN/CSA-A3000-98,
Cementitious Materials Compendium;

O86-01,
Engineering Design in Wood;

CAN/CSA-S16.1-94 (R2000),
Limit States Design of Steel Structures;

S136-94 (R2001),
Cold Formed Steel Structural Members;

CAN3-S157-M83 (R2000),
Strength Design in Aluminum;

S304.1-94 (R2001),
Masonry Design for Buildings (Limit States Design);

S413-94 (R2000),
Parking Structures;

S478-95 (R2001),
Guideline on Durability in Buildings.

ANSI* Standard
Z124,
Plastic Fixture Standards.

ASTM† Standards
C 39/C 39M-99,
Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens;

C 138-92 (R2000),
Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete;

C 143/C 143M-00,
Standard Test Method for Slump of Hydraulic Cement Concrete;

C 144-99,
Standard Specification for Aggregate for Masonry Mortar;

C 192/C 192M-98,
Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory;

C 234 (Discontinued in 2000),
Standard Test Method for Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel;

C 260-00,
Standard Specification for Air-Entraining Admixtures for Concrete;

C 293-94,
Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading);

C 330-00,
Standard Specification for Lightweight Aggregates for Structural Concrete;

C 393-00,
Standard Test Method for Flexural Properties of Sandwich Constructions;

C 469-87,
Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression;

C 494/C 494M-99ae1,
Standard Specification for Chemical Admixtures for Concrete;

C 511-98,
Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes;

C 518-98,
Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter;

C 531-00,
Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes;

C 581-94,
Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service;

C 617-98,
Standard Practice for Capping Cylindrical Concrete Specimens;

C 1185-99,
Standard Test Methods for Sampling and Testing Non-Asbestos Fiber-Cement Flat Sheet, Roofing and Siding, Shingles, and Clapboards;

D 149-97a,
Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies;

D 150-98,
Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation;

D 256-97,
Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics;

D 257-99,
Standard Test Methods for DC Resistance or Conductance of Insulating Materials;

D 495-99,
Standard Test Method for High-Voltage, Low-Current, Dry Arc Resistance of Solid Electrical Insulation;

D 543-95,
Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents;

D 570-98,
Standard Test Method for Water Absorption of Plastics;

D 635-98,
Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position;

D 638-99,
Standard Test Method for Tensile Properties of Plastics;

D 648-98c,
Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position;

D 695-96,
Standard Test Method for Compressive Properties of Rigid Plastics;

D 696-98;
Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between –30°C and 30°C With a Vitreous Silica Dilatometer;

D 732-99,
Standard Test Method for Shear Strength of Plastics by Punch Tool;

D 746-98,
Standard Test Method for Brittleness Temperature of Plastics and Elastomers by Impact;

D 785-98,
Standard Test Method for Rockwell Hardness of Plastics and Electrical Insulating Materials;

D 790-99,
Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials;

D 792-98,
Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement;

D 953-95;
Standard Test Method for Bearing Strength of Plastics;

D 1037-99,
Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials;

D 1141-98e1,
Standard Practice for Substitute Ocean Water;

D 1602 (Discontinued in 1987),
Method of Test for Bearing Load of Corrugated Reinforced Plastic Panels;

D 2247-99,
Standard Practice for Testing Water Resistance of Coatings in 100% Relative Humidity;

D 2344/D 2344M-00,
Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates;

D 2583-95,
Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor;

D 2584-94,
Standard Test Method for Ignition Loss of Cured Reinforced Resins;

D 2734-94,
Standard Test Methods for Void Content of Reinforced Plastics;

D 2834-95,
Standard Test Method for Nonvolatile Matter (Total Solids) in Water-Emulsion Floor Polishes, Solvent-Based Floor Polishes, and Polymer-Emulsion Floor Polishes;

D 2863-97,
Standard Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index);

D 2990-95,
Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics;

D 3039/D 3039M-00,
Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials;

D 3045-92 (1997),
Standard Practice for Heat Aging of Plastics Without Load;

D 3164-97,
Standard Test Method for Strength Properties of Adhesively Bonded Plastic Lap-Shear Sandwich Joints in Shear by Tension Loading;

D 3165-00,
Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies;

D 3171-99,
Standard Test Method for Constituent Content of Composite Materials;

D 3410/D 3410M-95,
Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading;

D 3479/D 3479M-96,
Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials;

D 3528-96,
Standard Test Method for Strength Properties of Double Lap Shear Adhesive Joints by Tension Loading;

D 3841-97,
Standard Specification for Glass-Fiber-Reinforced Polyester Plastic Panels;

D 3846-94,
Standard Test Method for In-Plane Shear Strength of Reinforced Plastics;

D 3914-96,
Standard Test Method for In-Plane Shear Strength of Pultruded Glass-Reinforced Plastic Rod;

D 3916-94,
Standard Test Method for Tensile Properties of Pultruded Glass-Fiber-Reinforced Plastic Rod;

D 4065-95,
Standard Practice for Determining and Reporting Dynamic Mechanical Properties of Plastics;

D 4329-99,
Standard Practice for Fluorescent UV Exposure of Plastics;

D 4541-95e1,
Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers;

D 5028-96,
Standard Test Method for Curing Properties of Pultrusion Resins by Thermal Analysis;

D 5379/D 5379M-98,
Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method;

D 5420-98a,
Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimen by Means of a Striker Impacted by a Falling Weight (Gardner Impact);

E 4-99,
Standard Practices for Force Verification of Testing Machines;

E 84-00a,
Standard Test Method for Surface Burning Characteristics of Building Materials;

E 104-85 (1996),
Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions;

E 119-00a,
Standard Test Methods for Fire Tests of Building Construction and Materials;

E 178-94,
Standard Practice for Dealing With Outlying Observations;

E 662-97,
Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials;

E 1142-97,
Standard Terminology Relating to Thermophysical Properties;

G 154-00,
Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials.

CPCI‡ Publication
Design Manual, 3rd edition, 1996.

National Research Council Canada Publication
National Building Code of Canada, 1995.

Precast/Prestressed Concrete Institute (PCI) Publication
Recommended Practice for Glass Fiber Reinforced Concrete Panels, 3rd edition, 1993.

SAE§ Standard
J-400-2001,
Test for Chip Resistance of Surface Coatings.

ULC Standards**
CAN/ULC-S101-1989,
Standard Methods of Fire Endurance Tests of Building Constructions and Materials;

CAN4-S102-M88,
Standard Methods of Test for Surface Burning Characteristics of Building Materials and Assemblies;

CAN/ULC-S102.2-M88,
Standard Methods of Test for Surface Burning Characteristics of Flooring, Floor Covering, and Miscellaneous Materials and Assemblies;

CAN4-S114-M80,
Standard Method of Test for Determination of Non-Combustibility in Building Materials.

Other Publications
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**American National Standards Institute.*
†*American Society for Testing and Materials.*
‡*Canadian Precast/Prestressed Concrete Institute.*
§*Society of Automotive Engineers.*
***Underwriters' Laboratories of Canada.*

4 Drawings and Related Documents

In addition to the information required by the applicable building codes, the drawings and related documents for components designed in accordance with this Standard shall include the following:
(a) size and location of all structural elements, reinforcement, and prestressing tendons;
(b) provision for dimensional changes resulting from prestress, creep, shrinkage, and temperature;
(c) locations and details of expansion or contraction joints and permissible locations and details for construction joints;
(d) magnitude and location of prestressing forces;
(e) specified strength of concrete in various parts of the structure at stated ages or stages of construction, and nominal maximum size and type of aggregate;
(f) required cover;
(g) specified type and strength/grade of all reinforcement, both steel and FRP;
(h) anchorage length;
(i) protective coatings and grout as applicable, for all reinforcement, hardware, and connections; and
(j) anchorage method details for FRP tendons, laminates, and sheets.

5 General Design Requirements

5.1 Structural Design

5.1.1 General

Conventional methods of structural analysis shall be used unless otherwise specified herein. Designs shall be made using limit states design procedures.

5.1.2 Alternative Design Procedures

Designs using procedures not covered by this Standard, which are carried out by a person qualified in the specific methods applied and which provide a level of safety and performance equivalent to designs conforming to this Standard, are acceptable if carried out by one of the following methods:
(a) analysis based on generally established theory;
(b) evaluation of prototype components by load testing; or
(c) studies of model analogues.

When method (b) is used, at least three replicate components shall be tested, and each shall satisfy the requirements of Clause 5.1.3.

5.1.3 Criteria for Component Testing

When testing is used as permitted by Clause 5.1.2, Item (b), as the basis for the acceptance of components, loading equivalent to
(a) 1.67 times the effect of the loads specified in Clause 6.2.1 shall be applied when checking for ultimate limit states; and
(b) 1.25 times the effect of the loads, including the effects specified in Clause 6.2.2, shall be applied when checking for serviceability.

Components sustaining the test loads without exceeding deflection and other serviceability limits and not demonstrating evidence of failure shall be considered to meet the intent of Clause 6 for short-term loading.

Results of these tests shall not be used as the basis for the determination of design properties of components or their FRP reinforcement.

5.2 Structural Integrity

Consideration shall be given to the integrity of the overall structural system to minimize the likelihood of a progressive type of collapse.

5.3 Fire Performance

5.3.1 General

Components with FRP materials shall satisfy the fire performance requirements of the *National Building Code of Canada (NBCC)* or other applicable building codes. The building shall satisfy the fire performance requirements of the *NBCC*, including fire resistance ratings, flame-spread ratings, smoke development classifications, and noncombustibility requirements. Fire test standards specified in Clauses 5.3.2, 5.3.3, and 5.3.4 shall be used for determining compliance with requirements of the governing codes.

5.3.2 Fire Resistance

5.3.2.1

Except as provided for in Clause 5.3.2.2, the fire resistance ratings of concrete walls, floors, roofs, columns, and beams incorporating FRP reinforcing materials shall be determined in accordance with ULC Standard CAN/ULC-S101.

5.3.2.2

As an alternative to the requirements of Clause 5.3.2.1, the fire resistance of concrete slabs reinforced with FRP may be determined using calculation methods, provided that these have been proven to be reliable on the basis of actual tests and are in accordance with the *NBCC*.

5.3.2.3

If FRP is used as external reinforcement in the repair or reinforcement of a structural assembly, then the unsheathed assembly shall satisfy the relevant fire rating and safety requirements of the *NBCC.*

5.3.3 Flame Spread and Smoke Development

5.3.3.1

Except as provided in Clause 5.3.3.2, the flame-spread rating and smoke-development classification of a FRP material, assembly of FRP materials, or structural member constructed using FRP materials shall be determined in accordance with ULC Standard CAN4-S102.

5.3.3.2

Where a material, assembly of materials, or structural member constructed of FRP is designed in such a way that only one, relatively horizontal, upper surface is exposed to air, the flame-spread rating and smoke-developed classification shall be determined in accordance with ULC Standard CAN/ULC-S102.2.

5.3.4 Noncombustibility

The noncombustibility of materials shall be determined in accordance with ULC Standard CAN4-S114.

5.4 Durability

Designs of buildings with FRP components and reinforcing materials shall take into consideration the deterioration mechanisms and agents identified in CSA Standard S478.

6 Limit States, Loading, Load Combinations, and Factored Resistance

6.1 Notation

The following symbols are used in Clause 6:

D = dead loads or related internal moments and forces
E = earthquake loads or related internal moments and forces
L = live loads due to intended use and occupancy (including loads due to cranes); snow, ice, and rain; earth and hydrostatic pressure; static or inertia forces excluding live load due to wind or earthquake
T = cumulative effects of temperature, creep, shrinkage, and differential settlement
W = live loads due to wind or related internal moments and forces
f'_c = specified compressive strength of concrete
f'_{os} = fifth percentile characteristic tensile strength of FRP sheets and laminates
α_D = load factor on dead loads
α_L = load factor on live loads
α_T = load factor on cumulative effects of temperature, creep, shrinkage, and differential settlement
α_W = load factor on wind loads
γ = importance factor
ϕ_c = resistance factor for concrete
ϕ_F = resistance factor for FRP
ϕ_m = member resistance factor
ϕ_p = resistance factor for steel prestressing tendons
ϕ_s = resistance factor for steel reinforcing bars
ψ = load combination factor

6.2 Limit States

6.2.1 Ultimate Limit State

Building components and connections shall be designed in such a way that
factored resistance $\geq$ effect of factored loads

where the effect of factored loads is determined in accordance with Clause 6.4 and the factored resistance is determined in accordance with Clause 6.5.

6.2.2 Serviceability Limit State

In the serviceability-limit-states design of building components, consideration shall be given to controlling vibrations within acceptable limits for the intended use.

6.3 Loading

6.3.1 Loads

Loads on buildings and their components shall be in accordance with Part 4 of the *National Building Code of Canada*.

6.3.2 Loads Not Listed

Where a structural member is expected to be subjected to the effects of loads or forces that are not covered by Clause 6.3.1, such effects shall be included in the design on the basis of rational judgment.

6.3.3 Imposed Deformations

Consideration shall be given to the effects of forces due to prestressing, temperature, differential settlement, and the restraint of shrinkage, swelling, and creep.

6.4 Load Combinations

6.4.1 Effects of Factored Loads

The effect of factored loads acting on a member, its cross-section, and its connections to other members in terms of moment, axial load, shear, and torsion shall be computed from factored loads and forces in accordance with the factored load combinations given in Clauses 6.4.2 and 6.4.5 using the values of the load factors, load combination factors, and importance factors given in Clauses 6.4.2 to 6.4.6.

6.4.2 Combinations Not Including Earthquake

For load combinations not including earthquake, the factored load combination shall be taken as

$$\alpha_D D + \alpha_T T + \gamma\psi(\alpha_L + \alpha_W) \quad \textbf{(6-1)}$$

6.4.3 Load Factors (α)

The load factors, α, shall be as follows:
(a) $\alpha_D = 1.25$, except that when the dead load resists overturning, uplift, or reversal of load effect, $\alpha_D = 0.85$;
(b) $\alpha_L = 1.5$;
(c) $\alpha_W = 1.5$; and
(d) $\alpha_T = 1.25$.

Prestressing forces and the effects of prestressing shall have a load factor of 1.0.

6.4.4 Load Combination Factor (ψ)

The load combination factor, ψ, shall be equal to
(a) 1.0 when only one of the loads, L, W, or T acts;
(b) 0.70 when two of the loads, L, W, or T act; and
(c) 0.60 when all three of the loads, L, W, or T act.

The most unfavourable effect shall be determined by considering the loads L, W, or T acting alone with $\psi = 1.0$ or in combination with $\psi = 0.70$ or 0.60.

6.4.5 Combinations Including Earthquake

For load combinations including earthquake, the factored load combinations shall be taken as

(a) 1.0D + γ(1.0E); and
(b) either
   (i) for storage and assembly occupancies, 1.0D + γ(1.0L + 1.0E); or
   (ii) for all other occupancies, 1.0D + γ(0.5L + 1.0E).

6.4.6 Importance Factor (γ)

The importance factor, γ, shall not be less than 1.0 for all buildings, except where it can be shown that collapse is not likely to cause injury or other serious consequences, in which case it shall be not less than 0.8.

6.4.7 Load Combination for Serviceability Checks

The load combination for checking serviceability requirements shall be taken as

$$D + \psi(L + Q + T). \quad \textbf{(6-2)}$$

The loads for checking serviceability shall be the specified loads, except in the case of long-time deflection where the sustained loads shall be used. Where applicable, the effects of prestressing shall be included.

6.5 Factored Resistance

6.5.1 General

The factored resistance of a member, its cross-sections, and its connections shall be taken as the resistance calculated in accordance with the requirements and assumptions of this Standard, multiplied by the appropriate material resistance factors.

Where specified, the factored member resistance shall be calculated using the factored resistance of the component materials with the application of an additional member resistance factor, ϕ_m, specified in Clauses 10.15.3, 10.16.3.2, and 23.4.1.3 of CSA Standard A23.3, as appropriate.

6.5.2 Factored Resistance of FRP Components and Reinforcing Materials

6.5.2.1

The factored resistance of FRP reinforcing materials shall be as specified in Clause 7.1.

6.5.2.2

The factored resistance of surface-bonded FRP reinforcing materials used in concrete shall be as specified in Clause 7.2.

6.5.2.3

The factored resistance of fibre-reinforced concrete (FRC) shall be as specified in Clause 7.3.

6.5.2.4

The factored resistance of FRP structural components shall be as specified in Clause 7.4.

6.5.3 Factored Resistance of Concrete

The factored concrete resistance used in checking ultimate limit states shall be taken as $\phi_c f'_c$ in compression and $0.6\phi_c\sqrt{f'_c}$ in tension where ϕ_c = 0.60, except that ϕ_c = 0.65 for precast concrete components produced in certified manufacturing plants in accordance with CSA Standard A23.4.

6.5.4 Steel Reinforcement and Tendons

The factored force in steel reinforcing bars and tendons used in combination with FRP reinforcing elements in concrete components shall be taken as the product of the relevant resistance factor and the respective steel force (as specified in other clauses of this Standard), where
(a) for steel reinforcing bars, $\phi_s = 0.85$; and
(b) for steel prestressing tendons, $\phi_p = 0.90$.

6.5.5 Factored Resistance of Other Structural Materials

The factored resistance used in checking ultimate limit states of other structural materials and connectors used in combination with FRP components or reinforcing materials shall be in accordance with the following CSA structural design standards:
(a) CSA Standard O86.1 for wood;
(b) CSA Standard CAN/CSA-S16.1 for steel;
(c) CSA Standard S136 for cold-formed steel;
(d) CSA Standard CAN3-S157 for aluminum; and
(e) CSA Standard S304.1 for masonry.

7 Properties of FRP Components and Reinforcing Materials

7.1 FRP Bars, Tendons, and Grids

7.1.1 General

FRP bars, tendons, and grids shall conform to the requirements of Clauses 7.1.2 to 7.1.4. Their physical properties shall be determined by testing in accordance with Clause 7.1.5, and their strengths and stiffness for design shall be based on their characteristic tensile and shear properties determined in accordance with Clause 7.1.6.

7.1.2 Materials and Composition

7.1.2.1

FRP reinforcing bars and grids covered by this Standard shall be manufactured of carbon, glass, or aramid fibres and vinyl-ester or epoxy resins. Typical fibre properties are given in Table 1. Specific fibre properties shall be provided by the manufacturer. When glass fibres are used, the requirements of Clauses 7.1.2.2 and 7.1.2.3 shall apply.

7.1.2.2

Glass FRP reinforcement (GFRP) may be used for nonstructural purposes such as partition walls, cladding, slabs on grade, and linings of floors and walls.

7.1.2.3

When GFRP reinforcement is used for structural purposes, the tensile stress in the fibre under sustained factored loads shall not exceed 30% of its tensile failure stress.

7.1.3 Non-Prestressed FRP Reinforcement

7.1.3.1

Non-prestressed FRP reinforcement shall be in the form of individual bars, premanufactured grids, or 3-dimensional cages. Premanufactured cages, and cages assembled from bars and grids, may be used to provide both tensile and shear reinforcement for beams.

7.1.3.2
FRP reinforcing bars and grids shall have surface treatments consistent with the development length requirements of Clauses 9.3 and 9.4.

7.1.3.3
In order to minimize shear lag in the reinforcing bars, the cross-sectional area of round and rectangular bars shall not exceed 500 mm^2.

7.1.3.4
The properties of non-prestressed FRP reinforcement shall be provided by the manufacturer. Typical mechanical properties of some commercially available non-prestressed FRP reinforcements are given in Table 2.

7.1.4 FRP Prestressing Tendons

7.1.4.1
FRP prestressing tendons may be in the form of bars, multiwire strands, or cables.

7.1.4.2
Bonded prestressed tendons shall have a surface capable of developing the required tensile strength and transferring the developed stresses to the concrete.

7.1.4.3
The cross-sectional area of round and rectangular prestressing tendons shall not be greater than 300 mm^2.

7.1.4.4
The properties of FRP prestressing tendons shall be provided by the manufacturer. Typical mechanical properties of some commercially available structural FRP prestressing tendons are given in Table 3.

7.1.5 Testing and Acceptance

7.1.5.1
All of the design properties of FRP reinforcement listed in Table 4 shall be considered, and the relevant design properties shall be obtained from tests conducted in accordance with the annexes of this Standard, using specimens of production line quality.

7.1.5.2
FRP reinforcement other than AFRP shall be tested for creep unless previous experience, as confirmed by the manufacturer, demonstrates that such testing is unnecessary. AFRP reinforcing shall always be tested for creep.

7.1.5.3
Preshaped FRP reinforcement such as ties, stirrups, and cages for beams shall be tested for strength development.

7.1.5.4
The following acceptance limits shall apply to FRP reinforcement used in structural components:
(a) axial elongation at ultimate load not less than 1.2%; and
(b) for outdoor applications, transverse coefficient of thermal expansion not greater than 40×10^{-6}/°C.

7.1.6 Characteristic Values for Design

7.1.6.1
The characteristic tensile, bond, and anchorage strengths for FRP reinforcement shall be the lower fifth percentile values determined from tests specified in the relevant annexes of this Standard.

7.1.6.2
For non-prestressed reinforcement, the resistance factor, ϕ_F, shall be taken as $\phi_F = 0.75$. For prestressed reinforcement, the value of the resistance factor, ϕ_F, shall be as shown in Table 5.

7.1.6.3
For the purpose of design, FRP reinforcing elements in the concrete compression zone shall be deemed to have zero compressive strength and stiffness.

7.1.6.4
The design elastic modulus for FRP reinforcement, E_F, shall be the mean modulus determined in accordance with Annex C.

7.1.6.5 Thermal Expansion Coefficients
In the absence of experimental data or manufacturer's specifications, the longitudinal coefficient of linear thermal expansion, α_L, and the transverse coefficient of linear thermal expansion, α_T, of FRP bars, grids, and tendons may be taken from Table 6.

7.1.6.6
Because the thermal coefficients in Table 6 are based on an average fibre volume content of 60% and because an increase in the volume content will reduce the thermal coefficients of FRP bars, grids, and tendons, thermal coefficients less than those shown in Table 6 may be used, subject to verification.

7.2 Surface-Bonded FRP Reinforcing Materials

7.2.1 General
Surface-bonded FRP reinforcing materials shall conform to the requirements of Clauses 7.2.2 to 7.2.4. Their physical properties shall be determined by testing in accordance with Clause 7.2.5. The physical and mechanical properties of FRP composites shall be determined in accordance with Clause 7.2.6. Design strength and stiffness shall be based on characteristic properties determined in accordance with Clause 7.2.7.

7.2.2 Materials and Composition

7.2.2.1
Component materials and combination thereof shall be in accordance with Clause 7.2.2.2 through 7.2.2.8. The FRP systems and components used shall be selected by the manufacturer and approved by the engineer. In choosing an FRP system, consideration shall be given to its impact on the environment, including toxicity and emission of volatile organic compounds.

7.2.2.2
FRP reinforcing materials can be in the form of fibre mat, fibre sheet, prepreg sheet, or pultruded plate.

7.2.2.3
Continuous fibres shall be glass, aramid, or carbon fibre, which are common reinforcements for commercially available FRP strengthening systems. Typical fibre properties are given in Table 1. Specific fibre properties shall be provided by the manufacturer.

7.2.2.4
Thermoset resins such as epoxy and vinylester shall be used for the composites and shall be specified by the manufacturers.

7.2.2.5
Primers shall be selected by the system manufacturer from the general classes of epoxy, vinylester, polyester, and other suitable materials and shall be compatible with substrate.

7.2.2.6
Putties shall be selected by the system manufacturer from the general classes of epoxy, vinylester, polyester, and other suitable materials.

7.2.2.7
Saturating resins shall be selected by the manufacturer from the general classes of epoxy, vinylester, polyester, and other suitable materials.

7.2.2.8
Protective coatings shall be selected from the general classes of epoxy, vinylester, urethane, polyester, and other suitable materials. Selection of protective coatings shall be based on the requirements of the composite repair, resistance to environmental effects (including, but not limited to, moisture, chemicals, temperature extremes, fire, impact, UV exposure), resistance to site-specific effects, and resistance to vandalism.

7.2.3 General Properties of Surface-Bonded FRP Materials
The properties of FRP composite materials shall be provided by the system manufacturer. Typical mechanical properties of some commercially available structural FRP systems are given in Table 7.

7.2.4 General Requirements of Installation
Construction process and quality control of surface-bonded FRP reinforcement shall be in accordance with the specifications of the system manufacturer. A typical installation sequence of prepreg FRP patching onto concrete is shown schematically in Figure 1. Non-preg fibres, shall, whenever practicable, be saturated in epoxy resin before applying to the concrete surface. The concrete surface preparation shall be in accordance with Clause 14.9, Item (c).

7.2.5 Testing for Materials of the FRP Reinforcing Systems
Relevant design properties and quality control of the materials used in FRP reinforcing systems shall be determined in accordance with the test procedures and methods given in the relevant annexes of this Standard.

7.2.6 Physical and Mechanical Properties of FRP Composites
Required physical and mechanical properties of FRP composite shall be determined from the relevant test methods and standards listed in Table 8. Environmental durability of FRP composites shall be tested in accordance with the test methods and standards given in Table 9.

7.2.7 Characteristic Values for Design

7.2.7.1
Required physical and mechanical properties of FRP composites shall be determined in accordance with Clause 7.2.6.

7.2.7.2
For surface-bonded FRP reinforcing materials, a resistance factor, ϕ_F, of 0.75 shall be used for design for ultimate limit states.

7.2.7.3
The factored resistance of surface-bonded FRP reinforcing material used to resist factored loads shall be calculated as the product of its resistance factor and the fifth percentile characteristic strength, f_{05}, of the reinforcement sheet or plate.

7.2.8 Other Performance Tests
All relevant tests described in the annexes and any additional tests identified for special features of the product or system shall be specified in the test plan. Overall qualification testing shall provide data on material properties, forces and deformations limit states, and modes of failure, in order to support a rational analysis procedure. The specimens shall be constructed and cured under conditions specified by the manufacturer. Tests shall simulate the anticipated loading conditions, load levels, deflections, ductility, and environmental conditions.

7.3 Fibre-Reinforced Concrete Cladding

7.3.1 General
When fibre-reinforced concrete (FRC) is used in the design and construction of exterior cladding, the basic substrate of the FRC shall comprise the combination of a cement/sand ratio together with additives and fibre reinforcement. The materials and composition of the cladding shall be in accordance with Clause 7.3.2, and the relevant physical properties shall be determined in accordance with Clause 7.3.3. If FRC is applied to the surface of a panel, it shall be in accordance with Clause 7.3.4.

7.3.2 Materials and Composition of FRC Cladding

7.3.2.1
The cementitious matrix of FRC shall consist of cementitious materials (Portland cement, fly ash, slag, or silica fume), fibre reinforcement, aggregate, admixtures, and water.

7.3.2.2
The Portland cement shall be in accordance with CSA Standard CAN/CSA-A5 (part of CSA Standard CAN/CSA-A3000).

7.3.2.3
The sand shall be properly graded silica sand, shall be washed and dried, and shall be free of contaminants and lumps.

7.3.2.4
Admixtures shall be in accordance with the relevant provisions of CSA Standards CAN/CSA-A23.1 and A23.4. If, in order to reduce slump and hold sand in suspension, thixotropic agents are used when spraying, they shall not be lower than the design strength of the concrete.

7.3.2.5
Mixing water shall be in accordance with CSA Standard CAN/CSA-A23.1.

7.3.2.6
For glass fibre, consideration shall be given to the need for alkali resistance, which shall be determined in accordance with Annex O, and only those fibres deemed to have sufficient alkali resistance in the prevailing design circumstances shall be used.

7.3.2.7
The decision to use of fibres made of carbon, aramid, polypropylene, polyethylene, and polyester shall take into account the manufacturer's advice as to their suitability for the design circumstances prevailing.

7.3.2.8
Aggregates for facing materials shall be in accordance with the relevant requirements of CSA Standards CAN/CSA-A23.1 and A23.4.

7.3.3 Determination of Physical Properties

7.3.3.1
The physical properties of FRC to be used in design shall be determined either by reference to the manufacturer or by direct testing. The primary properties used in design shall be the compressive strength and tensile strength. Other physical properties that shall be considered, if relevant, are modulus of elasticity, impact resistance, shrinkage, thermal expansion, transport properties, freeze-thaw resistance, and fire resistance.

7.3.3.2
FRC cladding shall be tested in accordance with ASTM Standards C 518, C 531, C 1185, and D 1037, and its flammability and combustibility shall be tested in accordance with ASTM Standard E 84 and UL Standard CAN4-S102.

7.3.4 FRC as an Exterior Layer Added to the Surface of a Panel
Proprietary FRC may be used in exterior add-on layers to panels, provided that the entire finished product is in accordance with Clause 7.3.3.

7.4 FRP Cladding

7.4.1 General
In the design of exterior cladding incorporating FRP, the FRP products shall comprise surface-applied laminates or shall be components of composite panels, aggregate-type panels, or sandwich panels.

The materials for FRP composites, including thermoset resins, additives, fibres, and core materials, shall be in accordance with Clause 7.4.2, and the relevant physical properties shall be tested in accordance with Clause 7.4.3.

7.4.2 Material Composition of FRP
The materials of FRP composites, including thermoset resins, curing agents, fillers, additives, core materials, and fibres, shall be in accordance with the environmental conditions and with the following relevant provisions:

(a) The type of resin for a particular application shall be determined in relation to its physical properties including weatherability, corrosion resistance, and combustibility.

(b) If materials are added to resin/binder systems in order to achieve specified results, the resulting strength and durability of the FRP shall be in accordance with the design requirements. Fire-retardant agents shall be used as necessary to meet combustibility requirements and shall be in accordance with the recommendations of the resin manufacturer. Ultraviolet absorbers, when needed, shall be used in accordance with the recommendations of the resin manufacturer.
(c) Reinforcing fibres used in FRP cladding shall normally be of fibreglass, aramid, or carbon and may be in the form of unidirectional strand, chopped strand mat, continuous roving, or woven roving. The sizing and binder on all reinforcing materials shall be compatible with the resin.

7.4.3 Determination of Physical Properties

The physical properties of FRP to be used in design shall be determined either by reference to the manufacturer or by direct testing. The primary properties used in design shall be the tensile strength, flexural strength, flexural modulus of elasticity, compressive strength, fire resistance, and thermal expansion. Other physical properties that shall be considered according to necessity are impact resistance, shrinkage, freeze-thaw resistance, density, and light transmission.

FRP cladding shall be tested in accordance with the ASTM Standards listed in Table 10, when relevant.

8 Design of Concrete Components with FRP Reinforcement

8.1 Notation

The following symbols are used in Clause 8:

a = shear span
A = effective tension area of concrete surrounding the flexural tension reinforcement and extending from the extreme tension fibre to the centroid of the flexural tension reinforcement and an equal distance past the centroid, divided by the number of bars. When the flexural reinforcement consists of different bar sizes, the number of bars or wires used to compute A shall be taken as the total area of reinforcement divided by the area of the largest bar used.
A_c = cross-sectional area of the core of a compression member measured to the centreline of the perimeter hoop or spiral
A_F = area of FRP tension reinforcement
A_g = gross area of section
A_s = area of steel tension reinforcement
A_{st} = total area of longitudinal reinforcement
A_v = area of shear reinforcement perpendicular to the axis of a member within the distance s
b_w = minimum effective web width
c = distance from extreme compression fibre to neutral axis
d = distance from the extreme compression fibre to the centroid of longitudinal tension force
d_c = distance from extreme tension fibre to the centre of the longitudinal bar or wire located closest thereto
D = dead loads or related internal moments and forces
E = earthquake loads or related internal moments and forces
E_c = modulus of elasticity of concrete
E_F = modulus of elasticity of longitudinal FRP reinforcement
E_p = modulus of elasticity of prestressing tendons
E_s = modulus of elasticity of reinforcement
f'_c = specified compressive strength of concrete
f_F = stress in FRP reinforcement under specified loads
f_{Fh} = design stress in the spiral, hoop, or transverse rectilinear FRP reinforcement in a column
f_{Fu} = ultimate strength of FRP shear reinforcement
f_r = modulus of rupture of concrete
f_y = specified yield strength of reinforcement

I_{cr} = transformed moment of inertia of cracked reinforced concrete section, expressed as the moment of inertia of the equivalent concrete section
I_g = moment of inertia of gross concrete section about the centroidal axis, neglecting the reinforcement
k_b = coefficient dependent on the reinforcing bar bond characteristics
k_c = coefficient representing the efficiency of transverse reinforcement
L = live loads due to intended use and occupancy (includes loads due to cranes); snow, ice, and rain; earth and hydrostatic pressure; static or inertia forces excluding live load due to wind or earthquake
L_g = distance from the support to the point where $M = M_{cr}$ in a simply supported beam, or distance from the free end to the point where $M = M_{cr}$ in a cantilever beam
M_{cr} = cracking moment
P = applied concentrated load
P_f = factored axial load
P_{ro} = factored axial load resistance at zero eccentricity
q = uniformly distributed applied load
s = spacing of shear reinforcement, measured parallel to the longitudinal axis of the member
s_l = spacing of laterally supported longitudinal reinforcement
S = factor for creep deflection under sustained loads
S_G = FRP grid spacing parallel to the bending direction of interest
T = cumulative effects of temperature, creep, shrinkage, and differential settlement
T_{cr} = pure torsional cracking resistance
T_f = factored torsional moment
V_c = factored shear resistance provided by concrete
V_f = factored shear resistance calculated in accordance with Clause 8.4
V_p = component in the direction of the applied shear of the effective prestressing force or, for variable depth members, the sum of the component of the effective prestressing force and the components of flexural compression and tension in the direction of the applied shear; positive if resisting applied shear
V_s = factored shear resistance provided by shear reinforcement
V_{ss} = factored shear resistance provided by steel shear reinforcement
V_{sF} = factored shear resistance provided by FRP shear reinforcement
W = live loads due to wind or related internal moments and forces
γ = importance factor
γ_c = density of concrete
y_t = distance from centroidal axis of cross-section (neglecting the reinforcement) to the extreme fibre in tension
z = quantity limiting distribution of flexural FRP reinforcement bars
z_G = quantity limiting the spacing of flexural grid reinforcement
α_1 = ratio of average stress in rectangular compression block to the specified concrete strength
α_D = load factor on dead loads
α_L = load factor on live loads
α_T = load factor on cumulative effects of temperature, creep, shrinkage, and differential settlement
α_W = load factor on wind loads
β_1 = ratio of depth of rectangular compression block to depth of the neutral axis
ϵ_{cs} = shrinkage strain of concrete
ϵ_F = strain in FRP reinforcement under specified loads
ϵ_{Fu} = ultimate strain of FRP reinforcement
ϵ_s = strain in steel reinforcement under specified loads
λ = factor to account for concrete density
ϕ_a = resistance factor for structural steel
ϕ_c = resistance factor for concrete
ϕ_F = resistance factor for FRP reinforcement
ϕ_m = member resistance factor

ϕ_p = resistance factor for steel prestressing tendons
ϕ_S = resistance factor for steel reinforcing bars
ψ = load combination factor
κ = curvature
ρ_{Fh} = ratio of volume of hoop or rectilinear transverse reinforcement to total volume of core (out-to-out of hoop or transverse reinforcement)
ρ_{Fs} = ratio of volume of spiral reinforcement to total volume of core (centre-to-centre of spirals) of a spirally reinforced compression member
ρ_w = longitudinal reinforcement ratio (%)

8.2 Design Requirements

8.2.1 General

All FRP reinforced concrete sections shall be designed in such a way that failure of the section is initiated by crushing of the concrete in the compression zone.

8.2.2 Buildings Other than Parking Structures

The design of concrete with FRP reinforcement shall be in accordance with the *National Building Code of Canada* and CSA Standard A23.3 except as specified herein. In the event of conflict between this Standard and the referenced Standards, this Standard shall take precedence.

8.2.3 Parking Structures

The design of concrete with FRP reinforcement for use in parking structures shall be in accordance with this Standard, taking into account as well the relevant requirements of CSA Standard S413.

8.3 Beams and One-Way Slabs

8.3.1 Distribution of Flexural Reinforcement

8.3.1.1

When the maximum strain in FRP tension reinforcement under full service loads exceeds 0.0015, cross-sections of maximum positive and negative moment shall be so proportioned that the quantity, z, given by

$$z = k_b \frac{E_s}{E_F} f_F \sqrt[3]{d_c A} \qquad \textbf{(8-1)}$$

does not exceed 45 000 N/mm for interior exposure and 38 000 N/mm for exterior exposure. The calculated stress in the reinforcement at specified load, f_F, shall be computed as the internal moment divided by the product of the reinforcement area and the internal moment arm. In lieu of such computation, f_F may be taken as 60% of the design ultimate stress in the reinforcement layer closest to the extreme tension fibre. The value of k_b shall be determined experimentally, but in the absence of test data it may be taken as 1.2 for deformed rods. In calculating d_c and A, the effective clear cover need not be taken as greater than 50 mm.

8.3.1.2

The provisions of Clause 8.3.1.1 shall not be deemed sufficient for structures subject to aggressive environments or designed to be watertight; for such structures, investigations and precautions relevant to the particular circumstances shall be undertaken.

8.3.1.3
For structural elements designed to have both steel and FRP reinforcement in combination, the crack control requirements shall be those for steel-reinforced concrete elements.

8.3.2 Deflection under Service Loads

8.3.2.1
The computed deflections shall not exceed the limits stipulated in Table 11.

8.3.2.2
FRP reinforced concrete members subjected to flexure shall be designed to have adequate stiffness in order to limit deflections or any deformations that may adversely affect the strength or serviceability of a structure.

8.3.2.3
Where deflections are to be computed, deflections that occur immediately on application of load shall be computed by methods based on the integration of curvature at sections along the span.

8.3.2.4
For the common cases of loading and support conditions shown, in lieu of integration of curvature, the maximum deflections may be calculated using the formulas in Table 12.

8.3.2.5
The moment-curvature relation of FRP reinforced concrete members shall be assumed to be trilinear as shown in Figure 2, with the slope of the three segments being $E_c I_g$, zero, and $E_c I_{cr}$.

8.3.2.6
Cracking moment shall be calculated using

$$M_{cr} = f_r \times \frac{I_g}{y_t} \qquad \textbf{(8-2)}$$

where f_r is calculated according to Clause 8.5.4.

8.3.2.7
Unless values are obtained by a more comprehensive analysis, the total of immediate plus long-time deflection for flexural members shall be obtained by multiplying the immediate deflections caused by the sustained load considered by the factor

[1 + S]

where
S (the time-dependent factor) = 2.0 for 5 years or more
= 1.4 for 12 months
= 1.2 for 6 months
= 1.0 for 3 months

8.3.3 Vibrations
In the design of structures and structural members, consideration shall be given to keeping vibrations within acceptable limits for the intended use.

8.4 Ultimate Limit States

8.4.1 Flexural Strength

8.4.1.1
Strain in reinforcement and concrete shall be assumed to be directly proportional to the distance from the neutral axis in cases where there is a perfect bond. This does not apply to unbonded tendons and deep flexural members and in regions of discontinuities.

8.4.1.2
The ultimate strain at the extreme concrete compression fibre shall be assumed to be 0.0035.

8.4.1.3
The tensile strength of concrete shall be neglected in the calculation of the factored flexural resistance of reinforced and prestressed concrete members.

8.4.1.4
The extreme compressive strain in concrete at failure shall be assumed to have reached 0.0035 provided that

$$(c/d) \geq 7/(7 + 2000\epsilon_{Fu}) \qquad \textbf{(8-3)}$$

8.4.1.5
When c/d satisfies the requirements of inequality (see Equation 8-3), the distribution of the concrete stress on the cross-section may be defined by the following:
(a) a concrete stress of $\alpha_1 \phi_c f'_c$ shall be assumed to be uniformly distributed over an equivalent compression zone bounded by edges of the cross-section and a straight line located parallel to the neutral axis at a distance $a = \beta_1 c$ from the fibre of maximum compressive strain;
(b) the distance c shall be measured in a direction perpendicular to that axis; and
(c) the factors α_1 and β_1 shall be taken as

$$\alpha_1 = 0.85 - 0.0015 f'_c \geq 0.67 \qquad \textbf{(8-4)}$$

$$\beta_1 = 0.97 - 0.0025 f'_c \geq 0.67 \qquad \textbf{(8-5)}$$

8.4.1.6
The relationship between the compressive stress and strain in the concrete shall be based on stress-strain curves that are representative of the concrete used or may be assumed to be any graphical form that results in prediction of strength in substantial agreement with results of the comprehensive tests.

8.4.1.7
The tensile stress in each FRP reinforcement layer shall be found using strain compatibility and a linear relationship between its tensile stress and strain.

8.4.1.8
The compressive strength of FRP reinforcement shall be disregarded in the calculation of the factored flexural resistance of reinforced and prestressed concrete members.

8.4.2 Minimum Reinforcement

8.4.2.1
At every section of a flexural member, the minimum reinforcement shall be proportioned so that

$M_r > 1.5\ M_{cr}$

where the cracking moment, M_{cr}, is calculated using the modulus of rupture, f_r.

8.4.2.2
In slabs, a minimum area of reinforcement (mm^2) of $400E_F/A_g$ shall be used in each of the two orthogonal directions. This reinforcement shall be greater than 0.0025 A_g and shall be spaced no farther apart than four times the slab thickness or 400 mm, whichever is less.

8.4.3 Members under Flexure and Axial Load

8.4.3.1
FRP reinforcement shall not be used as longitudinal reinforcement in members subjected to combined flexure and compressive axial load. In cases where these members are reinforced longitudinally with steel and transversely with FRP the requirements of CSA Standard A23.3 shall apply for the steel reinforcement and Clauses 8.4.3.2 and 8.4.3.3 shall apply for FRP.

8.4.3.2
FRP spirals for compression members shall conform to the following:
(a) spiral reinforcement shall have a minimum diameter of 6 mm;
(b) the pitch or distance between turns of the spirals shall not exceed 1/6 of the core diameter;
(c) the clear spacing between successive turns of a spiral shall not exceed 75 mm nor be less than 25 mm; and
(d) the volumetric ratio of spiral reinforcement shall be not less than the value given by

$$\rho_{Fs} = 0.6\frac{f_c'}{f_{Fh}}\left(\frac{A_g}{A_c}-1\right)\left(\frac{P_f}{P_{ro}}\right) \qquad \textbf{(8-6)}$$

where

$$P_{ro} = \alpha_1\phi_c f_c'\left(A_g - A_{st}\right) + \phi_s f_y A_{st} \qquad \textbf{(8-7)}$$

$$\frac{P_f}{P_{ro}} \geq 0.2$$

$$\frac{A_g}{A_c} - 1 \geq 0.3$$

f_{Fh} = $\phi_F f_{Fu}$, or the stress corresponding to a strain of $0.004E_F$ in the FRP, or the stress corresponding to the failure of corners, hooks, bends, and laps, whichever is least.

8.4.3.3
FRP ties for compression members shall conform to the following:
(a) FRP ties shall consist of one or more of the following:
  (i) preshaped rectilinear ties with corners having an angle of not more than 135°;
  (ii) prefabricated rectilinear grids with corners having an angle of not more than 135°;
  (iii) cross ties with hooks where the hooks engage peripheral longitudinal bars;
  (iv) preshaped circular ties or rings; and

(v) other types of transverse FRP reinforcement possessing performance characteristics at least equal to those of the ties listed in Items (i) to (iv), as verified by sufficient experiments.

(b) The spacing of FRP ties shall not exceed the least of the following dimensions:
(i) 16 times the diameter of the smallest longitudinal bars or the smallest bar in a bundle;
(ii) 48 times the minimum cross-sectional dimension (or diameter) of FRP tie or grid;
(iii) the least dimension of the compression member; or
(iv) 300 mm in compression members containing bundled bars.

For specified concrete compressive strength in excess of 50 MPa, the tie or grid spacing determined above shall be multiplied by 0.75.

(c) Ties at column-slab, column-beam, and column-bracket connections shall be placed in accordance with Clauses 7.6.5.3 and 7.6.5.4 of CSA Standard A23.3.

8.4.3.4

All non-prestressed bars for tied compression members shall be enclosed by FRP ties having a minimum cross-sectional dimension (or diameter) of at least 30% of the diameter of the largest longitudinal bar when these are No. 30 or smaller, and a minimum cross-sectional dimension (or diameter) of at least 10 mm for No. 35, No. 45, No. 55, and bundled longitudinal bars.

8.4.4 Method for Design for Shear in Flexural Regions

8.4.4.1

The following method of design shall be used for shear of flexural members not subjected to significant axial tension.

8.4.4.2

Where the reaction force in the direction of the applied shear introduces compression into a support region, the following shall apply:

(a) for non-prestressed members, sections located less than a distance d from the face of the support may be designed for the same shear, V_f, as that computed at a distance d; and

(b) for prestressed members, sections located less than a distance h/2 from the face of the support may be designed for the same shear, V_f, as that computed at a distance h/2.

8.4.4.3

Members subjected to shear shall be proportioned so that $V_r \geq V_f$.

8.4.4.4

The factored shear resistance, V_r, shall be determined as follows:

(a) For FRP stirrups

$$V_r = V_c + V_{sF} \leq V_c + 0.6\lambda\phi_c\sqrt{f'_c}\,b_w d \quad \textbf{(8-8)}$$

(b) For steel stirrups

$$V_r = V_c + V_{ss} \leq V_c + 0.8\lambda\phi_c\sqrt{f'_c}\,b_w d \quad \textbf{(8-9)}$$

(c) For sections having either
(i) at least the minimum amount of transverse reinforcement given by Equation 8-14; or
(ii) an effective depth not exceeding 300 mm

$$V_c = 0.035\lambda\phi_c\left(f'_c\rho_w E_F \frac{V_f}{M_f}d\right)^{1/3} b_w d \quad \textbf{(8-10)}$$

but V_c need not be taken as less than $0.1\lambda\phi_c\sqrt{f_c'}b_w d$ nor shall it exceed $0.2\lambda\phi_c\sqrt{f_c'}b_w d$. The quantity $\frac{V_f d}{M_f}$ shall not be taken as greater than 1.0 where $V_f d/M_f$ is the value of factored shear divided by factored moment at the section under consideration corresponding to the load combination causing maximum moment to occur at the section.

8.4.4.5

For sections with an effective depth greater than 300 mm and with no transverse shear reinforcement or less transverse reinforcement than that required by Equation 8-14, the value of V_c shall be calculated from

$$V_c = \left(\frac{130}{1000+d}\right)\lambda\phi_c\sqrt{f_c'}b_w d \geq 0.08\lambda\phi_c\sqrt{f_c'}b_w d \qquad \textbf{(8-11)}$$

8.4.4.6

Transverse reinforcement shall be perpendicular to the longitudinal axis of the member.

For members with FRP flexural and shear reinforcement, the value of V_{sF} shall be calculated from

$$V_{sF} = \frac{0.4\phi_F A_v f_{Fu} d}{s} \qquad \textbf{(8-12)}$$

For members with FRP flexural reinforcement and steel shear reinforcement, the value of V_{ss} shall be calculated from

$$V_{ss} = \frac{\phi_s A_v f_y d}{s} \qquad \textbf{(8-13)}$$

8.4.5 Minimum Shear Reinforcement

8.4.5.1

A minimum area of shear reinforcement shall be provided in all regions of flexural members where the factored shear force, V_f, exceeds $0.5V_c + \phi_F V_p$ or the factored torsion, T_f, exceeds $0.25\ T_{cr}$. This requirement may be waived for

(a) slabs and footings;
(b) concrete joist construction;
(c) beams with a total depth not greater than 250 mm; and
(d) beams cast integrally with slabs where the overall depth is not greater than one-half the width of the web or 600 mm.

8.4.5.2

Where shear reinforcement is required by Clause 8.4.5.1 or by calculation, the minimum area of shear reinforcement shall be such that

$$A_v = \frac{0.3\sqrt{f_c'}b_w s}{f_{Fh}} \qquad \textbf{(8-14)}$$

8.4.6 Types of Shear Reinforcement

Transverse reinforcement provided for shear may consist of

(a) stirrups or ties perpendicular to the axis of the member; or
(b) FRP two-dimensional grids or three-dimensional cages with ribs located perpendicular to the axis of the member.

8.5 Concrete Properties for Design

8.5.1 Design Strength of Concrete

8.5.1.1

Specified concrete compressive strengths used in design shall not be less than 30 MPa nor more than 80 MPa except as allowed in Clause 8.5.1.2.

Notes:

(1) *Designers planning to use specified concrete strengths in excess of* 50 MPa *should determine whether such concretes are available in their particular locality. Higher strengths may require prequalification of concrete suppliers and contractors, and special construction techniques.*

(2) *Additional limitations on concrete strengths are given in Clauses 21.2.3.1 and 21.2.3.2 of CSA Standard A23.3.*

8.5.1.2

The upper limit of 80 MPa on specified concrete compressive strength may be waived if the structural properties and detailing requirements of reinforced concretes having a higher strength are established for concretes similar to those to be used.

Note: *High-strength concretes vary both in their brittleness and their need for confinement.*

8.5.2 Modulus of Elasticity

8.5.2.1

The modulus of elasticity of concrete in compression, E_c, used in design shall be taken as the average secant modulus for a stress of $0.40f'_c$ determined for similar concrete in accordance with ASTM Standard C 469. If the modulus of elasticity is critical to the design, a minimum value of E_c shall be specified and shown on the drawings.

8.5.2.2

In lieu of results from tests of similar concrete, it shall be permissible to take the modulus of elasticity, E_c, for concrete with γ_c between 1500 and 2500 kg/m^3 as

$$E_c = \left(3300\sqrt{f'_c} + 6900\right)\left(\frac{\gamma_c}{2300}\right)^{1.5} \qquad \textbf{(8-15)}$$

8.5.2.3

In lieu of Clauses 8.5.2.1 and 8.5.2.2, it shall be permissible to take the modulus of elasticity, E_c, of normal density concrete with compressive strength between 30 and 40 MPa as

$$E_c = 4500\sqrt{f'_c} \qquad \textbf{(8-16)}$$

8.5.3 Concrete Stress-Strain Relationship

The concrete compressive stress-strain relationship used in design shall conform to Clause 10.1.6 of CSA Standard A23.3.

8.5.4 Modulus of Rupture of Concrete

The modulus of rupture, f_r, shall be taken as

$$f_r = 0.6\lambda\sqrt{f'_c} \qquad \textbf{(8-17)}$$

where

λ is determined from Clause 8.5.5

8.5.5 Modification Factors for Concrete Density

The effect of concrete density on tensile strength and other properties shall be accounted for by the factor λ

where

λ = 1.00 for normal density concrete
= 0.85 for structural semi-low-density concrete in which all the fine aggregate is natural sand
= 0.75 for structural low-density concrete in which none of the fine aggregate is natural sand

Linear interpolation may be applied based on the fraction of natural sand in the mix.

8.6 Reinforcement and Tendon Properties for Design

8.6.1 Design Strength for Reinforcement

Design calculations shall be based on

(a) the characteristic tensile properties of FRP reinforcement or tendons in accordance with Clause 7.1; and

(b) the specified yield strength of steel reinforcement or tendons, f_y, in accordance with CSA Standard A23.3.

8.6.2 Compression Reinforcement

FRP reinforcement in the compression zone shall be deemed to provide no compressive resistance in design.

8.6.3 Stresses Derived from Stress-Strain Relationship

8.6.3.1

The force in the reinforcement shall be calculated from strain compatibility based on a stress-strain curve representative of the reinforcing material multiplied by its appropriate resistance factor (ϕ_s for reinforcing bars, ϕ_p for prestressing tendons, and ϕ_F for FRP reinforcement and tendons).

8.6.3.2

For FRP reinforcement, or steel with a specified yield strength of 500 MPa or less, the following assumptions may be used:

(a) for strains ε_F less than the ultimate strain, ϵ_{Fu}, the force in the FRP shall be taken as $\phi_F A_F E_F \varepsilon_F$;

(b) for strains ε_s less than the yield strain, f_y/E_s, the force in the steel reinforcement shall be taken as $\phi_s A_s E_s \varepsilon_s$;

(c) and for strains greater than the yield strain, the force in the steel reinforcement shall be taken as $\phi_s A_s f_y$.

8.6.4 Modulus of Elasticity

8.6.4.1

The modulus of elasticity, E_s, for steel reinforcement shall be taken as 200 000 MPa.

8.6.4.2

The modulus of elasticity, E_F, for FRP reinforcement and tendons and E_p for steel tendons, shall be determined in accordance with Clause 7.1.

8.6.5 Analysis

8.6.5.1

All members of frames or continuous construction shall be designed for the maximum effects of the factored loads.

8.6.5.2

All structural analyses shall satisfy equilibrium conditions.

8.6.5.3

Assumptions made for determining the flexural and torsional stiffness of columns, walls, and roof systems shall be consistent throughout the analysis.

8.6.6 Methods of Analysis

8.6.6.1

All structural analysis shall be based on assumptions of linear elasticity, assuming uncracked sections except for lateral load effects in frames.

8.6.6.2

Load redistribution or moment redistribution or other methods of plastic analysis are not permitted.

8.6.6.3

Member stiffness used in analysis of the lateral deflections of frames or in second-order frame analyses (P-delta effect) shall be representative of the degree of member cracking and inelastic action at the loading stage for which analysis is being performed

8.6.6.4

Analysis by strut and tie models is not permitted.

8.6.6.5

Finite element methods of analysis may be used, provided that the assumed model can closely simulate the actual boundary and load conditions of the structure.

9 Development Length and Splices

9.1 Notation

The following symbols are used in Clause 9:

A_b = area of an individual bar
A_G = area of an individual rib or bar in a grid to be developed
b_w = minimum effective web width
d = distance from the extreme compression fibre to the centroid of longitudinal tension force
d_b = nominal diameter of a circular bar or equivalent diameter of a rectangular bar
d_{cs} = the smaller of
(a) the distance from the closest concrete surface to the centre of the bar being developed; or
(b) two-thirds of the centre-to-centre spacing of the bars being developed
f'_c = specified compressive strength of concrete
f_F = design stress in FRP tension reinforcement at ultimate limit state
f_{Fu} = ultimate strength of FRP shear reinforcement
k_1 = bar location factor

k_2 = concrete density factor
k_3 = bar size factor
k_4 = bar fibre factor
k_5 = bar surface profile factor
l_d = the development length of bars in tension
S_G = FRP grid spacing parallel to the bending direction under investigation
V_f = factored shear resistance calculated in accordance with Clause 8.4
V_{sF} = factored shear resistance provided by FRP shear reinforcement
V_{ss} = factored shear resistance provided by steel shear reinforcement
β_b = the ratio of the area of bars cut off to the total area of bars at the section

9.2 Development of Reinforcement — General

The calculated tension in reinforcement at each section of a reinforced concrete member shall be developed on each side of that section by embedment length or mechanical device, or by a combination of both. Hooks may be used in developing bars in tension provided that proper testing has demonstrated their capability to enhance the development length.

9.3 Development Length of Bars in Tension

9.3.1 General

The development length, l_d, of bars in tension shall either be determined directly from the tests in accordance with Annexes D and E or shall be calculated in accordance with Clauses 9.3.2 and 9.3.3. The maximum permissible value of $\sqrt{f'_c}$ in Equations 9-1 and 9-2 shall be 8 MPa.

9.3.2 Development Length — Normal Requirement

Except as provided for in Clause 9.3.3, the development length, l_d, of bars in tension shall be taken as

$$l_d = 1.15\frac{k_1k_2k_3k_4k_5}{d_{cs}}\frac{f_F}{\sqrt{f'_c}}A_b \qquad \textbf{(9-1)}$$

but d_{cs} shall not be taken greater than $2.5d_b$.

9.3.3 Development Length — Permitted Variation

The development length, l_d, of bars in tension may be taken as

$$l_d = 0.5k_1k_2k_3k_4k_5\frac{f_F}{\sqrt{f'_c}}d_b \qquad \textbf{(9-2)}$$

provided that the clear cover and clear spacing of the bars being developed are at least $1.5d_b$ and $1.8d_b$, respectively.

9.3.4 Modification Factors

The following modification factors shall be used in calculating the development length in Clauses 9.3.2 and 9.3.3.

(a) Bar location factor:
k_1 = 1.3 for horizontal reinforcement placed so that more than 300 mm of fresh concrete is cast in the member below the development length or splice
= 1.0 for other cases

(b) Concrete density factor:
k_2 = 1.3 for structural low-density concrete
= 1.2 for structural semi-low-density concrete
= 1.0 for normal density concrete

(c) Bar size factor:
k_3 = 0.8 for $A_b \le 300\ mm^2$
= 1.0 for $A_b > 300\ mm^2$

(d) Bar fibre factor:
k_4 = 1.0 for CFRP and GFRP
= 1.25 for AFRP

(e) Bar surface profile factor:
The bar surface profile factor may be taken as less than 1.0, but not less than 0.5, if this value has been shown by experiment. In the absence of direct experimental values, the following values shall be used:
k_5 = 1.0 for surface-roughened or sand-coated surfaces
= 1.05 for spiral pattern surfaces
= 1.0 for braided surfaces
= 1.05 for ribbed surfaces
= 1.80 for indented surfaces

9.4 Development of Grid Reinforcement

The design strength of the FRP grid shall be considered to be developed by the embedment of three cross bars with the closer cross bar not less than 50 mm from the critical section. However, the development length, l_d, measured from the critical section to the outermost cross bar shall be not less than

$$l_d = 3.3 k_2 k_4 \frac{A_G}{S_G} \frac{f_F}{\sqrt{f_c'}} \qquad \textbf{(9-3)}$$

The value for l_d shall not be less than 250 mm.

9.5 Development of Flexural Reinforcement — General

The following requirements shall be met:
(a) Critical sections for the development of reinforcement in flexural members are at points of maximum stress and at points within the span where adjacent reinforcement terminates. The location of the points of maximum stress and the points at which reinforcement is no longer required to resist flexure shall be derived from the factored bending moment diagram.
(b) The flexural tension reinforcement shall be extended a distance of d or $12d_b$, whichever is greater, beyond the location required for flexure alone except at the supports of simple spans, at the free ends of cantilevers, and at the exterior supports of continuous spans.
(c) At the supports of simple spans, at the exterior supports of continuous spans, and near the free ends of cantilevers subjected to concentrated loads, the longitudinal reinforcement on the flexural tension side of the member shall be capable of resisting a tensile force of $V_f - 0.5V_{ss}$ or $V_f - 0.5V_{sF}$, whichever is applicable, at the inside edge of the bearing area where V_{ss} or V_{sF} is the value based on the stirrups at that location.
(d) Flexural reinforcement shall not be terminated in a tension zone unless one of the following conditions is satisfied:
(i) the shear at the cutoff point does not exceed one-half of that permitted, including the shear strength of the shear reinforcement provided; or
(ii) the stirrup area in excess of that required for shear and torsion is provided along each terminated bar, over a distance from the termination point equal to three-fourths of the effective depth of the member. The excess stirrup area, A_v, shall be not less than $\frac{b_w s}{1.2 f_{Fu}}$. The spacing, s, shall not exceed $\frac{d}{8\beta_b}$
(e) Special attention shall be given to the provision of adequate anchorage for tension reinforcement in

flexural members such as sloped, stepped, or tapered footings; brackets; deep flexural members; or members in which the tension reinforcement is not parallel to the compression face.

9.6 Splice Lengths

Splice lengths shall be provided by the bar manufacturer and shown on the contract documents.

10 Design of Concrete Components Prestressed with FRP

10.1 Notation

The following symbols are used in Clause 10:

A = effective tension area of concrete surrounding the flexural reinforcement and extending from the extreme tension fibre to the centroid of the flexural tension reinforcement and an equal distance past the centroid, divided by the number of bars and wires. When the flexural reinforcement consists of different bar or wire sizes, the number of bars or wires used to compute A shall be taken as the total area of reinforcement divided by the area of largest bar or wire used.
A_F = area of tension FRP reinforcement
A_{Fp} = area of FRP prestressing tendons
A'_s = area of compression steel reinforcement
b = width of tension face of cross-section
b_w = width of web
c = depth of neutral axis
d_b = bar diameter
d_c = distance from extreme tension fibre to the centre of the longitudinal bar or wire located closest to it
d_{Fp} = effective depth of section with FRP tendons
E_{ci} = modulus of elasticity of concrete at time of tensioning
E_F = Young's modulus of FRP
E_s = Young's modulus of steel
f'_c = compressive strength of concrete
f'_{ci} = compressive stress in concrete at time of prestress transfer
f'_{cpg} = compressive stress of concrete at tendon centroid due to tensioning, calculated using E_{ci}
f_F = stress in FRP reinforcement due to specified loads
f_{Fp} = stress in prestressing tendon due to specified loads
f_{Fpe} = effective stress in FRP prestressing tendons (after allowance for all prestressing losses)
f_{Fpi} = initial prestress in FRP tendons
f_{Fpr} = stress in unbonded tendon at ultimate limit state
f_{Fpu} = tensile strength of FRP prestressing tendons
f_{Fu} = tensile strength of FRP reinforcement (non-prestressed)
f'_y = yield of compression steel reinforcement
h_f = thickness of flange
l_d = development length
L = length of tendon between anchorages
L_{fb} = flexural bond length
L_T = transfer length
L_1 = length of loaded span or sum of the lengths of loaded spans affected by the same tendon
L_2 = length of tendon between the anchorages
M_{cr} = cracking moment
M_f = factored moment
M_r = factored moment resistance
n = modular ratio

N = number of tendon groups tensioned
$P(x)$ = prestress force in design section under consideration
P_i = tensile force at position of prestressing jack
P_x = tensile force of tendon at design section
ΔP_T = variation of prestressing force due to temperature
t = time in days
ΔT = temperature change
V_c = factored shear resistance provided by concrete
V_{cw} = factored shear resistance provided by web concrete
V_f = factored shear force
V_p = vertical component of all effective prestress forces crossing the critical section
V_r = factored shear resistance
V_{sF} = factored shear resistance provided by FRP shear reinforcement
V_{ss} = factor shear resistance provided by steel shear reinforcement
x = distance from tensioned edge of tendon to design section
α = angular change (radians)
α_1 = rectangular stress block parameter
α_c = thermal expansion coefficient of concrete
α_f = regression coefficient: 1.0 for CFRP rebars and 2.8 for CFRP strands
α_F = thermal expansion coefficient of FRP
α_t = regression coefficient: 1.9 for CFRP rebars and 4.8 for CFRP strands
β = ratio of the distance from extreme tension fibre to neutral axis to the distance from centroid of tension to neutral axis
β_1 = rectangular stress block parameter
ε_{cu} = ultimate compressive strain in concrete
ϕ_c = resistance factor for concrete
ϕ_F = resistance factor for FRP rebars
ϕ_S = resistance factor for steel rebars
λ = factor to account for low density concrete; or friction parameter per unit length of tendon
μ = coefficient of friction
Δ_{AS} = magnitude of anchorage slip
$\Delta\sigma_{pAS}$ = prestress loss due to anchorage slip
$\Delta\sigma_{pES}$ = prestress loss due to elastic shortening
$\Delta\sigma_{pT}$ = prestress loss due to temperature change
Ω_u = bond reduction coefficient
ΔP_Y = variation of prestressing force due to change in temperature

10.2 General

Design shall be in accordance with the following:

(a) The provisions of Clause 10 shall apply to members prestressed with CFRP and AFRP strands and bars, which are in accordance with Clause 7.1.4. The use of GFRP for flexural reinforcement of prestressed concrete is not permitted.

(b) A perfect bond shall be effected between FRP and concrete.

(c) The effects of the loads at all loading stages that may be critical during the life of the member from the time the prestress is first applied shall be considered.

(d) The deflection of FRP prestressed concrete members shall be determined either by using Clause 9.8.4 of CSA Standard A23.3 or by integration of curvature along the span of the beam.

(e) In order to limit the crack width in concrete members prestressed with FRP, the quantity z shall be calculated from Equation 8-1 and z shall not exceed 15 000 N/mm for exterior exposure and 20 000 N/mm for interior exposure.

(f) The effect of temperature expansion and lateral expansion of released tendon, often identified as the Hoyer effect, shall be considered in accordance with Clause 10.3.2.

(g) When adjoining parts of the structure can restrain the elastic and long-term deformations

(deflections, changes in length, and rotation) of a member caused by prestressing, applied loading, foundation settlement, temperature, and shrinkage, the restraint shall be estimated and its effects both on the member and on the restraining structure shall be considered.
(h) The possibility of buckling in a member between points where concrete and prestressing tendons are in contact, and of buckling in thin webs and flanges, shall be considered.
(i) In computing section properties, the loss of area due to open ducts or conduits shall be considered.

10.3 Design Assumptions for Flexure and Axial Load

10.3.1 Basic Assumptions

The design of FRP prestressed members for flexure shall be based on the following assumptions:
(a) Sections plane before bending shall remain plane after bending.
(b) The maximum concrete strain in compression fibre shall be assumed to be 0.0035.
(c) Balanced failure strain conditions for FRP prestressed members exist at a cross-section when the tensile FRP reinforcement reaches its ultimate strain just as the concrete in compression reaches its maximum strain of 0.0035.
(d) The tensile strength of concrete may be neglected in the calculation of the factored flexural resistance of prestressed concrete members.
(e) For all FRP prestressed concrete members, it is permissible to allow rupture of the FRP, provided that the structure as a whole contains supplementary reinforcement designed to carry the unfactored dead loads or has alternative load paths so that the failure of the member does not lead to progressive collapse of the structure.

10.3.2 Concrete Cover

Minimum clear concrete cover in pretensioned members shall be $3.5d_b$ or 40 mm, whichever is greater, to account for the effect of temperature expansion and the Hoyer effect, defined in Clause 10.2(f). If concrete of higher strength than 80 MPa is used, the cover may be reduced to $3d_b$ or 35 mm, whichever is greater.

Concrete cover may also be reduced if sufficient reinforcement in transfer regions is provided or if prestressing tendons are partially debonded over the length of transfer region. However, the limit of $3.5d_b$ for minimum concrete cover shall be satisfied.

10.4 Permissible Stresses in Concrete

10.4.1 Stresses Immediately after Prestress Transfer

10.4.1.1

Except as provided in Clause 10.4.1.2, stresses in concrete immediately after prestress transfer due to prestress and the specified load present at transfer shall not exceed the following:
(a) extreme fibre stress in compression: $0.6f'_{ci}$
(b) extreme fibre stress in tension except as permitted in Item (c): $0.25\lambda\sqrt{f'_{ci}}$
(c) extreme fibre stress in tension at ends of simply supported members: $0.5\lambda\sqrt{f'_{ci}}$

10.4.1.2

Where computed tensile stresses exceed the values given in Clauses 10.4.1.1, Items (b) and (c), bonded reinforcement shall be provided in the tensile zone to resist the total tensile force in the concrete computed on the basis of an uncracked section.

10.4.2 Stresses after Allowance for All Prestress Losses

Stresses in concrete under specified loads and prestress (after allowance for all prestress losses) shall not exceed the following:

(a) extreme fibre stress in compression due to sustained loads: $0.45f'_c$

(b) extreme fibre stress in compression due to total load: $0.60f'_c$

(c) extreme fibre stress in tension in precompressed tensile zone: $0.25\lambda\sqrt{f'_c}$

10.5 Permissible Stresses in Tendons

10.5.1 Permissible Stresses at Jacking and Transfer

Permissible stresses at jacking and transfer, as a function of $f_{Fpu,}$ shall be in accordance with Table 13. Special attention shall be given when jacking draped strands to avoid local failure at the bends.

Even when failure is initiated by the tensile rupture of the FRP strands and/or bars, the ultimate resistance moment of the section shall be based on the stresses given in Table 13.

10.5.2 Anchorage for FRP Tendons

Anchors shall be tested prior to application in order to check that they are capable of developing at least 90% of the specified tensile strength of FRP tendons. The number of samples required shall be specified on the plan and shall not be less than two.

10.5.3 Reinforcement of Disturbed Regions

Disturbed regions, such as the anchorage zone, anchor buttress, parts of beams around openings, and beams with dapped ends shall be reinforced against splitting and bursting.

10.6 Losses of Prestress

10.6.1 Effective Prestressing Force

Effective prestressing force shall be calculated according to

$$P(x) = P_i - \sum \Delta P_i(x) + \Delta P_T(x) \qquad \textbf{(10-1)}$$

10.6.2 Prestress Losses

10.6.2.1

To determine the effective prestress, $f_{Fpe,}$ allowance for the following sources of loss of prestress shall be considered:

(a) anchorage seating loss;
(b) elastic shortening of concrete;
(c) friction loss due to intended and unintended curvature in post-tensioning tendons;
(d) creep of concrete;
(e) shrinkage of concrete;
(f) relaxation of tendon stress; and
(g) temperature change.

10.6.2.2

When jacking is performed using steel strands connected to FRP tendons through steel couplers, the accumulation of setting loss due to anchorage of steel and FRP tendons shall be considered. For different anchoring systems, the amount of setting shall be provided by the manufacturer or determined by testing.

The loss due to anchor slip shall be computed using the formula

$$\Delta\sigma_{pAS} = (\Delta_{AS} E_F) / L \qquad \textbf{(10-2)}$$

where

L = length of tendon between anchorages

10.6.2.3

Prestress loss due to elastic shortening shall be computed using the following formulas:

for pretensioned strands:

$$\Delta\sigma_{PES} = nf'_{cpg} \quad \textbf{(10-3)}$$

for post-tensioned strands:

$$\Delta\sigma_{PES} = 0.5n'_{cpg}(N-1)N \quad \textbf{(10-4)}$$

10.6.2.4

The effect of friction loss in post-tensioning tendons shall be computed by

$$P_x = P_i e^{-(\mu\alpha+\lambda x)} \quad \textbf{(10-5)}$$

The values of μ and λ shall be determined by testing, except that where the sheaths are used with CFRP, the values $\mu = 0.3$ and $\lambda = 0.004$/m may be used.

10.6.2.5

The loss of prestress due to creep and shrinkage shall be calculated as in steel prestressed concrete, taking into account the modulus of elasticity of FRP.

10.6.2.6

The amount of relaxation shall be evaluated appropriately for each type of FRP tendons used and shall be reflected in the design. In the absence of more specific information, the following values may be used:
(a) for CFRP: relaxation (%) = 0.231 + 0.345 log(t); and **(10-6)**
(b) for AFRP: relaxation (%) = 3.38 + 2.88 log(t). **(10-7)**

where
t = time in days.

10.6.2.7

Special care shall be taken in estimating relaxation losses of FRP tendons when steam curing is used or when tendons of low-fibre volume are used.

10.6.2.8

The variation of prestress due to change of temperature shall be obtained using the formula

$$\Delta\sigma_{pT} = \Delta T(\alpha_F - \alpha_c)E_F \quad \textbf{(10-8)}$$

10.7 Flexural Resistance

10.7.1 Strain Compatibility Analysis

Strain compatibility analysis shall be based on the stress-strain curves of the FRP to be used and on the assumption of a perfect bond in the bonded tendons.

10.7.2 Bond Reduction Coefficient

The analysis of concrete elements prestressed with unbonded FRP tendons shall be based on the concept of bond reduction coefficient. The stress in unbonded FRP tendon at ultimate shall be calculated by solving Equations 10-9 and 10-10 simultaneously for f_{Fp}.

$$f_{Fpr} = f_{Fpe} + \Omega_u E_F \varepsilon_{cu}\left(\frac{d_{Fp}}{c} - 1\right)\left(\frac{L_1}{L_2}\right) \quad \textbf{(10-9)}$$

$$A_{Fp}\phi_{Fp} f_{Fpr} + A_F \phi_F f_F - A_s' \phi_s f_y' = \alpha_1 \phi_c f_c' (b - b_w) h_f + \alpha_1 \phi_c f'_c b_w \beta_1 c \quad \textbf{(10-10)}$$

where the values of the bond reduction coefficient, Ω_u, are

$$\Omega_u = \frac{3.0}{L/d_{Fp}} \text{ for single point loading} \quad \textbf{(10-11)}$$

$$\Omega_u = \frac{1.5}{L/d_{Fp}} \text{ for one-third point or uniform loading} \quad \textbf{(10-12)}$$

10.7.3 Inclusion of Reinforcement in Flexural Resistance

Compression FRP reinforcement shall not be included in the calculation of flexural resistance; compression steel reinforcement may be considered to contribute to the flexural resistance, with force $\phi_s A_s f_y'$, provided that it is located at least 0.75c from the neutral axis.

Other reinforcement may be included in the calculation of flexural resistance provided that a strain compatibility analysis is made to determine the stress in such reinforcement.

10.8 Minimum Factored Flexural Resistance

The following requirements shall be met:

(a) At every section of FRP prestressed flexural member, the factored moment resistance, M_r, shall satisfy the following

$$M_r \geq 1.5 M_{cr} \quad \textbf{(10-13)}$$

unless the factored flexural resistance is 50% greater than M_f.

(b) If an FRP prestressed member is failing in tension due to rupture of tendons before the ultimate compression strain, ε_{cu}, is reached in the concrete, the factored moment resistance, M_r, shall satisfy the following:

$$M_r \geq 1.5 M_f \quad \textbf{(10-14)}$$

(c) If ultimate failure is initiated by rupture of FRP tension reinforcement before concrete reaches its ultimate compressive strain, the equivalent rectangular stress block shall not be used. The ultimate moment capacity shall be based on strain compatibility and the relevant stress-strain relations of concrete and reinforcement.

10.9 Minimum Area of Bonded Non-Prestressed Reinforcement

In beams and one-way slabs that are prestressed with FRP, bonded non-prestressed reinforcement shall also be provided for control of cracking. The minimum area of the bonded non-prestressed reinforcement, which depends upon whether the tendons are bonded or unbonded and also upon the level of concrete tensile stress, shall be in accordance with Table 14.

10.10 Shear Reinforcement

Members subjected to shear shall be proportioned so that

$$V_f \leq V_r \quad \textbf{(10-15)}$$

For FRP shear reinforcement, the factored shear resistance shall be calculated from

$$V_r = V_c + V_{sF} + 0.90V_p \quad \textbf{(10-16)}$$

For steel shear reinforcement, the factored shear resistance shall be calculated from

$$V_r = V_c + V_{ss} + 0.90V_p \quad \textbf{(10-17)}$$

The values of V_c, V_{sF}, and V_{ss} shall be computed from Equations 8-10, 8-12, and 8-13, respectively. In Equations 10-16 and 10-17, V_p shall be taken as positive if it resists the applied shear.

10.11 Web Crushing

Web crushing shall be checked.

10.12 Minimum Length of Bonded Reinforcement

The minimum length of bonded reinforcement shall be determined as follows:

(a) The minimum development length shall be calculated as

$$l_d = L_T + L_{fb} \quad \textbf{(10-18)}$$

Development length for straight rebars shall not be less than $20d_b$ or 380 mm.

(b) The transfer length of CFRP reinforcement shall be taken as

$$L_T = \frac{f_{Fpi} d_b}{\alpha_t f_c'^{0.67}} \quad \textbf{(10-19)}$$

and shall not be less than the relevant value shown in Table 15.

(c) The flexural bond length shall be taken as

$$L_{fb} = \frac{\left(f_{Fpu} - f_{Fpe}\right) d_b}{\alpha_f f_c'^{0.67}} \quad \textbf{(10-20)}$$

(d) For AFRP, Table 15 may be used as an alternative to performing the calculations required by Clauses 10.12, Item (a), and 10.12, Item (c), in order to obtain values of development length and transfer length.

(e) For CFRP the relevant requirements of Clauses 10.12(a), (b), and (c) and Table 15 shall apply.

11 Strengthening of Concrete and Masonry Components with Surface-Bonded FRP

11.1 Notation

The following symbols are used in Clause 11:

A_{cv} = effective concrete shear transfer area of a column taken as $0.80A_g$

A_e = effective concrete shear transfer area of a wall taken as 0.8Lb

A_F = cross-sectional area of FRP composite reinforcement or of unit width of continuous FRP wrap

A_g = gross area of section

A_h = area of one leg of the transverse reinforcement

A_v = area of shear reinforcement perpendicular to the axis of a member within a distance, s_F

b = shorter dimension of a rectangular column; thickness of a wall

b_w = width of the web of a beam

D = diameter of circular columns or dimension in the loading direction of rectangular columns

D' = core dimension from centre-to-centre of the peripheral hoops of a column
d = distance from extreme compression fibre to centroid of tension reinforcement
d_f = distance from extreme compression fibre to centroid of tension FRP reinforcement
E_F = modulus of elasticity of FRP composite
ΔF = increase in axial force
f'_c = specified compressive strength of concrete
f'_{cc} = specified confined compressive strength of concrete in columns
f_F = stress in FRP composites
f_{Fu} = ultimate tensile strength of FRP composites
f_l = average confining stress of concrete
f'_l = effective confining stress of concrete
f'_m = specified compressive strength of masonry
f_y = specified yield strength of steel reinforcement
f_{yh} = specified yield strength of the transverse reinforcement of columns
H = side length of a rectangular wall
h = longer dimension of a column
k_c = confinement coefficient
L = width of shear wall
m = 1 or 2 depending on the number of wall faces reinforced
n = number of legs of transverse column ties in the loading direction
s = spacing of stirrup of a beam, spacing of transverse reinforcement or spiral pitch of a column, or spacing of transverse reinforcement of a wall
s_F = spacing of FRP shear reinforcement of a beam or unit width (ie, 1.0) of a continuous FRP shear reinforcement
ρ_F = volumetric ratio of transverse FRP reinforcement of a column
t_j = thickness of the FRP jacket
V_c = shear resistance provided by concrete
V_F = shear resistance provided by FRP reinforcement
V_m = shear resistance provided by masonry
V_{ms} = shear resistance provided by steel reinforcement in the masonry
V_r = shear resistance capacity
V_s = shear resistance provided by steel reinforcement
ε_{cu} = ultimate compression strain of concrete
ε_F = tensile strain at the level of FRP composites under factored loads
ε_{Fi} = initial tensile strain at the level of FRP before applying FRP
ϕ_c = resistance factor of concrete
ϕ_F = resistance factor of FRP composites
ϕ_s = resistance factor of reinforcing steel
λ = factor to account for low-density concrete
θ = acute angle of fibre direction to member axis

11.2 General Design Requirements

11.2.1 General

An assessment of the existing structures shall be undertaken in accordance with Clause 11.6. Surface-bonded FRP reinforced materials shall conform to the requirements of Clause 7.2. All surface-bonded FRP reinforced components shall be designed as structural elements in accordance with Clauses 5 and 6. When surface-bonded FRP reinforcement is used for enhancement of seismic resistance, the relevant portions of Clause 12 shall apply, in addition to those of Clause 11. Strengthening of a member shall not result in the transformation of a ductile failure mode of the unstrengthened member to a brittle failure mode of the strengthened member.

11.2.2 Required Information

11.2.2.1
A detailed description of the system shall be provided, including
(a) a description and identification of the product or system; and
(b) restrictions or limitations of the system.

11.2.2.2
Installation instructions shall include
(a) a description of how the product or system will be used or installed in the field;
(b) procedures for establishing quality control in field installation;
(c) requirements for product handling and storage;
(d) a procedure for fastener installation into structural elements; and
(e) for systems that depend on bond between the system and the substrate, procedures for on-site testing of bond to the substrate.

11.2.3 Structural Design

11.2.3.1
When concrete and masonry components are to be strengthened with surface-bonded FRP, a check shall first be made to ensure that the existing structure, prior to addition of the surface bonding, is capable of supporting service loads without collapse. If the existing structure is not capable of doing this, the strengthening system shall, in addition to the surface-bonded FRP, include such features as will ensure this capability if bond or other failure should occur in the FRP. The engineering analysis shall consider both ultimate and serviceability limit states and shall take into account the following three conditions of the structure:
(a) the existing structure prior to strengthening;
(b) the structure after strengthening with the FRP surface bonding, fully functional; and
(c) the structure after strengthening with the FRP surface bonding, no longer functional.

11.2.3.2
The design criteria outlined in Clauses 11.3 to 11.5 do not eliminate the need for structural testing. Situations not covered in Clauses 11.3 to 11.5 shall be given special consideration and shall be tested in accordance with Clause 7.2.8, and design values should be compatible with the conservative approach adopted in Clauses 11.3 to 11.5.

11.3 Design Requirements for Concrete Beam Strengthening

11.3.1 Flexural Strength

11.3.1.1
The factored moment resistance shall be based on strain compatibility and equilibrium using material resistance factors and material properties specified in Clause 7.2.7 and the following additional assumptions:
(a) plane sections shall remain plane;
(b) the bond between concrete, steel, and FRP composites shall be perfect;
(c) the maximum compressive concrete strain shall be assumed to be 0.0035; and
(d) the maximum tensile FRP strain shall be no greater than 0.007, assuming no anchorage failure.

11.3.1.2

11.3.1.2.1

At service loads, stresses shall be calculated based on elastic analysis. At ultimate loads, the following flexural failure modes shall be investigated for a section strengthened with FRP laminates:
(a) crushing of the concrete in compression before rupture of the FRP or yielding of the reinforcing steel; and
(b) yielding of the steel and/or rupture of the FRP in tension followed by concrete crushing.

11.3.1.2.2

In addition to the failure modes specified in Clause 11.3.1.2.1, the following modes of debonding failure shall be considered, using currently available information appropriate to the combination of sheets and adhesive:
(a) shear/tension failure of concrete substrate at the FRP cutoff point (anchorage failure); and
(b) debonding of adhesive bond line due to vertical section translations from cracking (delamination).

11.3.1.3

The initial strains and stresses in a beam before strengthening shall be considered. This effect can be taken into account by reducing the axial stress in the FRP composite, assuming a linear strain distribution across the depth of the cross section, using the equation

$$f_F = E_F\left(\varepsilon_F - \varepsilon_{Fi}\right) \quad \textbf{(11-1)}$$

11.3.1.4

Debonding of the FRP shall be considered in the design. Alternatively, transverse anchorage using FRP sheets or other proven anchorage methods may be used to prevent anchorage failures as described in Clause 11.3.1.2.

11.3.2 Shear Strength

11.3.2.1

FRP sheets or plates may be used to increase the shear capacity of a beam by applying fibres perpendicular to the longitudinal axis of the beam. Other fibre orientation angles or multiaxial fibres may also be used in the strengthening of a beam against shear. The FRP composites may be continuous or cut with certain widths and bonded to the sides of the web. The FRP sheets may be totally wrapped, continuously wrapped around the bottom of the web in a U-shape, or bonded on the sides of the web only. For the latter two cases, sufficient development length shall be provided or mechanical anchorage shall be used. The FRP sheets used to strengthen the shear may also be used to prevent anchorage failure of FRP flexural reinforcement as discussed in Clause 11.3.1.4.

11.3.2.2

The factored shear resistance shall be determined by

$$V_r = V_c + V_s + V_F \le V_c + 0.6\lambda\phi_c\sqrt{f_c'}\,b_w d \quad \textbf{(11-2)}$$

where

$$V_c = 0.2\lambda\phi_c\sqrt{f_c'}\,b_w d \quad \textbf{(11-3)}$$

$$V_s = \frac{\phi_s A_v f_y d}{s} \quad \textbf{(11-4)}$$

$$V_F = \frac{\phi_F A_F E_F \varepsilon_F d_f}{s_F} \tag{11-5}$$

In the absence of more precise information, the value of ε_F may be conservatively assumed to be as follows:
(a) for U-shaped wrap continuous around the bottom of the web, $\varepsilon_F = 4000\mu\varepsilon$; and
(b) for side bonding to the web (and only in cases where sufficient development length cannot be provided), $\varepsilon_F = 2000\mu\varepsilon$.

11.3.2.3

Bond length of FRP composites shall be sufficient to avoid anchorage failure of the FRP, except that if the bond length is limited, other rational methods for shear design may be used; in particular, the shear strength may be improved by bonding additional longitudinal FRP strips over the ends of U-shaped bands.

11.4 Design Requirements for Concrete Column Strengthening

11.4.1 Flexural Strength Enhancement

11.4.1.1

Normally, for the enhancement of flexural strength of columns, FRP composites having longitudinally oriented fibres shall be used. If fibres having another orientation are used, the provisions of Clause 11.5.1 shall apply. Only the tension FRP reinforcement shall be considered effective. Section analysis shall be based on normal assumptions and strain compatibility among concrete, reinforcement, and FRP composites. The enhancement of tensile force per unit width provided by a fibre element of effective thickness, t_F, shall be

$$\Delta F = t_j f_F \tag{11-6}$$

where

$$f_F = E_F \varepsilon_F \le \phi_F f_{Fu}$$

where

ε_F = the axial strain in the concrete to which the fibre is bonded, and the maximum value shall not exceed 0.007

Unless the compression zone is confined by transversely oriented fibre outside the flexural fibre in accordance with Clause 11.4.2, an extreme compression strain of $\varepsilon_{cu} = 0.0035$ shall be assumed in determining flexural strength.

11.4.1.2

Debonding or anchorage failure of the FRP flexural reinforcement shall be considered in the design.

11.4.1.3

Proven anchorage methods shall be used to ensure development of the strength of the FRP at the section considered.

11.4.2 Axial Load Capacity Enhancement

11.4.2.1

FRP composites may be bonded to external surfaces of concrete columns to enhance the axial load capacity of the columns. Circular sections, and rectangular sections where the ratio of longer (h) to shorter (b) section side dimension is not greater than 1.5, may have their axial compression capacity enhanced by the confining effect of FRP composite material placed with fibres running essentially perpendicular, $\theta \geq 75°$, to the longitudinal axis of the member.

For rectangular sections confined with transverse FRP composites, section corners shall be rounded to a radius not less than 20 mm before placing composite material. Axial compression capacity enhancement by fibre-reinforced composite material to rectangular sections with an aspect ratio h/b > 1.5 shall be subject to special analysis confirmed by test results.

11.4.2.2

The confined compressive strength of concrete, f'_{cc}, in FRP wrapped columns shall be computed by

$$f'_{cc} = 0.85f'_c + k_l + k_c + f_l \quad \textbf{(11-7)}$$

where

$$k_l = 6.7(k_c f_l)^{-0.17} \quad \textbf{(11-8)}$$

k_c = 1.0 for circular and oval jackets
= 0.25 for square and rectangular jackets

$$f_l = \frac{2t_j f_{Fj}}{D} \quad \textbf{(11-9)}$$

where

f_{Fj} = $0.004E_F$ or $\phi_F f_{Fu}$, whichever is less

11.4.3 Ductility Enhancement

FRP composites oriented essentially transversely to the axis of columns may be used to enhance the flexural ductility capacity of circular and rectangular sections where the ratio of longer to shorter section dimension does not exceed 1.5. The enhancement is provided by increasing the effective compression strain of the section and may be calculated in accordance with Clause 12.5.3.

11.4.4 Shear Strength Enhancement

11.4.4.1

Shear strength of circular and rectangular columns can be enhanced by FRP composites with fibre oriented essentially perpendicular, $\theta \geq 75°$, to the members' axis.

For rectangular sections with shear enhancement provided by transverse FRP composite material, section corners shall be rounded to a radius not less than 20 mm before placing composite material.

11.4.4.2

The shear resistance of a column strengthened by FRP composite with fibre oriented at angle $\theta \geq 75°$ to the longitudinal axis of the columns shall be determined by

$$V_r = V_c + V_s + V_F \leq V_c + 0.6\lambda\phi_c\sqrt{f'_c}A_{cv} \quad \textbf{(11-10)}$$

where

$$V_c = 0.2\lambda\phi_c\sqrt{f'_c}A_{cv} \quad \textbf{(11-11)}$$

For both circular and rectangular columns, the transverse steel reinforcement contribution, V_s, shall be determined by

$$V_s = \frac{\phi_s A_v f_y d}{s} \quad \textbf{(11-12)}$$

For both circular and rectangular columns, the contribution from the FRP composites, V_F, shall be determined by

$$V_F = 2\phi_F f_{Fd} t_j D \quad \textbf{(11-13)}$$

where

$$f_{Fd} = 0.004E_F \le \phi_F f_{Fu} \quad \textbf{(11-14)}$$

11.5 Design Requirements of Concrete and Masonry Wall Strengthening

11.5.1 Flexural Strength

11.5.1.1

FRP composites bonded to surfaces of concrete and masonry walls with $\theta \le 15°$ may be used to enhance the design flexural strength of the walls. Only the tension FRP reinforcement shall be considered effective. Section analysis shall be based on normal assumptions and strain compatibility between concrete or masonry reinforcement and composite material. Unless the flexural strength is proven by tests, an extreme compression concrete strain of $\varepsilon_{cu} = 0.0035$, an extreme masonry compression strain of $\varepsilon = 0.003$, and the maximum FRP tensile strain of 0.007 shall be assumed in determining flexural strength. The enhancement of tensile force per unit width provided by a fibre element of effective thickness t_F, oriented at angle θ to the direction of member axis, shall be

$$\Delta F = t_j f_F \quad \textbf{(11-15)}$$

where

$$f_F = E_F \varepsilon_F \cos^2\theta \le \phi_F f_{FU}$$

where

ε_F = the strain in the concrete to which the fibre is bonded

If $\theta > 15°$, the fibre contribution to flexural strength shall be ignored, except if equal fibre quantities are provided with a mirror orientation of θ to the member axis thereby creating an overall symmetry of fibre orientation with respect to the column axis, the contribution of fibres with $\theta = 45°$ shall be considered.

11.5.1.2

Debonding or anchorage failure of the FRP flexural reinforcement shall be considered in the design.

11.5.1.3

Proven anchorage methods shall be used to ensure development of the strength of the FRP at the section considered.

11.5.2 Shear Strength Enhancement

11.5.2.1

The shear-resistant capacity of FRP reinforced concrete or masonry shear walls shall be determined from the following:

(a) For FRP reinforced concrete walls

$$V_r = V_c + V_s + V_F \le V_c + 0.6\lambda\phi_c\sqrt{f_c'}A_e \quad \text{(11-16)}$$

(b) For FRP reinforced masonry walls

$$V_r = V_m + V_{ms} + V_F \le V_m + 0.4\phi_m\sqrt{f_c'}A_e \quad \text{(11-17)}$$

11.5.2.2

The concrete contribution, V_c, in Clause 11.5.2.1 shall be determined from

$$V_c = 0.2\lambda\phi_c\sqrt{f_c'}A_e \quad \text{(11-18)}$$

where

A_e = effective area of concrete
= 0.8Lb

The masonry contribution, V_m, shall be determined from

$$V_m = 0.20\phi_m\sqrt{f_m'}A_e \quad \text{(11-19)}$$

where

$\phi_m = 0.55$

11.5.2.3

The steel reinforcement contribution, V_s, in Clause 11.5.2.1 shall be determined from the following:
(a) For FRP reinforced concrete walls

$$V_s = \frac{n\phi_s A_h f_{yh} D'}{s} \quad \text{(11-20)}$$

(b) For FRP reinforced masonry walls

$$V_{sm} = \frac{\phi_s(0.6A_h f_{yh} d)}{s} \quad \text{(11-21)}$$

11.5.2.4

The contribution from the FRP composites, V_F, in Clause 11.5.2.1 shall be determined from

$$V_F = m\phi_F t_F f_F D' \quad \text{(11-22)}$$

where
m = 1 or 2, depending on the number of wall faces reinforced

$$f_F = 0.004E_F \le \phi_F f_{Fu} \quad \text{(11-23)}$$

11.5.2.5

The provisions in Clause 11.5.2.1 apply only to walls strengthened by fibre covering the entire width of the walls. The sliding shear failure at construction joints shall be checked.

11.6 Evaluation of Existing Structures

Prior to developing a strengthening strategy, an assessment of the existing structure or elements shall be conducted to identify the causes of any deficiencies, to determine the condition of the existing concrete, to establish the structure's load-carrying capacity, and to evaluate the feasibility of using externally bonded FRP systems.

11.7 Seismic Requirements for Shear Wall Retrofit and Rehabilitation

In addition to the relevant requirements of Clause 11, Clause 12.5 shall apply.

12 Provisions for Seismic Design

12.1 Notation

The following symbols are used in Clause 12:

A_c = cross-sectional area of the core of a compression member measured to the centreline of the perimeter hoop or spiral
A_{Fh} = total area of rectangular FRP hoop reinforcement in each cross-sectional direction
A_g = gross area of section
A_v = area of shear reinforcement perpendicular to the axis of a member within a distance s
b_w = width of web of a beam
d = distance from extreme compression fibre to centroid of tension reinforcement
D = diameter of circular columns or dimension in the loading direction of rectangular columns
E_F = elastic modulus of FRP composite
f_F = stress in FRP composite
f_{Fd} = design stress level in the FRP wrap
f_{Fh} = design stress level in FRP transverse confinement reinforcement
f_{Fu} = ultimate tensile strength of FRP composites
f_y = specified yield strength of steel reinforcement
f'_c = specified compressive strength of concrete
g = gravity constant
h_c = cross-sectional dimension of column core
i = level
k_c = confinement coefficient
P_f = factored axial load
P_{ro} = factored axial load resistance at zero eccentricity
s = spacing of transverse reinforcement or the spiral pitch
s_l = spacing of tie legs or the spacing of grid openings in the cross-sectional plane of the column
T = the fundamental period
t_j = thickness of the FRP jacket
V_c = shear resistance provided by concrete
V_F = shear resistance provided by FRP jacket
V_r = shear resistance capacity
V_s = shear resistance provided by the transverse steel reinforcement
W_i = lumped seismic gravity load assigned to level i
ϕ_c = resistance factor of concrete
ϕ_F = resistance factor or FRP composites
ϕ_s = resistance factor for reinforcing bars
δ = design lateral drift ratio (ie, horizontal drift/building height)
δ_i = elastic deflection at level i
λ = factor to account for concrete density
ε_{cu} = ultimate compressive strain of concrete

12.2 General

Structural systems and structural components shall be designed and detailed with particular recognition of the effects of the differences in the mechanical characteristics of fibre-reinforced plastic materials and steel, when considered as reinforcements during earthquakes. These differences include FRP's lack of ductile behaviour from the essentially linear elastic stress-strain relationship of the materials until rupture, lower modulus of elasticity, and higher ultimate strength, resulting in significantly different stiffness, damping, and energy dissipation characteristics for structures reinforced with FRP materials.

12.3 Applicability

The provisions of Clause 12 shall apply to the use of FRP reinforcing materials in two general areas:
(a) the design of new structural members and complete systems primarily reinforced with FRP materials; and
(b) the rehabilitation and repair of existing structures, in which case any relevant provisions of Clause 10 shall also apply.
The provisions of Clause 12 shall apply to pre-engineered systems.

12.4 Seismic Loads

12.4.1 Seismic Loads for Repair and Rehabilitation

The seismic loads acting on concrete structures repaired or rehabilitated with FRP materials shall be determined in accordance with Clause 4.1.9 of the *National Building Code of Canada* (*NBCC*).

12.4.2 Seismic Loads for New Construction

12.4.2.1

The seismic loads for new concrete structures having primary lateral-load-resisting systems that include FRP reinforcement shall be determined in accordance with Clause 4.1.9 of the *NBCC*, with the modifications specified in Clauses 12.4.2.2 and 12.4.2.3.

12.4.2.2

The fundamental period, T, of the structure shall be determined in accordance with the *NBCC* and the Rayleigh formula as follows:

$$T = 2\pi \sqrt{\frac{\sum_{i=1}^{n} W_i \delta_i^2}{g \sum_{i=1}^{n} W_i \delta_i}} \qquad \textbf{(12-1)}$$

The fundamental period shall be that calculated in accordance with Equation 12-1, subject to an upper limit of 1.2 times the value calculated from *NBCC* formulas.

12.4.2.3

To allow for the lack of hysteretic behaviour in dissipating seismic energy through inelastic action when using FRP materials, the seismic base shear shall be determined using a force modification factor of R = 1.5, regardless of the type of lateral-load-resisting system.

12.5 Design Requirements for Column Retrofit and Rehabilitation

12.5.1 General

FRP composites may be bonded to external surfaces of concrete columns to enhance shear resistance, ductility, and lap splice performance under seismic loads for circular sections and for rectangular sections where the ratio of longer (h) to shorter (b) section side dimension is not greater than 1.5. The FRP composites shall be placed with the fibres running perpendicular to the longitudinal axis of the member. For rectangular sections confined with transverse FRP composites, section corners shall be rounded to a radius not less than 20 mm before placing composite material.

12.5.2 Retrofit for Shear Strength Enhancement

12.5.2.1
For the purpose of seismic retrofit and rehabilitation, the shear resistance, V_r, of a column shall be determined from

$$V_r = V_c + V_s + V_F \leq V_c + 0.6\lambda\phi_c\sqrt{f_c'}b_w d \quad \textbf{(12-2)}$$

12.5.2.2
The concrete contribution, V_c , in Clause 12.5.2.1 shall be determined from

$$V_c = 0.2\lambda\phi_c\sqrt{f_c'}b_w d \quad \textbf{(12-3)}$$

provided that the design stress level in FRP used in Equation 12-5 is limited to $0.004E_F$. Otherwise, V_c shall be taken as zero.

12.5.2.3
For members subjected to significant axial tension, V_c in Clause 12.5.2.1 shall be taken as zero unless a more detailed analysis is made.

12.5.2.4
The steel reinforcement contribution, V_s, in Clause 12.5.2.1 shall be determined from

$$V_s = \frac{\phi_s A_v f_y d}{s} \quad \textbf{(12-4)}$$

12.5.2.5
The contribution of the FRP jacket, V_F, in Clause 12.5.2.1 shall be determined from

$$V_F = 2\phi_F f_{Fd} t_j D \quad \textbf{(12-5)}$$

where
f_{Fd} = design stress level in the FRP, taken as $0.4f_{Fu}$.

12.5.2.6
A column that satisfies Clause 12.5 shall have a factored shear resistance that exceeds the greater of
(a) the forces resulting from the development of the probable moment resistance of the beams framing into the column; or
(b) shear forces due to the factored load effects.

12.5.2.7
The shear retrofit length, L_v, shall extend 1.5 D, or 1.5 times the column dimension in the loading direction, as appropriate, measured from the point of maximum moment.

12.5.3 Retrofit for Enhancement of Concrete Confinement

12.5.3.1
The thickness of the FRP jacket shall be determined from Equation 12-6 for concrete confinement unless a larger amount is required by Clause 12.5.2 or 12.5.4.

$$t_j = 2D \frac{f'_c}{f_{Fj}} \frac{P_f}{P_{ro}} \frac{\delta}{\sqrt{k_c}} \quad \textbf{(12-6)}$$

where

$\frac{P_f}{P_{ro}} \geq 0.2$, and P_{ro} is calculated in accordance with Equation 8-7

f_{Fj} = $0.004E_F$ or $\phi_F f_{Fu}$, whichever is less

δ = design lateral drift ratio, which shall not be less than 0.04

k_c = 1.0 for circular and oval jackets
= 0.25 for square and rectangular jackets

12.5.3.2

The length of column segment to be confined by an FRP jacket shall extend to cover potential hinging regions. At any rate, this length shall not be less than L/8 or D/2, measured from the maximum moment section.

12.5.3.3

A FRP jacket of one-half the thickness computed by Equation 12-6 shall be provided within the secondary confinement region extending L/8 or D/2 beyond the region specified in Clause 12.5.3.2.

12.5.3.4

A gap of 25 mm shall be provided between the surface of the column support and the FRP jacket to avoid increases in moment capacity and stiffness. In cases where an additional concrete jacket is provided prior to the application of the FRP jacket, the gap may be increased up to 50 mm.

12.5.4 Retrofit for Lap Splice Clamping

12.5.4.1

An FRP jacket shall be provided within lap splice regions of circular columns if these regions coincide with regions of potential plastic hinges.

12.5.4.2

The requirement of Clause 12.5.4.1 may be met by providing the FRP jacket as required by Equation 12-6, with f_{Fj} limited to $0.002E_F$ or $\phi_F f_{Fu}$, whichever is less.

12.5.4.3

An FRP jacket for lap splice clamping shall extend to cover the entire lap region.

12.5.4.4

A region extending L/8 or D/2 beyond the region specified in Clause 12.5.4.3 shall be jacketed with FRP having a thickness equal to one-half the thickness required in Clause 12.5.4.2.

12.5.4.5

Lap splice regions in square and rectangular columns shall not be retrofitted by FRP jacketing. Other retrofit strategies shall be sought for such columns.

12.6 Design for Shear Wall Retrofit and Rehabilitation

12.6.1 General

Ductile reinforced concrete shear walls retrofitted and/or repaired with FRP shall be designed to continue to respond in a ductile manner by ensuring that the failure mode at ultimate limit state is initiated by yielding of the flexural steel reinforcement prior to shear failure.

12.6.2 Strength Enhancement

Externally bonded FRP sheets may be used as additional reinforcement in the seismic strengthening and repair of reinforced concrete and masonry shear walls. The strength enhanced by FRP shall be determined in accordance with Clause 11.5. The sliding shear failure at construction joints shall be checked.

12.6.3 Detailing Requirements for Strengthening and Repairing with FRP Sheets

12.6.3.1

For flexural strengthening and repair, the FRP sheets shall, whenever practicable, be applied symmetrically over the entire height on both ends of the shear wall. When the FRP sheets are only applied to one face of the wall, the torsional effects in the response of the shear wall shall be considered.

12.6.3.2

When multiple layers of FRP sheets are applied to a wall, the orientation of the fibres in adjacent sheets shall be mutually perpendicular.

12.6.3.3

The bonding surface shall be prepared in accordance with Clause 14.9, Item (c).

12.6.3.4

The vertical FRP sheets shall be anchored at the base and top of the wall by an anchoring system designed to sustain cyclic loading.

12.6.4 Shear Wall Deflection

In the calculation of shear wall deflection, the effect of FRP reinforcement may be disregarded.

12.7 FRP Reinforcement for Concrete Confinement in New Construction

12.7.1 Amount of Transverse Reinforcement

Transverse FRP reinforcement shall be provided in the form of circular spirals, circular hoops, rectilinear hoops, overlapping hoops, grids, and cross ties, unless a larger amount is required by Clause 8.4.4 for shear. Transverse FRP reinforcement shall be calculated as follows:

$$A_{Fh} = 14sh_c \frac{f_c'}{f_{Fh}}\left(\frac{A_g}{A_c} - 1\right)\frac{\delta}{\sqrt{k_c}}\frac{P_f}{P_{ro}} \qquad \textbf{(12-7)}$$

where

$$\frac{P_f}{P_{ro}} \geq 0.2$$

$$\left(\frac{A_g}{A_c} - 1\right) \geq 0.3$$

δ = design lateral drift ratio, which shall not be less than 0.03
f_{Fh} = $0.004E_F$ or $\phi_F f_{Fu}$, whichever is less
k_c = 1.0 for circular spirals and circular hoops

$$= 0.15\sqrt{\frac{h_c}{s}\frac{h_c}{s_l}} \text{ for rectilinear transverse reinforcement} \quad \textbf{(12-8)}$$

12.7.2 Spacing of Transverse Reinforcement

Transverse reinforcement shall be spaced at distances not exceeding the least of the following:
(a) one-quarter of the minimum member dimension;
(b) 150 mm;
(c) 6 times the diameter of the smallest longitudinal bar; or
(d) the requirements of Clauses 8.4.3.2 and 8.4.3.3.

12.7.3 Positioning of Transverse Reinforcement

Transverse reinforcement in the amount specified in Clauses 12.7.1 and 12.7.2 shall be provided over the length, l_o, from the face of each joint and on both sides of any section where flexural yielding may occur in connection with inelastic lateral displacements of the frame. The length, l_o, shall be not less than the greatest of the following:
(a) the depth of the member at the face of the joint or at the section where flexural yielding may occur;
(b) one-sixth of the clear span of the member; or
(c) 450 mm.

12.7.4 Use of Spiral or Hoop Reinforcement

Where transverse reinforcement, as specified in Clauses 12.7.1 to 12.7.3, is not provided throughout the length of the column, the remainder of the column length shall contain spiral or hoop reinforcement with centre-to-centre spacing not exceeding 150 mm.

12.7.5 Allowance for Plastic Hinges

Columns that, due to their connection to rigid members such as discontinued walls or foundations or due to their position at the base of the structure, may develop plastic hinges shall be provided with transverse reinforcement as specified in Clauses 12.7.1 and 12.7.2 over their full height. This transverse reinforcement shall extend up into the discontinued member for at least the development length of the largest longitudinal reinforcement in the column in accordance with Clause 21.6.5 of CSA Standard A23.3. If the lower end of the column terminates on a wall, this transverse reinforcement shall extend into the wall for at least the development length of the largest longitudinal reinforcement in the column at the point of termination. If the column terminates on a footing or mat, this transverse reinforcement shall extend at least 300 mm into the footing or mat.

13 Design of FRC/FRP Composites Cladding

13.1 General

All FRP components, including FRP cladding, shall be designed as structural elements in accordance with Clauses 5 and 6.

13.2 Design Considerations

13.2.1 General
The design of FRP cladding shall be in accordance with Clauses 13.2.2 through 13.2.7, as relevant.

13.2.2 Provision for Movement
Provision shall be made for movement of a cladding assembly, sufficient to accommodate all movements, including those due to thermal expansion and the effects of wind loading. The design and detailing of anchorages, connections, and joints shall allow for dimensional changes of FRP components and the primary structure arising from thermal effects or other causes of movement.

13.2.3 Anchorages and Connections
The design of anchorages and connections shall include consideration of the tolerances and eccentricities of loads. The edge-to-end distances of inserts and embedment shall conform to industry standards and be in accordance with Clause 20 of CSA Standard A23.4 and Chapter 4 of the CPCI Design Manual.

13.2.4 Joints
The design of the joints between FRP cladding panels shall be treated as an integral part of the overall design. Joint width shall be selected not for reasons of appearance alone but shall relate to unit size, building tolerances, anticipated movement and storey drift, joint materials, and adjacent surfaces. If used, a joint sealant shall be appropriate to width and depth of the joint.

13.2.5 Handling and Transportation
The FRP components shall be designed in such a way that their structural properties, durability, and appearance are not impaired during mould release, handling, and transportation.

13.2.6 Drawings
Details of anchorages, connections, joints, handling, and transportation shall be included in shop drawings in accordance with Clause 4.

13.2.7 Surface Finishes
When surface finishes are used, they shall not adversely affect the durability and serviceability of the FRP composites.

14 Construction

14.1 General

14.1.1 Prior to Construction

14.1.1.1
Prior to construction, all design documents shall be reviewed in detail by the contractors and suppliers, and the designers should communicate the intended functions and critical aspects of the final design. The contractors and suppliers shall confirm that they have a clear understanding of the proposed building and component functions, specified materials, and the proposed methods for fabrication of components and for construction of the building. Unclear items shall be resolved with the designers before construction begins.

14.1.1.2
Prior to construction, the trades shall be briefed on any new or unusual construction procedures or design innovations to ensure that they are aware of special conditions.

14.1.2 During Construction
During construction, those involved shall provide for the proper and adequate transport, handling, and storage of materials, components, and assemblies, to protect them against damage or deterioration during the construction period. Designers shall inform contractors and suppliers of component materials and assemblies that may require special care and protection prior to installation.

14.2 Reinforcement
The following requirements shall apply:
(a) All reinforcement shall meet the physical and mechanical properties specified on the construction documents.
(b) At the time concrete is placed, reinforcement shall be free from mud, oil, or other contaminants.

14.3 Handling and Storage of Materials
The following requirements shall apply:
(a) All materials shall be stored in a manner that will prevent contamination or deterioration. Access shall be provided to the storage facilities to allow for inspection.
(b) Materials shall be stored and protected to prevent damage due to high temperatures, ultraviolet rays, or foreign substances such as chemicals. Material stored outdoors shall be covered at all times.
(c) Unless otherwise approved by the designer, damaged materials and/or components shall not be used.
(d) Protective gloves shall be worn when handling material in order to prevent injury due to chemicals, exposed fibres, or sharp edges.
(e) The manufacturer's recommendations shall be followed for the transportation, handling, lifting, and storage of materials and components.
(f) FRP reinforcing coils shall be unpacked so as to avoid injury to workers and damage to the reinforcement. For safety reasons, the manufacturer's instructions shall be strictly followed.
(g) Any foreign material shall be cleaned from interfacing surfaces. The manufacturer shall be consulted for proper cleaning products and procedures.
(h) If field cutting of material is necessary, it shall be ensured that cut ends have not been damaged by the cutting procedure. Checks shall be made for frayed ends, longitudinal splitting, etc. Ends of rods shall be cut by sawing, not shearing.
(i) FRP shall be stored with readily accessible identifying tags or markings that will permit easy identification.
(j) The manufacturer shall be required to provide a quality control plan for transportation, handling, and storage of external sheet reinforcement. All material shall be handled and stored according to the manufacturer's recommendations. The sheets shall be handled with care to avoid damage to the fibres. Cut sheets may be stored in rolls or laid flat, as permitted by the manufacturer, in a dry environment.
(k) Materials such as curing compounds, resins, primers, etc, shall be transported, stored, and used in accordance with the manufacturer's instructions.

14.4 Fabrication and Placement of Reinforcement
The following requirements shall apply:
(a) The sizes and spacing of the reinforcement and its concrete cover shall be within the tolerances shown in the construction documents.
(b) Unless otherwise stated on the construction documents, fabrication and detailing of hooks shall be carried out by the manufacturer. On-site bending shall only be carried out by personnel authorized by the manufacturer and approved by the designer.

(c) Hook configuration, radius, and extensions shall be in accordance with the manufacturer's recommendations and shall be as shown on the construction documents.

14.5 Support of Reinforcement

Reinforcement shall be accurately placed and supported by bar supports and side-form spacers to ensure proper concrete cover and spacing within allowable tolerances before and during placement of concrete.

14.6 Bar Supports

The following requirements shall apply:
(a) Bar supports shall be sufficient in number and strength to carry the reinforcement they support and prevent displacement before and during concreting. They shall be spaced so that any sagging between supports will not intrude on the specified concrete cover. Standing, stepping, walking, and placing equipment directly on the bars shall not be permitted. To prevent flotation of bars during placement of concrete, tie-downs shall be provided.
(b) Bar supports and tie-downs shall be of plastic or other noncorroding material.
(c) Side form spacers shall be used for all column and wall construction in order to secure the reinforcement against displacement and maintain the required cover distance between the reinforcement and the vertical formwork.
(d) Side form spacers shall be of a type and material that will not cause blemishes, rust spots, or spalling of the exposed concrete surfaces.
(e) Requirements for the ties shall be stipulated in the contract documents. Ties may be coated-wire ties, plastic ties, nylon ties, or plastic snap ties.

14.7 Splicing of Reinforcement

Splicing of reinforcement shall be made only as permitted by the construction documents.

14.8 Quality Control and Inspection

14.8.1 Compliance with Construction Documents

The quality control and inspection programs shall be carried out in accordance with the construction documents.

14.8.2 Consideration of Data from the Manufacturer

Prior to construction, the owner shall decide whether the recommended design values and quality assurance documentation provided by the manufacturer are acceptable. If not, verification tests shall be carried out on the FRP material prior to use. When deemed necessary, test reports carried out by a qualified independent testing company may be acceptable when available. The following information, based on production-run FRP product shall be available prior to construction:
(a) the results of quality tests performed by acceptable test methods to verify relevant properties if required; and
(b) the results of quality control tests carried out on each production run and a certificate of conformance, provided by the manufacturer, for any given lot of FRP materials.

14.9 FRP Sheet and Plate Reinforcement

The following requirements shall apply:
(a) Sheet and plate reinforcement shall be applied by qualified personnel only.
(b) Sheet reinforcement shall not be applied when the ambient temperature is below 5°C, unless provisions have been made for protection of the material during application and curing. The manufacturer's recommendations shall be followed.
(c) It shall be ensured that the substrate surface is dry, that irregularities have been removed, and that any voids have been properly filled. Sharp corners shall be rounded to meet the manufacturer's requirements. The surface preparation shall be approved by the owner prior to application of the wrap material.

(d) Pull-off tests shall be conducted on the substrate material to provide a baseline failure stress value.
(e) The manufacturer shall clearly define the resin working time. Any batch that exceeds the batch life shall not be used.
(f) Wrap configuration details shall be provided for unique situations. Application tolerances shall be compatible with mechanized wrapping equipment.
(g) When thermal curing is required, uniform heat distribution shall be provided.
(h) A curing log, recording temperature versus time, shall be kept and provided to the owner.
(i) Ventilation shall be provided during the installation and curing, in order to avoid a buildup of hazardous fumes.

14.10 Bond Check of External Sheets and Plates

The following requirements shall apply:
(a) All wrapped areas shall be inspected, in accordance with the manufacturer's installation specifications, for voids, bubbles, and delaminations. The contractor shall provide a report signed by a professional engineer certifying that the installation is acceptable.
(b) All testing shall be carried out after the area is fully cured and prior to the application of a finish coat.
(c) All defective areas with a leading edge greater than 25 mm or an area greater than 600 mm^2 shall be repaired.
(d) When specified, direct pull-off tests shall be conducted to verify the tensile bond between the existing substrate and the FRP sheet. The test result shall be considered acceptable when the stress has reached the design stress or the value established in Clause 14.9, Item (d).
(e) Frequency of pull-off tests shall be as specified in the construction documents.
(f) The test areas shall be reinstated to the satisfaction of the owner.

Table 1
Typical Fibre Properties
(See Clauses 7.1.2.1 and 7.2.2.3.)

Fibre	Tensile modulus, GPA	Tensile strength, MPa	Tensile strain, %
Carbon, general purpose	220–234	<3800	>1.2
Carbon, high strength (HS)	220–234	3800–4800	>1.4
Carbon, ultra-high strength	220–234	4800–6200	>1.5
Carbon, high modulus	350–517	>3100	>0.5
Carbon, ultra-high modulus	517–700	>2400	>0.2
Glass, E	65–73	1800–2700	>4.5
Glass, S	85–90	3400–4800	>5.4
Aramid, general purpose	68–83	3400–4100	>2.5
Aramid, high modulus (HM)	110–125	3400–4100	>1.6

Table 2
Typical Uniaxial Tensile Properties of Non-Prestressed Steel and FRP Reinforcement
(See Clause 7.1.3.4.)

Properties	Steel	AFRP	CFRP	GFRP
Nominal yield stress, MPa	276–517	N/A	N/A	N/A
Tensile strength, MPa	483–690	1720–2540	600–3690	483–1600
Elastic modulus, GPa	200	41–125	120–580	35–51
Yield strain, %	1.4–2.5	N/A	N/A	N/A
Rupture strain, %	6–12	1.9–4.4	0.5–1.7	1.2–3.1
Density, kg/m^3	7900	1250–1400	1500–1600	1250–2100

Table 3
Typical Uniaxial Tensile Properties of Steel and FRP Prestressing Tendons
(See Clause 7.1.4.4.)

Properties	Prestressing steel	AFRP	CFRP	GFRP
Nominal yield stress, MPa	1034–1396	N/A	N/A	N/A
Tensile strength, MPa	1379–1862	1200–2068	165–2410	1379–1724
Elastic modulus, GPa	186–200	50–74	152–165	48–62
Yield strain, %	1.4–2.5	N/A	N/A	N/A
Rupture strain, %	>4	2–2.6	1–1.5	3–4.5
Density kg/m^3	7900	1250–1400	1500–1600	1250–2400

Table 4
Properties of FRP Reinforcement to Be Considered
(See Clause 7.1.5.1.)

Properties	Non-prestressed	Prestressed
Axial tensile strength, modulus of elasticity, and ultimate elongation	✓	✓
Transverse compressive modulus of elasticity	✓	✓*
Shear strength and modulus	✓	
Bond strength, development length, and anchorage and junction strength	✓†	✓‡
Axial and transverse coefficients of thermal expansion	✓§	✓
Volume change due to moisture	✓	✓
Relaxation		✓
Fire performance characteristics		
(a) thermal properties at elevated temperatures		
(i) thermal conductivity (hot-wire method)	✓	✓
(ii) specific heat (differential scanning calorimeter)	✓	✓
(iii) thermal expansion (dilatometric apparatus)	✓	✓
(iv) mass loss (thermogravimetric analyzer)	✓	✓
(b) mechanical properties at elevated temperatures — stress/strain relationships at elevated temperatures	✓	✓

**Bonded tendons only.*
†*Bond strength for bars; junction strength for grid reinforcement.*
‡*Bond strength for bonded tendons; anchorage strength for unbonded end-anchored tendons.*
§*Transverse coefficient for bonded tendons only.*
Note: *Appropriate test procedures for determining some of these properties are given in the annexes.*

Table 5
Resistance Factors for Prestressed Reinforcement

(See Clause 7.1.6.2.)

Tendon	Pretensioned	Post-tensioned (bonded)	Post-tensioned (unbonded)
AFRP	0.7	0.7	0.65
CFRP	0.85	0.85	0.8

Table 6
Coefficient of Linear Thermal Expansion for FRP × 10^{-6}/°C

(See Clauses 7.1.6.5 and 7.1.6.6.)

Thermal coefficient	GFRP	CFRP	AFRP
Longitudinal (α_L)	10	1.0	–0.5
Transverse (α_T)	20	35	70

Table 7
Typical Uniaxial Tensile Properties of FRP Laminates

(See Clause 7.2.3.)

System	Fibre direction	Tensile strength, MPa	Tensile modulus, GPa	Density, kg/m^3	Failure strain, %	Coef. of thermal expansion, 10^{-6}/°C
HS-carbon/epoxy	0*	1400–2000	117–145	1700	1.0–1.5	0
	0/90†	690–1050	55–75	1700	1.0–1.5	5.5
E-glass/epoxy	0*	690–1400	35–48	2200	2.0–3.0	5.5
	0/90†	500–1050	14–35	2200	2.0–3.0	10.9
HM-aramid/epoxy	0	1050–1700	100–125	1400	2.0–3.0	0
	0/90†	690–1050	48–70	1400	2.0–3.0	5.5

**100% fibre oriented at 0° angle to the applied stress direction.*
†50% fibre oriented at 0° and 50% oriented at 90° angle to the applied stress direction.

Table 8
Test Methods for FRP Composites

(See Clause 7.2.6.)

Properties	Test method	Number of specimens*
Tensile strength	ASTM D 3039	20†
Elongation	ASTM D 3039	20†
Tensile modulus	ASTM D 3039	20†
Coefficient of thermal expansion (CET)	ASTM D 696 or E 1142	5†
Creep	ASTM D 2990‡	5†
Void content	ASTM D 2584§ or D 3171§	5
Glass transition (T_g) temperature	ASTM D 4065	20**
Impact	ASTM D 5420††	5
Composite interlaminar shear strength	ASTM D 2344	20
Curing properties	ASTM D 5028	
Fibre-resin ratio	ASTM D 2584	
Density	ASTM D 792	
Compression test	ASTM D 3410	
Shear test	ASTM D 5379	
Fatigue test	ASTM D 3479	

**Specimen sets shall exhibit a coefficient of variation (COV) of 6% or less. Outliers are subject to further investigation according to ASTM Standard E 178. If the COV exceeds 6%, the number of specimens shall be doubled.*
†*Values shall be determined in the primary and cross (90°) directions.*
‡*Test duration is* 3000 h, *minimum.*
§*Maximum void content by volume is 6%.*
***Minimum* 60°C T_g *is required for control and exposed specimens.*
††*Impact head is* 15.9 mm. *Specimens may be rectangular, measuring* 100 × 150 mm *(4 × 6 in), and are placed on* 75 × 125 mm *supports.* 1100 N *at* 2.54 mm *thick is the minimum requirement.*

Table 9
Environmental Durability Test Matrix

(See Clause 7.2.6.)

Environmental durability test	Relevant specifications	Test conditions	Test duration	% retention, h	
				1000	3000
Water resistance	ASTM D 2247 ASTM E 104	100%, 38 ± 1°C	1000, 3000, and 10 000 h	90	85
Saltwater resistance	ASTM D 1141 ASTM C 581	Immersion at 23 ± 1°C	1000, 3000, and 10 000 h		
Alkali resistance	ASTM C 581	Immersion in $CaCo_3$ at pH = 9.5 and 23 ± 1.5°C	1000 and 3000 h		
Dry heat resistance	ASTM D 3045	60 ± 3°C	1000 and 3000 h		

Table 10
List of ASTM Standards
(See Clause 7.4.3.)

Properties	ASTM Standard
Mechanical:	
Tensile strength and modulus	D 638 or D 3916
Compressive strength and modulus	D 695
Flexural strength and modulus	D 790
Izod impact strength	D 256
Bearing strength	D 953
Creep	D 2990
Chemical:	
Chemical resistance	D 543
Physical:	
Density	D 792
Hardness	D 785
Water absorption	D 570
Brittleness temperature	D 746
Void content	D 2734
Deflection temperature under load	D 648
Thermal expansion	D 696
Fire:	
Rate of burning	D 635
Smoke density	D 2834
Oxygen index	D 2863
Surface burning	E 84
Electrical:	
Dielectric strength	D 149
Dielectric constant	D 150
Resistivity	D 257
Arc resistance	D 495

Table 11
Maximum Permissible Computed Deflections

(See Clause 8.3.2.1.)

<table>
<tr><th>Type of member</th><th>Deflection to be considered</th><th>Deflection limitation</th></tr>
<tr><td>Flat roofs not supporting or attached to nonstructural elements likely to be damaged by large deflections</td><td>Immediate deflection due to specified live load, L</td><td>$\ell_n/180$*</td></tr>
<tr><td>Floors not supporting or attached to nonstructural elements likely to be damaged by large deflections</td><td>Immediate deflection due to specified live load, L</td><td>$\ell_n/360$</td></tr>
<tr><td>Roof or floor construction supporting or attached to nonstructural elements likely to be damaged by large deflections</td><td rowspan="2">That part of the total deflection occurring after attachment of the nonstructural elements (sum of the long-time deflection due to all sustained loads and the immediate deflection due to any additional live load)‡</td><td>$\ell_n/480$†</td></tr>
<tr><td>Roof or floor construction supporting or attached to nonstructural elements not likely to be damaged by large deflections</td><td>$\ell_n/240$§</td></tr>
</table>

*****Limit not intended to safeguard against ponding. Ponding should be checked by suitable calculations of deflection, including added deflections due to ponded water, and consideration of long-time effects of all sustained loads, camber, construction tolerances, and reliability of provisions for drainage.*

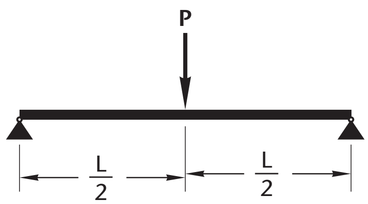
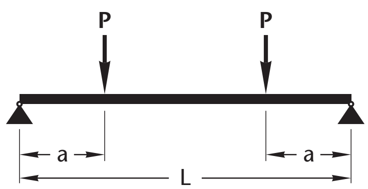
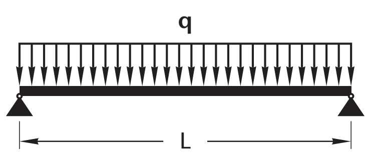
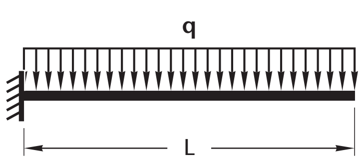
†*Limit may be exceeded if adequate measures are taken to prevent damage to supported or attached elements.*

‡*Long-time deflections shall be determined in accordance with Clause 8.3.2.4 but may be reduced by the amount of deflection calculated to occur before the attachment of nonstructural elements.*

§*Not to be greater than the tolerance provided for nonstructural elements. Limiting deflection may be exceeded if camber is provided so that the total deflection minus camber does not exceed the limit shown in this Table.*

Table 12
Maximum Deflection Formulas for Typical FRP Reinforced Concrete Beams and One-Way Slabs

(See Clause 8.3.2.4.)

Beam type	Maximum deflection
	$\delta_{max} = \frac{PL^3}{48\,E_c I_{cr}}\left[1 - 8\eta\left(\frac{L_g}{L}\right)^3\right]$
	$\delta_{max} = \frac{PL^3}{24\,E_c I_{cr}}\left[3\left(\frac{a}{L}\right) - 4\left(\frac{a}{L}\right)^3 - 8\eta\left(\frac{L_g}{L}\right)^3\right]$
	$\delta_{max} = \frac{5qL^4}{384\,E_c I_{cr}}\left[1 - \frac{192}{5}\eta\left[\frac{1}{3}\left(\frac{L_g}{L}\right)^3 - \frac{1}{4}\left(\frac{L_g}{L}\right)^4\right]\right]$
	$\delta_{max} = \frac{PL^3}{3\,E_c I_{cr}}\left[1 - \eta\left(\frac{L_g}{L}\right)^3\right]$
	$\delta_{max} = \frac{qL^4}{8\,E_c I_{cr}}\left[1 - \eta\left(\frac{L_g}{L}\right)^4\right]$

Note: $\eta = \left(1 - \frac{I_{cr}}{I_g}\right)$

Table 13
Permissible Stresses in Tendons as a Function of f_{Fpu}
(See Clause 10.5.1.)

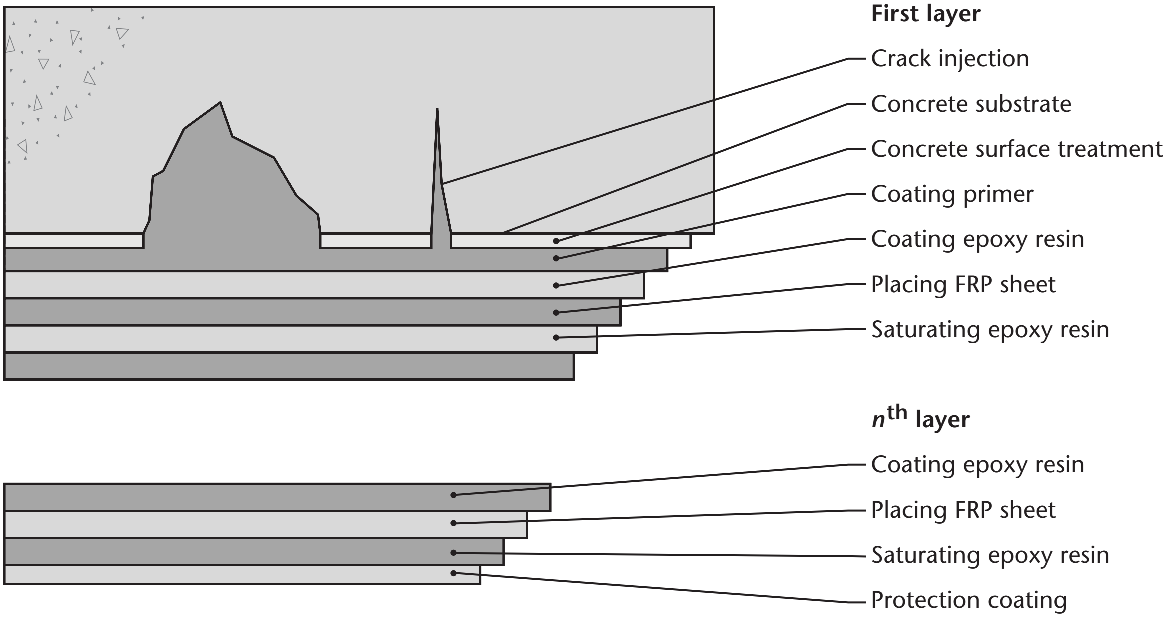
Tendon	Stresses at jacking: Pretensioned	Stresses at jacking: Post-tensioned	Stresses at transfer: Pretensioned	Stresses at transfer: Post-tensioned
AFRP	$0.40f_{Fpu}$	$0.40f_{Fpu}$	$0.38f_{Fpu}$	$0.35f_{Fpu}$
CFRP	$0.70f_{Fpu}$	$0.70f_{Fpu}$	$0.60f_{Fpu}$	$0.60f_{Fpu}$

Table 14
Minimum Area of Bonded Non-Prestressed Reinforcement
(See Clause 10.9.)

	Concrete tensile stress			
	$> 0.5\lambda\sqrt{f'_c}$		$> 0.5\lambda\sqrt{f'_c}$	
	Type of tendon			
Type of member	Bonded	Unbonded	Bonded	Unbonded
Beams				
CFRP	0	0.0044A	0.0033A	0.0055A
AFRP		0.0048A	0.0036A	0.0060A
One-way slabs				
CFRP	0	0.0033A	0.0022A	0.0044A
AFRP		0.0036A	0.0024A	0.0048A

Table 15
Development Length and Transfer Length for Certain Types of FRP
(See Clause 10.12.)

FRP tendon type	Diameter, mm	Development length	Transfer length
CFRP strand	N/A	$50d_b$	$20d_b$
CFRP rebar	N/A	$180d_b$	$60d_b$
AFRP	$8 \le d_b < 12$	$120d_b$	$50d_b$
AFRP	$12 \le d_b < 16$	$100d_b$	$40d_b$
AFRP	$16 \le d_b$	$80d_b$	$35d_b$



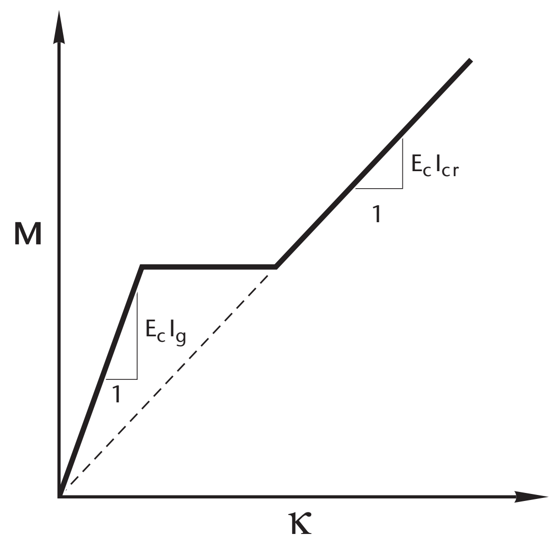
Notes:

(1) *The first coat of epoxy resin shall be applied over the primer within the time frame recommended by the manufacturer.*

(2) *Application of the entire first layer, including coating epoxy resin, placing FRP sheet, and saturating epoxy resin, may typically take* 0.5 *to* 3 h *in total.*

(3) *If a second layer is added, the saturating epoxy resin from the first layer may be used as the coating epoxy resin of the second, in which case the application of the second FRP sheet would typically follow within about* 30 min.

Figure 1
Typical Construction Process of FRP Patching
(See Clause 7.2.4.)



Legend:
M = moment
κ = curvature

Figure 2
Moment-Curvature Relation of FRP Reinforced Concrete
(See Clause 8.3.2.5.)

Annex A (Normative) Determination of Cross-Sectional Area of FRP Reinforcement

Note: *This Annex is a mandatory part of this Standard.*

A1 Scope

This Annex specifies a method for determining the cross-sectional area of FRP reinforcements of all shapes and sizes by the water-displacement method.

A2 Notation

The following symbols are used in this Annex:

A = cross-sectional area
d = nominal diameter of the specimen (for bars of a noncircular section, it is the diameter of a circular section having the same cross-sectional area)
L = combined total length of the specimens
V_o = volume of the specimen container, mL
V_1 = volume of water added to fill the specimen container with specimen in it, mL

A3 Apparatus

A3.1 Specimen Container

A glass or plastic cylinder of about 40 mm internal diameter and 300 mm height shall be used to contain the specimens in water. The container shall have a rigid cap with a 5 mm diameter hole that fits without any slack and does not allow water to leak from the cylinder brim (see Figure A1).

Note: *The container may be made from either a glass or a clear and rigid plastic tube by sealing one end with a flat plastic disk glued to the squarely cut tube end.*

A3.2 Weighing Scale

A scale of 2 to 5 kg capacity, capable of measuring weight with a resolution of 1 g, shall be used.

A4 Specimens

A4.1 Cutting Specimens

All specimens shall be cut squarely and cleanly.

A4.2 Specimen Length

The length of specimens shall preferably be 290 mm for bars that are of uniform cross-section along the length. For FRP grids, the longest possible specimens shall be cut from the parts between the grid joints.

A4.3 Number of Specimens

The number of specimens for bars that are of uniform cross-section along the length and the combined length of specimen for grids shall be as specified in Table A1.

A5 Test Environment

The temperature of the laboratory shall be maintained at 22 ± 2°C and the relative humidity at 50 ± 5%.

A6 Procedures

A6.1 Conditioning

The specimens shall be kept in the test environment for at least 24 hours prior to testing.

A6.2 Measuring Specimen Length

The lengths of all conditioned specimens shall be measured with a ±0.5% accuracy and shall be added in order to obtain the combined length of specimen.

A6.3 Measuring Container Volume

The container and cap shall be dried and weighed. The container shall be filled with water to the top of the hole in the cap, taking care not to trap any air bubbles, and weighed again. The difference between the two weights in grams shall be taken as the volume of the container, V_o, in millilitres.

A6.4 Placing Specimens in the Container

The container shall be dried and all the specimens placed in it so that no part protrudes above the brim (thereby preventing the cap from fitting onto the cylinder). Special care shall be taken in this regard for short specimens from grids. The container shall then be weighed together with its cap.

A6.5 Adding Water

Water shall be added to fill the container up to 1 cm below the brim without the cap in place. The container shall be gently shaken and/or the specimens shall be moved and turned, to drive out any air bubbles that have formed. The remaining part shall be filled, with the cap on, until water appears at the top of the hole; ensure that no bubbles are trapped inside.

A6.6 Measuring Volume of Added Water

The container with water and specimen shall be weighed once again. The volume of water added, V_1, shall be obtained by subtracting the weight of the container and specimens measured in Clause A6.4 from this new weight.

A7 Calculations

A7.1 Cross-Sectional Area

The average cross-sectional area, A, of the specimens shall be calculated as follows:

$$A = \frac{V_o - V_1}{L} \times 1000 \quad \textbf{(A-1)}$$

A7.2 Rounding

The combined total length shall be rounded to the nearest 1 mm and the cross-sectional area to the nearest 1 mm^2.

A8 Report

A8.1 Material Identification

The trade name, date of manufacture, nominal size, and a brief description of the shape and texture of each type of specimen tested shall be reported.

A8.2

The temperature and relative humidity at the beginning of the test shall be reported.

A8.3

The average cross-sectional area determined shall be reported.

Table A1
Number or Combined Length of Specimens
(See Clause A4.3.)

d, mm	No. of 290 mm specimens for uniform bars	Combined length of specimens for grids, mm
6–10	8	1600–2000
11–14	6	1200–1400
15–18	3	600–800
19 or more	1	250–290

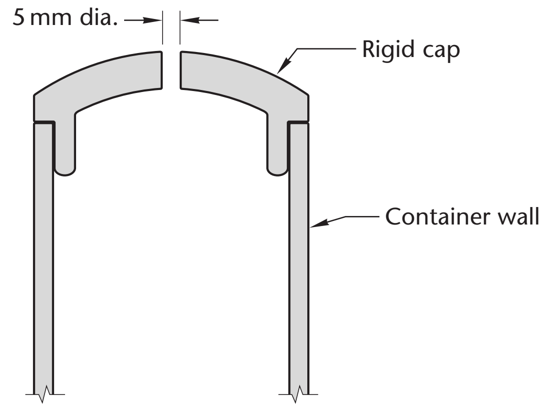


Figure A1
Specimen Container Cap
(See Clause A3.1.)

Annex B (Normative)
Anchor for Testing FRP Specimens under Monotonic, Sustained, and Cyclic Tension

Note: *This Annex is a mandatory part of this Standard.*

B1 Scope

This Annex specifies the requirements for an anchor for FRP reinforcement specimens, to facilitate gripping of the specimens for various types of tests carried out under tensile loading. It also specifies the requirements for the preparation of the specimens.

The following tests may be carried out using the anchor:
(a) monotonic tension;
(b) creep;
(c) relaxation; and
(d) pullout bond.

The anchor is not recommended for testing FRP specimens that require more than 300 kN of load in order to fail.

B2 Notation

The following symbols are used in this Annex:

A = cross-sectional area of specimen
d = nominal diameter of specimen (for specimens of noncircular section, it is the diameter of a circular section having the same cross-sectional area)
f_u = ultimate tensile strength
L_g = length of grip

B3 Specification of Anchor

B3.1 Geometry

The geometrical dimensions of the anchor shall be as shown in Figure B1. The cylinder wall thickness shall be at least 5 mm and its inner diameter 10 to 14 mm greater than d. The length of the cylinder, L_g, shall be at least equal to $f_u A/350$, but not less than 250 mm.

B3.2 Attachment to Testing Machine

The anchor shall be adapted to fit into the grips of different types of testing machines or frames, as shown in Figure B2.

B3.3 Anchor Filler Material

The cylinder shall be filled with pure resin, except that a 1:1 mixture of resin and clean sand (by weight) may be used for vertical casting. The resin shall be compatible with the resin of the test specimen.

Note: *Epoxy resin is deemed to be suitable for all types of FRP specimens. Expansive grouts are not entirely reliable and require a cylinder of larger diameter.*

B3.4 Specimen Preparation

B3.4.1 Cutting Specimens

Specimens of the required length shall be cut from the bars supplied. When obtaining specimens from grids and cages, cutting the cross bars too close to the specimen bar shall be avoided. Leaving a 2 mm projection of the cross bars is a good practice to enhance gripping.

B3.4.2 Specimen Length

The total length of the specimen shall be $40d + 2L_g$ or greater.

B3.4.3 Surface Preparation

Mechanical or chemical surface treatment for promoting adhesion of the specimen with the casting resin shall be permitted, provided that it does not affect the tensile properties of the specimen in the gauge length portion and that failure still takes place outside the anchors.

B3.5 Anchor Casting Procedure

B3.5.1 Casting Position

Whenever possible, the anchor shall be cast in a vertical position, as shown in Figure B1. The FRP bar shall be held axially inside the cylinder before the cylinder is filled with resin or resin/sand mix. If the specimen needs anchors at both ends, at least 12 hours shall elapse before the first anchor is flipped in order to cast the other anchor. A suitable jig, as shown in Figure B3, may be used to keep both cylinders and the specimen axially aligned.

If necessary (eg, when casting specimens with relatively long FRP bars that are cumbersome to cast vertically), the anchor may be cast in a horizontal position using the filling and bleeding holes shown in Figure B1. Only pure resin* shall be used in this case. The hole in the rubber cap shall fit tightly around the FRP bar so as to prevent resin from leaking out. Silicone caulking may be used to seal gaps around bars of a noncircular cross-section.

**Sand, if used, settles at the bottom and near the filling end, making an uneven anchor.*

B3.5.2 Preparation

The inner surface of the hole in the threaded plug shall be lightly oiled by running an oiled wick along the hole in order to prevent bonding of the FRP bar along the plug. Care shall be taken to wipe off any excess oil before inserting the FRP bar. Silicone caulking shall be applied at the bottom of the plug as shown in Figure B1 to prevent any possible leakage of resin.

B3.5.3 Mixing and Handling Resin

The resin shall be mixed and handled following the manufacturer's instructions, paying particular attention to safety.

B3.5.4 Filling Resin

For vertical casting, the resin shall be poured directly from a beaker with a narrow spout or with the aid of a funnel with a suitable stem. If the anchor has an internal thread at the filling end, the thread shall be suitably protected so that resin does not contact the thread. The cap shall be placed as soon as resin filling is completed.

For horizontal casting, the resin shall be poured by means of a funnel connected to the hole near the inner end of the specimen. Care shall be taken to avoid leaving any air pocket inside. Towards the end of the filling operation, the resin shall be added very slowly to prevent spillage through the bleed hole, and filling shall be stopped as soon as a resin column forms in the bleed hole. From time to time during the next 3 h, the resin shall be topped up, if necessary, through both holes as the resin shrinks.

B3.5.5 Curing

At least 48 hours shall be allowed before testing, to allow the resin to set inside the cylinder.

B3.5.6 Handling

The anchored specimen shall be handled by holding both grips, in order to avoid bending or twisting of it.

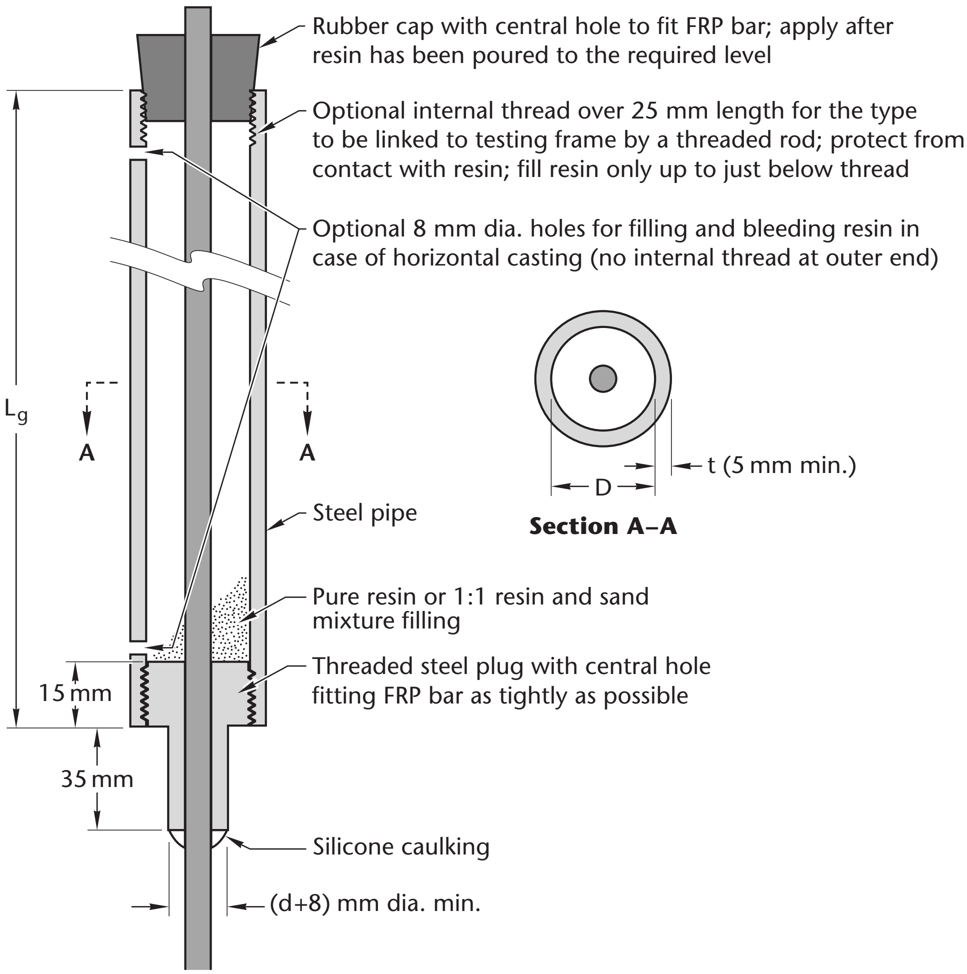


Figure B1
Anchor Details
(See Clauses B3.1, B3.5.1, and B3.5.2.)

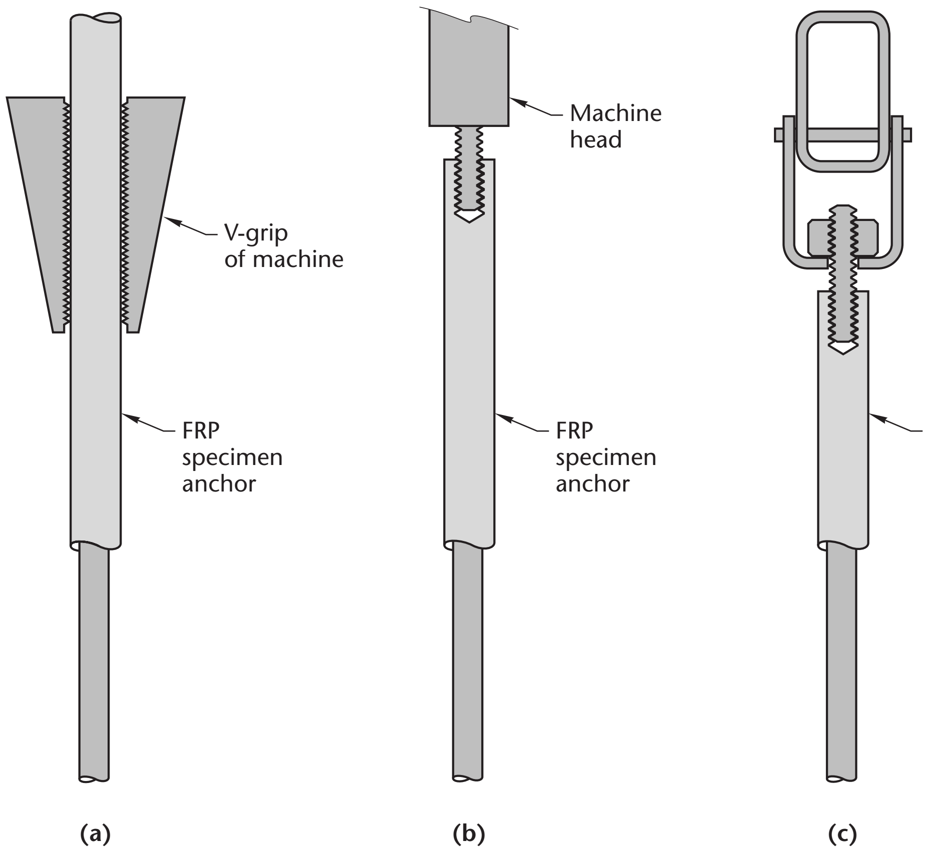


Figure B2
Attachment of Anchor to Various Testing Machines and Frames
(See Clause B3.2.)

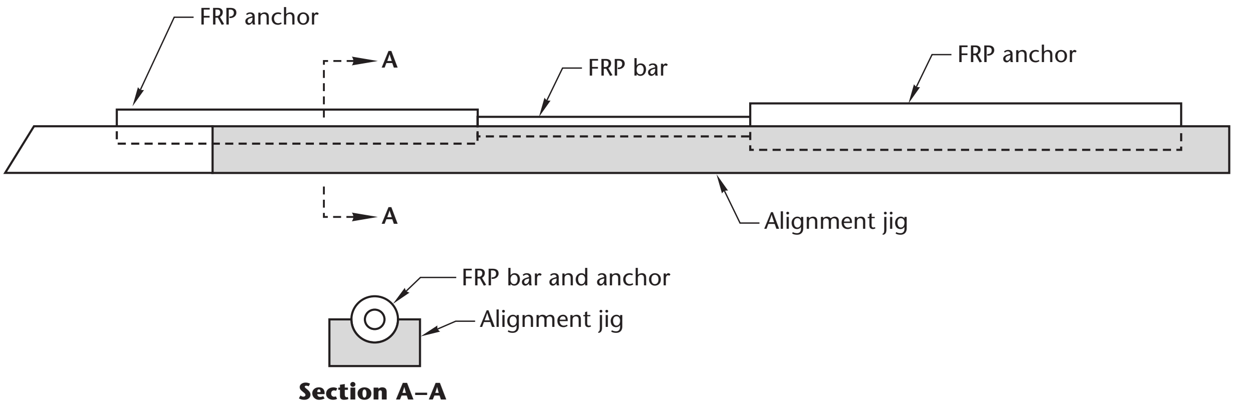


Figure B3
Jig to Align Specimen and Anchors
(See Clause B3.5.1.)

Annex C (Normative)
Test Method for Tensile Properties of FRP Reinforcements

Note: *This Annex is a mandatory part of this Standard.*

C1 Scope

This annex specifies a test method for determining the tensile strength, modulus of elasticity, and ultimate elongation of FRP reinforcements.

C2 Notation

The following symbols are used in this Annex:

A = cross-sectional area
d = nominal diameter of the specimen, mm (for bars of a noncircular section, it is the diameter of a circular section having the same cross-sectional area)
E = modulus of elasticity
f_u = ultimate tensile strength
L_g = length of grip
P_1 and ε_1 = load and corresponding strain, respectively, at about 50% of the ultimate load
P_2 and ε_2 = load and corresponding strain, respectively, at about 25% of the ultimate load

C3 Apparatus

C3.1 Testing Machine

The machine shall generally conform to ASTM Standard E 4. The machine shall have a loading capacity exceeding the expected strength of the specimen and shall preferably be equipped with strain-rate or load-rate control.

Note: *Universal testing machines may not have enough clearance to accommodate the relatively long anchors required by specimens of high load capacity. Special testing frames may be required in such cases.*

C3.2 Specimen-Anchoring Devices

The anchor specified in Annex B of this Standard may be used. Alternatively, another anchoring device may be used provided that it satisfies the following conditions:

(a) The load shall be transmitted to the specimen without any eccentricity or torsion.
(b) Failure shall occur in the gauge-length portion of the specimen, not within the grips.
(c) No alteration, chemical or mechanical, shall be made in the gauge-length portion.

Note: *For specimens of high load capacity, such as multiwire tendons of* 300 kN *capacity or greater, special grips are needed and may have to be supplied by the manufacturer.*

C3.3 Load-Measuring Device

Either a built-in device in the testing machine or a load cell of adequate capacity shall be used. The device shall be compatible with the data acquisition system.

C3.4 Strain-Measuring Devices

Any of the following devices may be used:
(a) a clip-on-type extensometer having a minimum gauge length of 5d, provided that the surface profile and texture of the specimen allow a secure attachment of the device;
(b) an LVDT of at least 50 mm gauge length mounted on brackets with quick-release features; and
(c) two strain gauges of minimum 12.5 mm gauge length, mounted back-to-back on the specimen, for specimens with a smooth surface of sufficient length to allow mounting the gauges.

C3.5 Ultimate-Elongation-Measuring Device

An LVDT may be set up to measure the displacement between the machine cross-heads or between the specimen anchors.

C3.6 Data Acquisition System

The system shall be capable of continuously logging load, strain, and displacement at a minimum rate of two readings per second. The minimum resolutions shall be 100 N for load, one microstrain for strain, and 0.01 mm for displacement.

C4 Specimens

C4.1 General

Specimens shall be representative of the lot or batch being tested. No chemical or mechanical alteration, such as machining of the specimens, shall be made for the purpose of testing.

C4.2 Specimen Length and Cutting Specimens

The total length of the specimen shall be $40d + 2L_g$ or greater. To obtain specimens from grids and cages, cutting the cross bars too close to the specimen bar shall be avoided. Leaving a 2 mm projection of the cross bars is good procedure for enhancing gripping.

C4.3 Number of Specimens

At least five specimens shall be tested.

C4.4 Cross-Sectional Area

The cross-sectional area shall be determined in accordance with Annex A of this Standard.

C5 Test Environment

Tests shall be carried out with the room temperature maintained at 20 ± 10°C and relative humidity at 50 ± 25%.

C6 Procedure

C6.1 Handling of Specimens

The specimen shall be handled, transported, and mounted on the testing machine carefully, so that no bending or torsion is applied to it.

C6.2 Mounting of Specimens

If the anchor described in Clause B3 of Annex B of this Standard or a similar anchor has been used, the specimen shall be mounted on the testing machine in such a manner that the cylinder ends are flush with the jaws of the machine's wedge grips as shown in Figure C1. For other anchors, the mounting shall ensure concentric and torsion-free loading.

C6.3 Attaching Measurement Devices

The strain-measurement device shall be mounted to measure strain in the middle part of the specimen between the grips. The specimen shall not be damaged in any manner in the process of mounting the strain- and displacement-measurement devices. If an LVDT is used, particular care shall be taken to avoid biting into the bar when clamping the brackets.

C6.4 Recording

The data acquisition system shall be started a few seconds before the commencement of loading.

C6.5 Rate of Loading

The loading shall be applied at a stressing rate of 250 to 500 MPa/min. For machines with displacement control only, the desirable strain rate may be obtained by dividing the desirable stress rate by the estimated modulus of elasticity. If the testing machine is equipped with neither load control nor displacement control, a timing device may be used to observe the time taken to apply a known increment of stress.

C6.6 Detaching Strain-Measurement Device

When the load reaches about 75% of the estimated ultimate, the extensometer or LVDT shall be detached in order to avoid damage to the instrument.

C6.7 Safety Measure

Because some FRP specimens fail explosively and with the release of a substantial amount of energy, protective eyeglasses shall be worn by all testing personnel.

C6.8 Rejection

If any test specimen fails partly or fully inside the grip, the test shall be discarded and another sample tested in its place.

C7 Calculations

C7.1 Tensile Strength

The highest load recorded shall be divided by the cross-sectional area in order to calculate the tensile strength.

C7.2 Modulus of Elasticity

The following equation shall be used to compute the value of the modulus of elasticity:

$$E = \frac{1000(P_1 - P_2)}{(\varepsilon_1 - \varepsilon_2)A} \qquad \textbf{(C-1)}$$

C7.3 Ultimate Elongation

The value of displacement (mm) corresponding to the highest load recorded shall be divided by the length of the specimen between grips (mm) and multiplied by 100 in order to obtain ultimate elongation as a percentage.

C7.4 Rounding
Tensile strength shall be rounded to the nearest 10 MPa and the modulus of elasticity to the nearest 1000 MPa. Ultimate elongation shall be rounded to the nearest one-tenth of a percentage point.

C8 Report

C8.1 Material Identification
The trade name, date of manufacture, nominal size, and a brief description of the shape and surface texture of each type of specimen tested shall be reported.

C8.2
A brief description of the gripping device used shall be given.

C8.3
The cross-sectional area of each type and size of specimen shall be reported.

C8.4
For each specimen the values of each the following shall be reported:
(a) tensile strength;
(b) modulus of elasticity; and
(c) ultimate elongation.

The average values of these three quantities for the set of specimens tested shall also be reported.

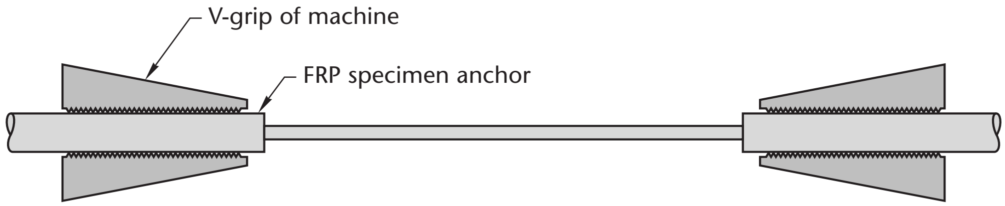


Figure C1
Mounting Specimen in Testing Machine With V-Grips
(See Clause C6.2.)

Annex D (Normative)
Test Method for Development Length of FRP Reinforcements

Note: *This Annex is a mandatory part of this Standard.*

D1 Scope

This Annex specifies a method of determining the development length of FRP reinforcement by attempting to pull out FRP bar specimens with various embedment lengths in concrete prisms.

D2 Notation

The following symbols are used in this Annex:

A = cross-sectional area
d = nominal diameter of the specimen (for bars of a noncircular section, it is the diameter of a circular section having the same cross-sectional area)
E = modulus of elasticity of FRP specimen
f_{Fu} = ultimate tensile strength of FRP specimen
k = embedment length multiplier
L_c = length of correcting slip
L_{da} = anticipated development length
L_e = length of embedment in concrete prism
L_g = length of grip
P = load
s_c = slip correction

D3 Apparatus

D3.1 Testing Machine

The machine shall generally conform to ASTM Standard E 4. The machine shall have a loading capacity exceeding the expected strength of the specimen and shall preferably be equipped with strain-rate or load-rate control.

Note: *Universal testing machines may not have enough clearance to accommodate the relatively long anchors required by specimens of high load capacity. Special testing frames may be required in such cases.*

D3.2 Specimen-Anchoring Devices

The anchor specified in Annex B of this Standard may be used. Alternatively, another anchoring device may be used, provided that it satisfies the following conditions:

(a) The load shall be transmitted to the specimen without any eccentricity or torsion.
(b) Failure shall occur in the gauge-length portion of the specimen, not within the grips.
(c) No alteration, chemical or mechanical, shall be made in the gauge-length portion.

Note: *For specimens of high load capacity, such as multiwire tendons of* 300 kN *capacity or greater, special grips are needed and may have to be supplied by the manufacturer.*

D3.3 Load-Measuring Device

Either a built-in device in the testing machine or a load cell of adequate capacity shall be used. The device shall be compatible with the data acquisition system.

D3.4 Displacement-Measuring Devices

Any of the following devices may be used:
(a) for automated reading, LVDTs or hybrid track rectilinear potentiometers (HTRPs) of at least 0.01 mm resolution and 10 mm stroke length (displacement-measuring capacity); or
(b) for manual reading, dial gauges of 0.025 mm graduation and 10 mm range.

D3.5 Data Acquisition System

The system shall be capable of continuously logging load, strain, and displacement at a minimum rate of two readings per second. The minimum resolutions shall be 100 N for load, one microstrain for strain, and 0.01mm for displacement.

D4 Specimens

D4.1 General

The test specimen shall be as shown in Figure D1. One end of the FRP bar shall be embedded in a concrete prism and the other end in an anchor that can be gripped in a testing machine.

D4.2 Specimen Length

The total length of the specimen shall be 40d + L_g + L_e or greater. When cutting specimens from grids and cages, a 25 mm projection of the cross bars on either side shall be maintained.

D4.3 Number of Specimens

A total of nine specimens (one for each embedment length) shall be prepared*.
**Not all these specimens may be required to be tested.*

D4.4 FRP Reinforcement

FRP reinforcement shall be representative of the lot or batch being tested.

D4.5 Precautions

No chemical or mechanical alteration, such as machining of the specimens, shall be made for the purpose of testing. During the process of specimen preparation and handling before testing, care shall be taken to prevent bond-reducing materials from coming in contact with the FRP bar surface and causing excessive bending of the bar.

D4.6 Cross-Sectional Area

The cross-sectional area of the FRP bar shall be determined in accordance with Annex A of this Standard.

D4.7 Tensile Strength

The tensile strength of the FRP bar shall be determined in accordance with Annex C of this Standard.

D4.8 Concrete Embedment Length

For prismatic bars, the embedment length in concrete in any specimen, L_e, shall be equal to kL_{da}. The anticipated development length, L_{da} , shall be obtained either from the reinforcement manufacturer or from estimating, using the following equation:

$$L_{da} = \frac{f_{Fu}d}{30} \qquad \textbf{(D-1)}$$

The nine values of k for the different embedment lengths may be taken in increments of 0.15, from 0.4 to 1.6.

For bars cut out from grids and cages, L_e may be 1, 2, 3, 4, and 5 grid lengths, or any other integer multiple of the grid length that is deemed suitable.

D4.9 Concrete

The concrete shall have a 28 day cylinder strength of 30 to 35 MPa. It shall be batched and mixed in accordance with the applicable clauses of ASTM Standard C 192. The slump of fresh concrete shall be measured and its ultimate strength determined after 28 days.

D4.10 Casting Specimens

The prism shall be cast with the FRP bar in a horizontal position. Bonding with the concrete shall be prevented along the last 25 mm length of the bar where it protrudes from the prism, (by using several layers of adhesive plastic tape, a thin-walled plastic sleeve, or other means. The bar shall be supported during casting to maintain a straight profile along the prism axis. If any form-release oil is used, care shall be taken to prevent the FRP bar from coming into contact with it.

D4.11 Curing Specimens

One day after moulding, the prisms shall be demoulded and transferred to a curing environment as stipulated in ASTM Standard C 192.

D4.12 Anchoring the Free End of an FRP Bar

On the 26th day after moulding, the anchor shall be attached to the free end of the FRP bar in accordance with Annex B of this Standard.

D5 Test Environment

Tests shall be carried out with the room temperature maintained at 20 ± 5°C and relative humidity at 50 ± 25%.

D6 Order of Testing Specimens

The specimen with an embedment length of $1.0L_{da}$ shall be tested first.

If the failure of the first specimen is by rupture of the FRP bar, only the remaining specimens with shorter embedment lengths shall be tested in decreasing order of embedment. When one of these tests shows the change in the failure mode to bond slippage, with or without splitting of concrete, only one of the remaining specimens in the sequence shall be tested to confirm the change.

Conversely, if the failure of the first specimen is by bond slippage, only the specimens with longer embedment lengths from the remaining ones shall be tested in increasing order of embedment length. When one of these tests shows the change in the failure mode to rupture of the FRP bar, only one of the remaining specimens in the sequence shall be tested to confirm the change.

D7 Test Procedure

D7.1 Mounting Specimen

The specimen shall be carefully transported, lifted, and mounted on the testing machine in the position shown in Figure D2. Axial alignment of the anchor with the machine grips shall be checked and necessary adjustments to the position of the specimen made before the mortar bed sets.

Note: *Alternatively, the prism may be supported on a spherically seated bearing block.*

D7.2 Attaching Measurement Devices

The displacement-measurement devices and the reference bar shall be mounted as shown in Figure D3.

D7.3 Rate of Loading

The loading shall be applied at a stressing rate of 250 to 500 MPa/min. For machines with displacement control only, the desirable strain rate may be obtained by dividing the desirable stress rate by the estimated modulus of elasticity of the FRP bar. If the testing machine is not equipped with load-displacement-control, a timing device may be used to measure the time taken to apply a known increment of stress.

D7.4 Data Recording

If a data acquisition system is used, it shall be started a few seconds before commencement of the loading. If dial gauges are used for displacement measurement, there shall be a minimum of four: three each to read and record the three dial gauges and one to operate the machine. The reading intervals shall be timed so that at least 15 readings are recorded before the first slip has occurred.

D7.5 Safety Measure

Because some FRP specimens fail explosively and with the release of substantial amount of energy, protective eyeglasses shall be worn by all testing personnel.

D7.6 Test Termination

The test shall be terminated when one of the following occurs:

(a) the FRP bar ruptures; or

(b) the FRP bar slips a distance at least equal to its diameter.

D7.7 Rejection

If any test specimen fails partly or fully inside the anchor, the test shall be discarded and the next specimen tested. If such rejection leads to uncertainty about the development length, a new series of specimens shall be tested. The number of specimens in the new series may be reduced based on the trend shown by the tests already completed.

D8 Calculations

D8.1 Bond Stress

The nominal average bond stress shall be the load on the bar divided by the nominal surface area of the embedded length of the FRP bar as follows:

$$u = \frac{P}{\pi d L_e} \qquad \textbf{(D-2)}$$

D8.2 Bond Slip

The slip at the loaded end shall be the average of the two displacement readings against the reference bar, minus the elongation in the length of the FRP bar between termination of embedment and the point of attachment of the reference bar. This elongation shall be calculated as follows:

$$s_c = \frac{PL_c}{AE} \qquad \textbf{(D-3)}$$

D8.3 Development Length

The development length of the FRP bar tested shall be taken as the longer of the embedment lengths of two consecutively tested specimens, one of which failed by FRP rupture and the other by bond slippage or splitting of concrete.

D9 Report

D9.1

The report shall include the following information:

(a) regarding properties of the concrete

(i) the mix proportions of cement, fine aggregate, coarse aggregate, admixtures (if used), and the water-cement ratio;

(ii) the slump of freshly mixed concrete as determined in accordance with ASTM Standard C 143;

(iii) the 28 day strength of control cylinders as determined in accordance with ASTM Standard C 138; and

(iv) any deviation from the stipulated standards in such aspects as mixing, curing, dates of demoulding, and testing control cylinders; and

(b) regarding properties of the FRP specimen bar

(i) the product name, batch, and nominal designation;

(ii) the nominal diameter and cross-sectional area as determined in accordance with Annex A of this Standard;

(iii) the modulus of elasticity and ultimate tensile strength as determined in accordance with Annex C of this Standard; and

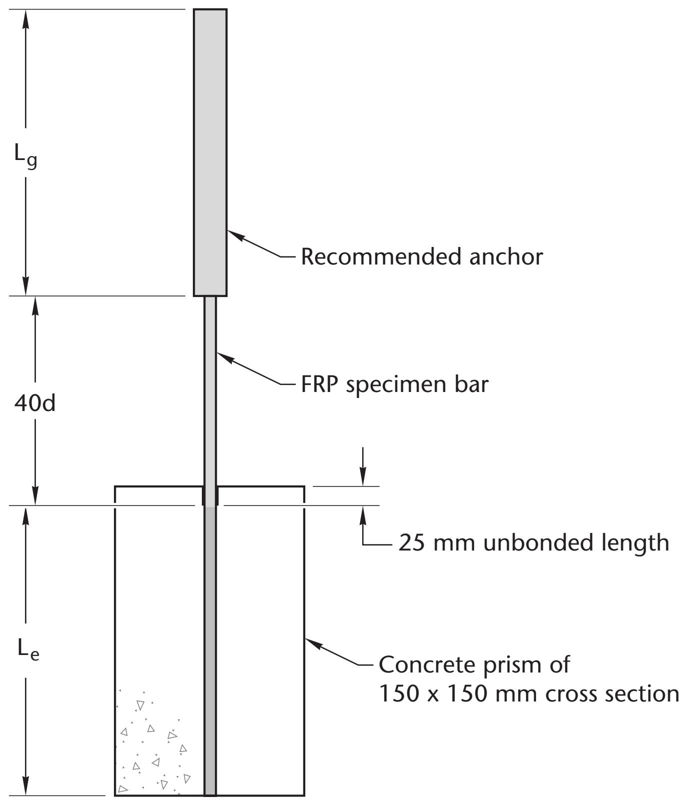
(iv) a close-up photograph of the bar showing surface deformations and characteristics.

D9.2

The development length determined shall be reported. The following plots shall be included:

(a) for each specimen tested, the bond stress as the ordinate and the bond slip expressed as a percentage of the nominal bar diameter as abscissa; and

(b) the nominal average bond stress corresponding to 5% slip as ordinate and development length expressed in multiples of nominal bar diameter as abscissa.



Note: *The specimen is shown in the position of casting the anchor at the top.*

Figure D1
General View of Specimen
(See Clause D4.1.)

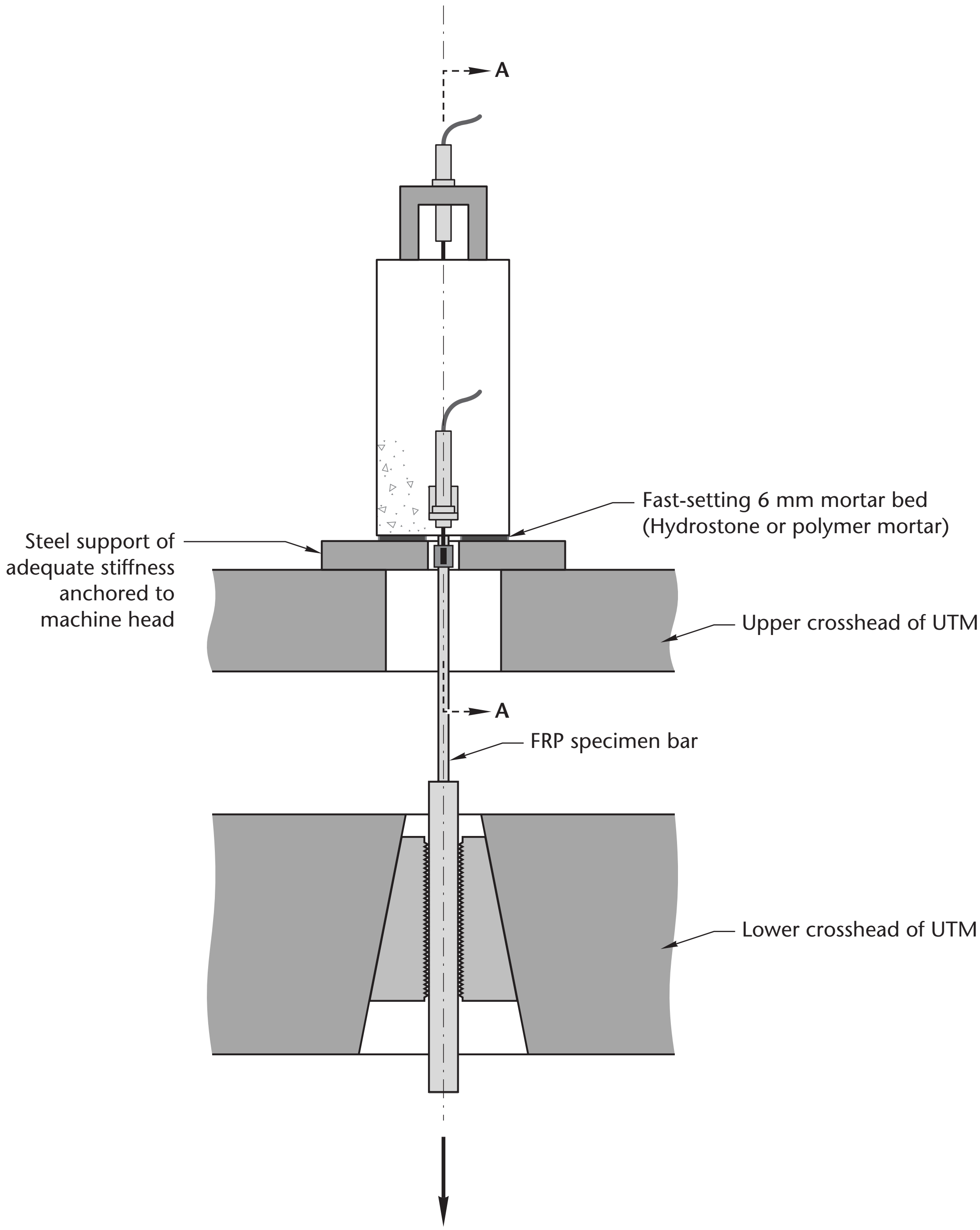


Figure D2
Specimen Shown Mounted in Testing Machine
(See Clause D7.1.)

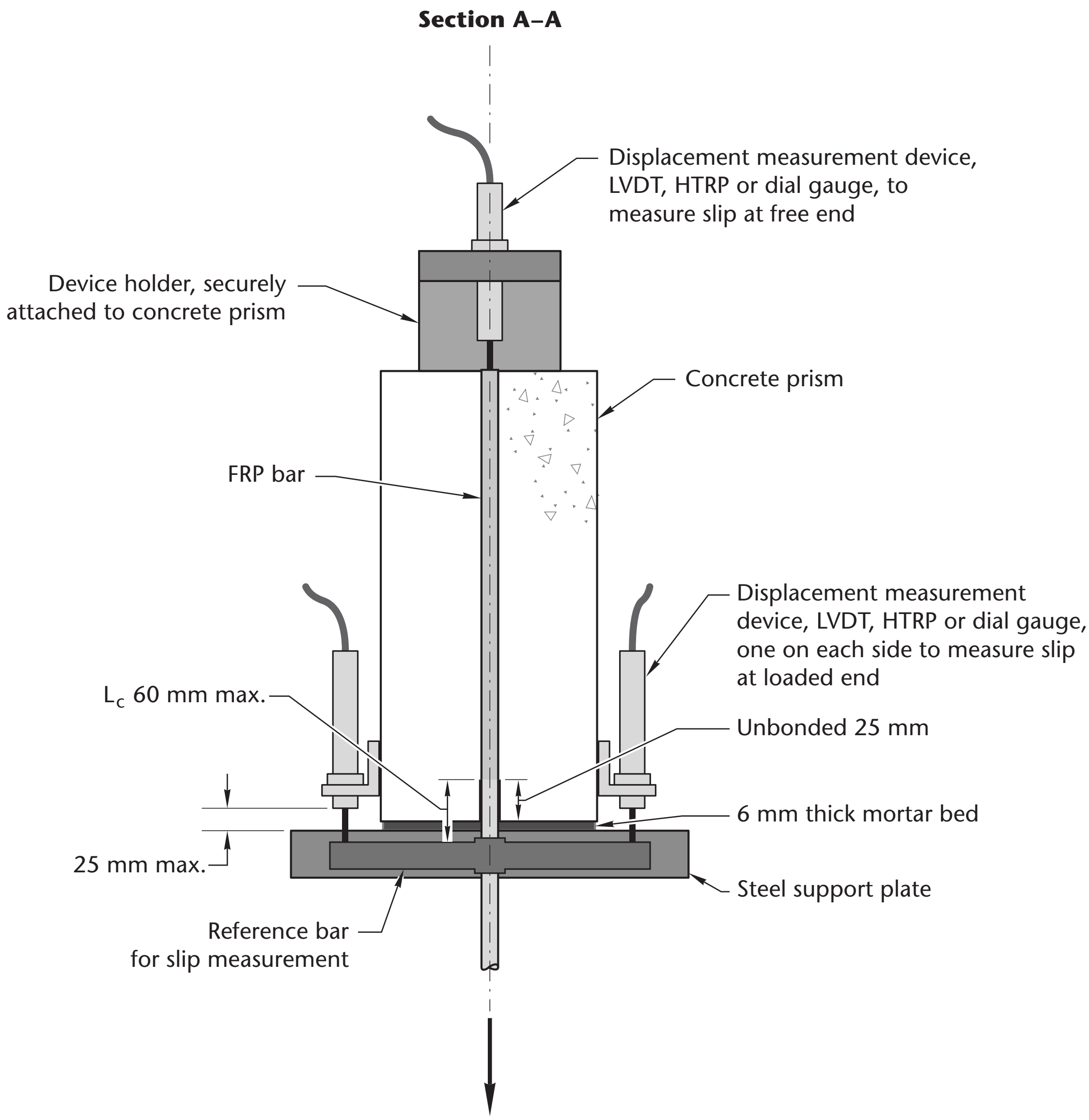


Figure D3
Detail of Test Procedure Set-up
(See Clause D7.2.)

Annex E (Normative) ***Test Method for FRP Bent Bars and Stirrups***

Note: *This Annex is a mandatory part of this Standard.*

E1 Scope

This Annex specifies the test requirements for determining the strength capacity of FRP bent bars used as anchorage for stirrups in concrete structures.

E2 Notation

The following symbols are used in this Annex:

A_b = nominal cross-sectional area of single leg of the FRP stirrup
f_{bend} = bend capacity of the FRP stirrup
f_{fu} = tensile strength parallel to the fibre determined in accordance with Annex C of this Standard
F_{ult} = ultimate load capacity according to bend tests
χ = strength reduction factor due to bend effect

E3 Significance and Use

E3.1

This test method is intended for use in laboratory tests that determine the strength capacity of the bend portion provided as an anchorage in which the principal variables are the size, bend radius, and type of the FRP stirrup.

E3.2

The bending of FRP stirrups in order to develop sufficient anchorage leads to a significant reduction in their strength capacity. The bend radius and tail length beyond the bend are important variables that affect the bend capacity.

E3.3

This test method measures the ultimate load capacity of a single FRP stirrup subjected to tensile force in the direction of the straight portion.

E4 Terminology

The following definitions apply in this Annex:

Bend capacity — ultimate tensile stress that can be carried by the FRP stirrup provided that failure occurred at the bend.

Bend radius — inside radius of the bend, as illustrated in Figure E1.

Effective bar diameter — the effective bar diameter, based on the nominal cross-sectional area of the FRP bar, which is calculated using the equation $\sqrt{4A_b/\pi}$.

Tail length — the length provided beyond the bend portion, as illustrated in Figure E1.

Tensile strength — ultimate tensile strength of FRP bars in the direction parallel to the fibres.

E5 Specimen Preparation

E5.1

The configuration of a typical specimen is shown in Figure E1. The dimensions of the concrete blocks used to anchor the FRP stirrups vary according to the dimensions of the stirrup used. However, the free length of the stirrup between the two blocks shall not exceed 200 mm. The concrete block shall be reinforced using steel stirrups, as shown in Figure E1, to prevent splitting of the concrete block prior to rupture of the stirrup at the bend. The dimensions of the stirrups may vary; however, it is recommended that the height of the FRP stirrup tested not exceed 750 mm.

E5.2

The number of test specimens for each test condition shall not be less than five. If a test specimen is found clearly to have failed by splitting of the concrete block, an additional test shall be performed on a separate test specimen taken from the same lot.

E5.3

The FRP stirrups used for the bend tests shall be fabricated using the same bending process used to fabricate other FRP stirrups with different dimensions.

E6 Test Method and Requirements

E6.1

The test set-up, shown in Figure E2, shall utilize a hydraulic jack to apply the relative displacement between the two concrete blocks and a load cell to measure the applied load. Steel plates and plaster bags shall be placed in front of the load cell and the hydraulic jack in order to distribute the applied load on the applied surface. The two blocks shall be placed on top of steel rollers in order to minimize the friction forces between the blocks and testing bed.

E6.2

The hydraulic jack and the load cell shall be calibrated prior to performing the bend tests.

E6.3

Extensometers shall be used on the stirrup's legs to ensure uniform distribution of the applied load.

E6.4

The tensile strength of straight FRP bars with the same diameter as the FRP stirrups shall be evaluated in accordance with Annex C of this Standard.

E6.5

The temperature shall normally be within the range of 20 ± 2°C.

E6.6

The test specimens shall not be subjected to any shock, vibration, or torsion.

E7 Calculation

E7.1

The bend capacity of the FRP stirrup shall be assessed only on the basis of the test specimen undergoing failure at the bend. In cases where block splitting has clearly taken place, the data shall be disregarded and additional tests shall be performed until the number of the test specimens failing at the bend is not less than three.

E7.2

The bend capacity of the FRP stirrup shall be calculated according to Equation E-1, to three significant digits:

$$f_{bend} = \frac{F_{ult}}{2A_b} \qquad \textbf{(E-1)}$$

E7.3

The strength reduction factor shall be calculated according to Equation E-2:

$$\chi = \frac{f_{bend}}{f_{fu}} \qquad \textbf{(E-2)}$$

E8 Report

The test report shall include the following items:
(a) the commercial name of the FRP bar used for stirrups;
(b) the type of fibre and matrix used in the FRP stirrup and the volumetric ratio of the fibres;
(c) the process used to fabricate the stirrups as reported by the manufacturer;
(d) the numbers or identification marks of test stirrups;
(e) the designation, nominal diameter, and nominal cross-sectional area;
(f) the configuration, bend radius, and tail length of the test stirrup;
(g) the date of test and test temperature;
(h) the type and capacity of load cell;
(i) the bend capacity and strength reduction factor for each test stirrup; and
(j) the average bend capacity and strength reduction factor for all specimens that failed at the bend as intended.

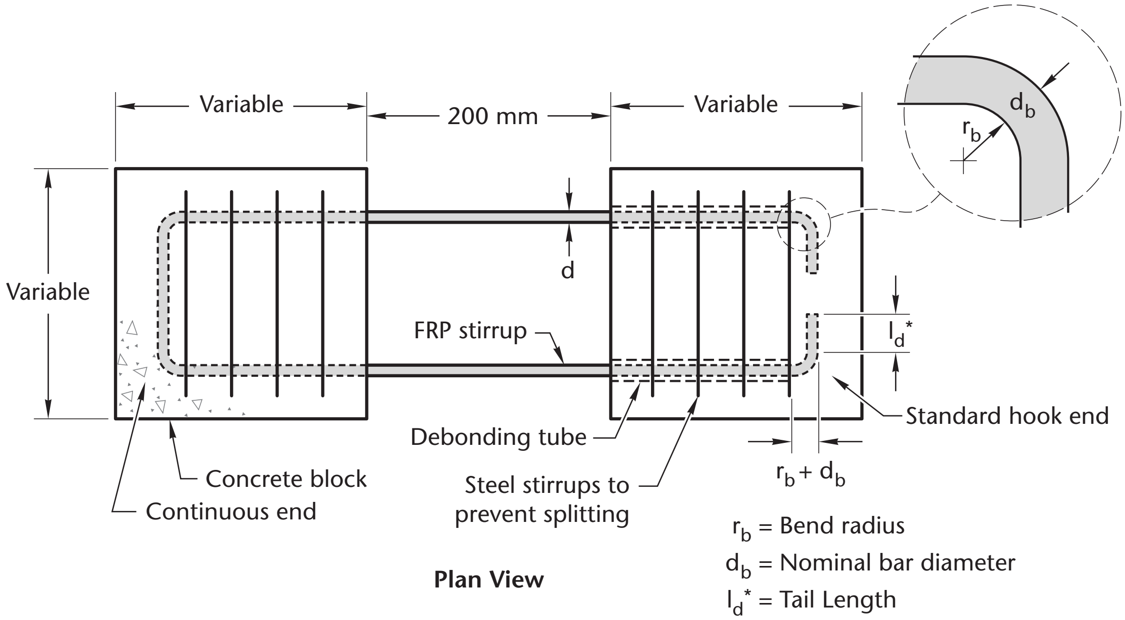
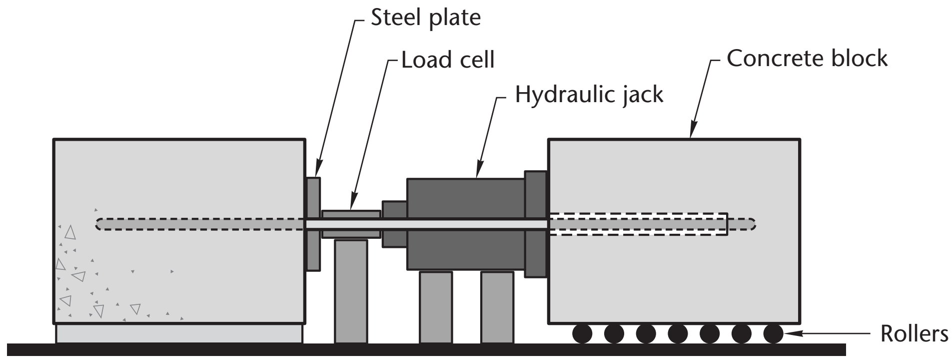
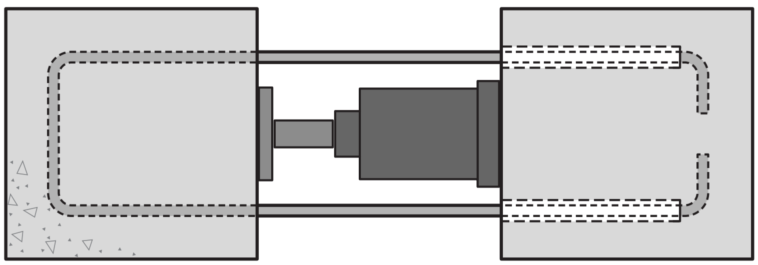


Figure E1
Configuration of Test Specimen
(See Clauses E4 and E5.1.)



Elevation



Plan View

Figure E2
Test Set-up
(See Clause E6.1.)

Annex F (Normative) ***Test Method for Direct Tension Pull-off Test***

Note: *This Annex is a mandatory part of this Standard.*

F1 Scope

This Annex specifies a method for the preparation and testing of the tensile bond strength of an FRP laminate bonded to the surface of a concrete member; the method may also be used to test the tensile strength of the substrate concrete.

F2 Referenced Document

ASTM Standard D 4541 provides the standard test method for pull-off strength of coatings, etc.

F3 Summary of Test Method

The portable pull-off test shall be performed by securing a 1290 mm^2 or larger adhesion fixture to the surface of the FRP or concrete with a bonding agent. After the bonding agent is cured, a test apparatus shall be attached to the loading fixture and aligned to apply tension perpendicular to the concrete. A constant loading rate shall be applied to the adhesion fixture, and the load shall be recorded until the adhesion fixture detaches from the surface. The pull-off strength shall be computed based on the maximum indicated load, the instrument calibration data, and the original stressed surface area.

F4 Test Apparatus

F4.1

The portable adhesion test apparatus should
(a) use a 1290 mm^2 or larger adhesion fixture. The fixture may be square or circular;
(b) use a manual or mechanized device for applying a uniform cross-head speed;
(c) have a method for recording peak load; and
(d) be adjustable for loading perpendicular to the sample and applying tensile force without torque.

F4.2

The portable adhesion tester shall include the following mandatory components, which are illustrated in Figure F1:
(a) Adhesion fixture: the adhesion fixture shall have a flat surface on one end and have a pinned or otherwise freely rotating attachment on the other end.
(b) Detaching assembly: the detaching assembly shall have a standoff support centred on the central attachment grip and a self-aligning device for engaging the adhesion fixture.
(c) Detaching assembly base: the detaching assembly base shall provide firm and perpendicular contact with the surface.
(d) Loading device: the manual or mechanized device for pulling the adhesion fixture shall apply a uniform cross-head speed until rupture occurs, so that the maximum stress is obtained in less than 100 s.
(e) Force indicator: the force indicator shall have calibration information and a maximum scale indicator not less than 4450 N.
(f) Bonding agent: an adhesive material that will provide at least 5.5 MPa tensile strength shall be used. The bonding agent shall be applied in accordance with manufacturer's instructions.

F5 Test Preparation and Procedure

F5.1
The manufacturer's instructions regarding the elapsed time between the application of FRP and the application of force shall be followed. The following procedure, when in accordance with the manufacturer's instructions, shall be used to make the adhesion measurement.

F5.2
Select a flat measurement site in accordance with the sampling schedule.

F5.3
Prepare the surface for bonding the fixture. Sand the FRP surface smooth with medium-grid sandpaper, rinse, and allow to dry. Clean the concrete surface according to prescribed cleaning methods.

F5.4
Core drill or square cut through the FRP laminate into the substrate concrete, according to the size and shape of the adhesion fixture, using carbide-tipped or diamond core bit or cutting wheel. Cut into the concrete to a depth of 6 to 12 mm.

F5.5
Attach the adhesion fixture with the designated bonding agent. Leave to cure in accordance with the bonding agent manufacturer's instructions.

F5.6
Position the detaching assembly over the adhesion fixture and attach the adhesion fixture to the detaching assembly. Align the load applicator in a perpendicular position. Adjust the legs of the detaching assembly as required.

F5.7
Take up the slack in the adhesion tester by screwing down the adjustment knob.

F5.8
Set the force indicator to the zero mark.

F5.9
Apply manual or mechanized loading in such a way that it provides a smooth cross-head motion until rupture occurs. The maximum load shall be obtained in less than 100 s.

F5.10
Record the pull-off force measurement, and compute and record the tensile bond strength or concrete strength, whichever is applicable, from the following formula:

Tensile bond strength = pull-off force/adhesion fixture contact area

F6 Interpretation of Results

F6.1
The adhesion of the FRP laminate to the concrete surface is necessary to enable the concrete member to transfer load to the FRP laminate. The interface bond and the strength and quality of the concrete itself

are critical. Possible failure modes in this tension test are
(a) adhesive failure occurring at the interface of the FRP laminate and the concrete;
(b) cohesive failure within the FRP laminate;
(c) cohesive failure within the concrete; and
(d) any combination of Items (a), (b), and (c).

F6.2
Bonding agent failure resulting from poor preparation shall not be an acceptable failure mode.

F6.3
The preferred mode of failure is cohesive failure within the concrete at a stress level in excess of 1.4 MPa.

F7 Report
The test report shall include the following:
(a) the date of test;
(b) the measurements of adhesive fixture;
(c) the identification of the commercial test device;
(d) the sample identification and test location;
(e) the sample failure stress and mode of failure;
(f) the average failure stress for the sample population; and
(g) the test operator.

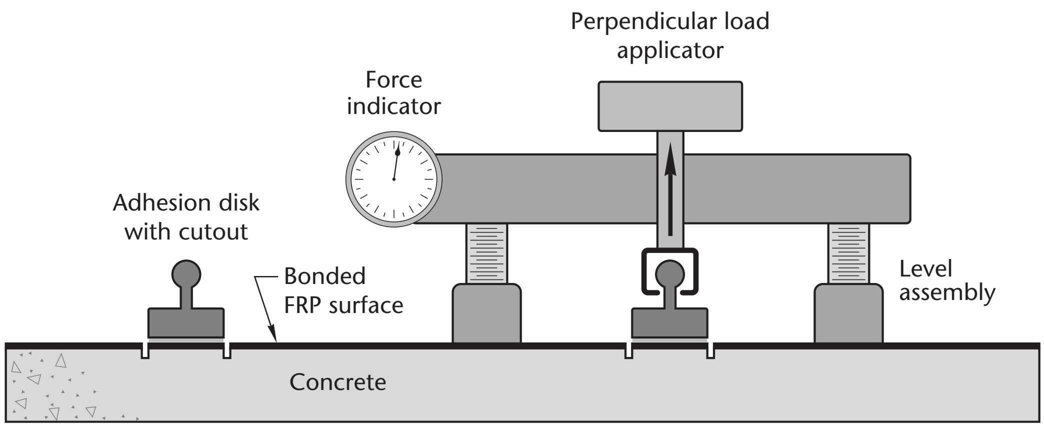


Figure F1
Direct Tension Pull-off Test
(See Clause F4.2.)

Annex G (Normative)
Test Method for Tension Test of Flat Specimens

Note: *This Annex is a mandatory part of this Standard.*

G1 Scope

This Annex specifies the requirements for sample preparation and a test method to determine tensile properties of unidirectional and bidirectional FRP materials used for external concrete reinforcement. It covers the determination of the tensile properties of resin matrix composites reinforced by oriented continuous high-modulus (> 69 GPa) fibres to be used as external tensile reinforcement for concrete structures, and includes requirements for continuous reinforcing fibres at 0 degrees and continuous bidirectional fabrics at 0/90 degrees. The method also provides specific instructions for calculating strength and modulus based on an equivalent cross-sectional area.

G2 Notation

The following symbols are used in this Annex:

b = width
d = thickness
d' = the equivalent thickness of a fibre layer with resin
dP/dl = slope of the linear portion of the load deformation curve
E = modulus of elasticity
E' = the equivalent elastic modulus of a fibre layer without resin
f_u = ultimate tensile strength
f'_u = the equivalent strength of a fibre layer without resin
l = gauge length of measuring instrument
P = maximum load

G3 Referenced Documents

ASTM Standard D 3039 provides the standard test method for tensile properties of fibre-resin composites.

G4 Terminology

The following definition applies in this Annex:

Gauge section — one specimen-width away from the tab edge on each end.

G5 Summary of Test Method

The tension specimen shown in Figure G1 shall be mounted in the grips of a self-aligning testing machine. A constant loading rate shall be applied to the specimen until failure. Load-deformation or load-strain curves shall be plotted during the test if the modulus properties are required.

G6 Test Apparatus

G6.1

The testing machine shall be in accordance with ASTM Standard D 3039.

G6.2
Micrometers shall be suitable for reading to 0.025 mm of the specimen thickness and width.

G6.3
Strain may be determined by means of an extension indicator or strain indicator attached mechanically or bonded directly to the sample. Cross-head motion is not a suitable indication of strain. If Poisson's ratio is to be determined, the specimen shall be instrumented to measure strain in both longitudinal and lateral directions.

G7 Specimen Preparation

G7.1 Field Preparation of Wet Layup Materials
Field specimens shall be made in a manner similar to the materials used in the actual field installation. A plastic sheet shall be placed on a smooth, flat, horizontal surface. The specified number of plies at the specified angles shall be sequentially resin-coated and stacked on the plastic surface using the same amount of resin per unit area as would be applied in the actual installation. Grooved rollers or flat spatulas may be used to work out the trapped air in the laminate. A second plastic sheet shall then be placed over the laminate, a smooth rigid flat plate placed on top of the plastic, and a weight placed on top of the plate. The weight shall be sufficient to produce a smooth surface upon cure but shall not cause significant flow of resin. After cure, the panel shall be cut and tabbed. For FRP systems requiring heat, pressure, or other mechanical/physical processing for cure, the engineer and material supplier shall agree on a representative specimen fabrication process.

G7.2 Laboratory Preparation of Wet Layup Materials
A plastic sheet shall be placed on a smooth, flat, horizontal surface. Resin shall be coated onto the film, and the FRP fabric or sheet material placed in the resin. Additional resin shall then be overcoated. This process shall be repeated for multiple plies. A grooved roller may be used to work out trapped air. A second plastic sheet shall then be placed over the assembly. The flat edge of a small paddle shall be used to push the excess resin forcibly out of the laminate with a screeding action in the fibre direction. The laminate shall be cured without removing the plastic. Specimens shall be cut and tabbed after cure. Alternatively, specimens may be cut with a steel rule and utility knife after gelation but before full cure. For FRP systems requiring heat, pressure, or other mechanical/physical processing for cure, the engineer and material supplier shall agree on a representative specimen fabrication process.

G7.3 Field/Laboratory Preparation of Precured FRP Laminates
Specimens shall be cut to size using an appropriate table saw. Because thickness is predetermined, specimen width and length may be altered by agreement between the engineer and laminate manufacturer. Care shall be taken to ensure that the specimen is flat because testing of nonflat specimens may result in lower tensile values due to induced moments.

G7.4 Geometry
The test specimen shall be as shown in Figure G1, where the specimen has a constant cross-section with tabs bonded to the ends. Table G1 gives the width and gauge length of specimens used for different fibre orientations. Variation in specimen width shall be no greater than ±1%. Variation in laboratory prepared-specimen thickness shall be no greater than ±2%. Variation in field-prepared specimen thickness shall be no greater than ±10%.

G7.5 Tabs
Moulded fibreglass and aluminum tabs shall be acceptable. The tabs shall be strain-compatible with the composite being tested. The tabs shall be bonded to the surface of the test specimen using a

high-elongation (tough) adhesive system that will meet the temperature requirements of the test. The width of the tab shall be the same as the width of the specimen. The length of the tabs shall be determined by the shear strength of the adhesive, the specimen, or the tabs (whichever is lower), the thickness of the specimen, and the estimated strength of the composite. If a significant proportion of failures occur within one specimen width of the tab, there shall be a re-examination of the tab material and configuration, gripping method, and adhesive, and necessary adjustments shall be made in order to promote failure within the gauge section.

G8 Conditioning

G8.1 Standard Dry Specimens

The test specimens shall be stored in an enclosed space maintained at a temperature of 23 ± 5°C and a relative humidity of 50 ± 10%, and shall be tested in a room maintained at the same conditions.

G8.2 Other Than Standard Dry Specimens

The test specimens shall be stored in an enclosed space maintained at the specified conditions. All conditioning shall be reported.

G9 Test Procedure

G9.1 Number of Specimens

At least five specimens shall be tested for each test condition.

G9.2 Measurement

The width and thickness of the specimen shall be measured at several points. The average value of cross-sectional area shall be recorded.

G9.3 Set-up and Speed

The specimen shall be placed in the grips of the testing machine, taking care to align the long axis of the specimen and the grips with an imaginary line joining the points of attachment of the grips to the machine. The speed of testing shall be set to give the strain rates in the specimen gauge section. Speed of testing shall be set to effect a constant strain rate in the gauge section, with standard strain rates between 16.7 and 33.4 (mm/mm)/s being preferred. A constant cross-head speed may also be used. The cross-head speed shall be determined by multiplying the strain rate by the distance between tabs, in inches or millimetres. If strain is to be determined, the extension indicator or the strain-recording equipment (if strain gauges are used as primary transducers) shall be attached to the specimen.

G9.4 Recording

Load and strain (or deformation) shall be recorded continuously, if possible. Alternatively, load and deformation may be recorded at uniform intervals of strain. The maximum load sustained by the specimen during the test and the strain at rupture shall both be recorded.

G9.5 Calculations — Method 1

The tensile strength and modulus may be calculated using the following equations, with the results being reported to a precision of three significant figures:

$$f_u = \frac{p}{bd} \quad \textbf{(G-1)}$$

$$E = \left(\frac{dP}{dl}\right)\left(\frac{l}{bd}\right) \quad \textbf{(G-2)}$$

G9.6 Calculations — Method 2

An alternative method based on equivalent fibre area may be used, in which case the tensile strength and elastic modulus are found from the following equations and the results reported with a precision of three significant figures:

$$f_u' = \frac{P}{bd'} \quad \textbf{(G-3)}$$

$$E' = \left(\frac{dP}{dl}\right)\left(\frac{l}{bd'}\right) \quad \textbf{(G-4)}$$

G9.7

For each series of tests, the average value, standard deviation, and coefficient of variation for the tensile strength, failure strain, and elastic modulus shall be calculated.

G10 Report

The report shall include the following:
(a) identification of the material tested;
(b) description of fabrication method and stacking sequence;
(c) test specimen dimensions;
(d) the conditioning procedure used;
(e) the number of specimens tested;
(f) the speed of testing, if other than specified;
(g) the tensile strength, failure strain, and elastic modulus, including average value, standard deviation, and coefficient of variation;
(h) the date of test; and
(i) the test operator.

Table G1
Width and Gauge Lengths of Specimens

(See Clause G7.4.)

Fibre orientation	Specimen minimum width, mm	Gauge length, mm
0°	12.7	127
90°	25.4	38
0/90°	25.4	127

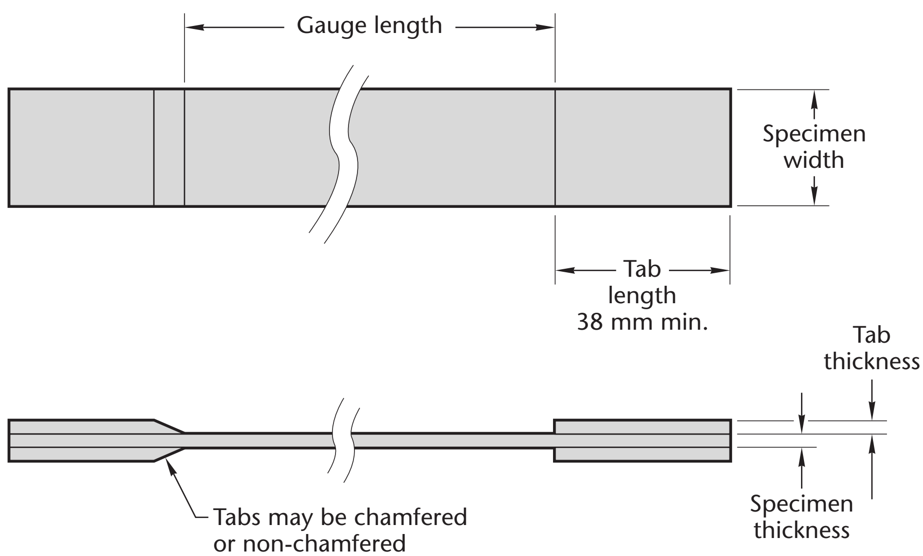


Figure G1
Direct Tension Pull-off Test

(See Clauses G5 and G7.4.)

Annex H (Informative) Test Method for Bond Strength of FRP Rods by Pullout Testing

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

H1 Scope

H1.1

This Annex specifies a method* of pullout testing to determine the bond strength of FRP rods used in place of steel reinforcing bars or prestressing tendons in concrete.

**Other types of tests include the double sliding test, cantilever beam test, beam test, etc. Each of these has merits and demerits; however, only the pullout test method has been established as a test method with the necessary degree of confidence.*

H1.2

This test method for measuring bond strength by pullout is intended for use in laboratory tests in which the principal variable is the size or type of FRP rods. The test method establishes values for comparison of bond performance and may also be used approximately for structural design purposes.

H1.3

This test method may also be used to determine whether a product or a treatment conforms to requirements relating to its effect on the bond developed between FRP rod and concrete.

H2 Notation

The following symbols are used in this Annex:

l = bonded length
P = tensile load
u = nominal peripheral length of FRP rod
τ = average bond stress

H3 Terminology

The following definition applies in this Annex:

Nominal peripheral length — the length of the FRP rod, which forms the basis for the calculation of bond strength; the length is determined separately for each FRP rod.

H4 Specimen Preparation

H4.1

H4.1.1

The test specimens shall be of two types: one containing one FRP rod embedded vertically and the other containing two FRP rods embedded horizontally. Five specimens of each type shall constitute a set of test specimens. If a test specimen is found to have failed at an anchoring section, or to have slipped out of an anchoring section, an additional test shall be performed on a separate test specimen taken from the same lot.

H4.1.2 Specimens for Vertically Embedded Bar (See Figure H1)

Each specimen shall consist of a concrete cube, 150 mm on each edge, with a single FRP rod embedded vertically along a central axis. The rod shall project upward from the top face a sufficient length to extend through the bearing blocks and the support of the testing machine and provide an adequate length to be gripped for application of load. Larger size cubes may be used to accommodate larger diameter rods in order to minimize splitting of the concrete, because if the minimum side cover of the cube is less than five or six rod diameters, splitting may become a problem.

H4.1.3 Specimens for Horizontally Embedded Bar (See Figure H2)

Each specimen shall consist of a concrete prism, 150 by 150 by 300 mm, with the longer axis in the vertical direction. Two rods shall be embedded in each specimen, perpendicular to the longer axis and parallel to and equidistant from the sides of the prism. In the vertical direction, one rod shall be located with its axis 75 mm from the bottom of the prism, and the other with its axis 225 mm from the bottom. Both rods shall project from the sides of the specimen by distances corresponding to those for specimens having a vertically embedded rod. A triangular groove shall be formed in each of the two opposite sides of the prism parallel to the axes of the rods and at the midheight of the prism. These grooves shall be at least 13 mm deep, measured perpendicular to the surface of the concrete, in order to facilitate breaking of the prism into two test specimens at this weakened plane, prior to performing the bond tests.

H4.1.4 FRP Rods

FRP rods used in a given series of tests shall be of the same type and size and shall have the same pattern of surface deformations. The length of an individual rod shall be sufficient to meet the requirements of the test specimens. The bonded length of the FRP rod shall be four times the diameter of the FRP rod, except if this length is thought to misrepresent the bonding characteristics of the FRP rod, it may be increased as appropriate. In order to equalize the stress from the loading plate on the loaded end side, sections other than the bonded section shall be sheathed with PVC or other suitable material so as to prevent bonding.

H4.2

The number of test specimens shall be at least five. The moulds for bond test specimens shall be in accordance with the moulds as shown in Figures H3 and H4, which were taken from the ASTM Standard C 234. Care shall be taken that the following requirements are observed:
(a) the opening in the form through which the FRP tendon is inserted shall be sealed using oil, putty, or similar materials in order to prevent ingress of water and other deleterious material; and
(b) the form shall be kept horizontal from the time of the placement of concrete to the time of its removal.

H4.3

The following procedures shall be used for placement of concrete in the moulds (unless another well-established method is employed):
(a) For the 150 by 150 by 300 mm cubes, the concrete shall be placed in two layers of approximately equal thickness and each layer shall be rodded 25 times with a 16 mm diameter tamping rod.
(b) For the 150 mm cubes, the concrete shall be placed in four layers of approximately equal thickness and each layer shall be rodded 25 times with a 16 mm diameter tamping rod.
(c) After the top layer has been consolidated, the surface shall be struck off with a trowel and protected against moisture evaporation; care shall be taken to ensure that evaporation does not take place in the area adjacent to the protruding vertically cast FRP rod specimens.

H4.4
The concrete shall be a standard mix, with coarse aggregates having a maximum dimension of 20 to 25 mm. The concrete shall have slump of 10 ± 2 cm, and the compressive strength at 28 days shall be 30 ± 3 MPa for bond testing. A minimum of five standard 150 by 300 mm or 100 by 200 mm control cylinders from each batch of concrete shall be made for determining the compressive strength.

H4.5
Moulds shall not be removed from the specimens earlier than 20 hours after casting. Extreme care shall be taken to prevent striking or otherwise disturbing the FRP rods. Immediately after the removal of the moulds, specimens shall be cured in accordance with ASTM Standard C 511 until the time of test. Specimens shall be tested after 28 days.

H4.6
When the specimens are between 7 and 14 days old, the 150 by 150 by 300 mm prisms shall be broken in half to form two 150 mm cubes. Specimens shall be broken as simple beams with centre-point loading in accordance with ASTM Standard C 293. The two triangular grooves in the upper and lower faces of the prisms shall be located at midspan. The load shall be applied to a 19 mm diameter bar laid in the upper groove until fracture occurs. Care shall be taken not to strike or otherwise disturb the FRP rods during the operation.

H4.7
The surface of the 150 mm cube containing the vertically embedded rod shall be capped; it can be utilized as the bearing surface in the pullout test. The applicable portions of ASTM Standard C 617 regarding capping materials and procedures shall be used.

H5 Test Equipment and Requirements

H5.1
The testing machine for pullout tests shall be capable of accurately applying the prescribed load. The load shall be applied to the reinforcement bar at a rate not greater than 22 000 N/min or at a no-load speed of the testing machine head that shall not be greater than 1.27 mm/min, depending on the type of testing used and the means provided for ascertaining or controlling speeds.

H5.2
The loading plate shall have a hole through which the FRP tendon shall pass. The diameter of the hole in the loading plate shall be 2 to 3 times the diameter of the FRP tendon.

H5.3
The loading end of the FRP tendon shall be fitted with an anchorage capable of transmitting loads until the tendon is pulled out of the concrete either by bond failure or because of splitting or cracking of the concrete. The load transmission device shall only transmit axial loads to the FRP tendons and shall not transmit either torsional or flexural forces.

H5.4
The displacement metres fitted to both the free end and loaded end of the FRP tendon shall be dial gauges or a similar apparatus, reading accurately to 1/1000 mm. Provision for bending compensation shall be made. At each end of the bar, either three gauges (LVTD) at 120° intervals or two gauges at 180° intervals shall be used.

H6 Test Method

H6.1
The specimen shall be mounted in the testing machine so that the surface of the cube from which the long end of the rod projects is in contact with the bearing block assembly. The spherically seated bearing block shall rest on a support that transfers the reaction from the block to the weighing table of the testing machine. The projecting FRP rod shall extend through the bearing block assembly and the support and shall be gripped for tension by the jaws of the testing machine as shown in Figure H5.

H6.2
The testing apparatus shall be assembled on the specimen, and care shall be taken to measure and record, to the nearest 2.5 mm, the distance between the bearing face of the concrete and the horizontal plane passing through the point on the FRP rod where the crossbar of the device for measuring slip plus elongation is attached. The elongation of the FRP rod over this distance shall be calculated and subtracted from the measured slip plus elongation in order to obtain the loaded-end slip. The free-end slip may also be measured to the nearest 0.5 mm.

H6.3
Load shall be applied to the FRP rod at a load rate not greater than 22 kN/min or at a testing machine head speed not greater than 1.27 mm/min, in accordance with Clause H5.1.

H6.4
The applied load and the dial-gauge readings shall be read and recorded at a sufficient number of intervals throughout the test to provide at least 15 readings by the time a slip of 0.25 mm has occurred at the loaded end of the FRP rod. The dial-gauge readings shall be taken to an estimated 0.1 of the least division of the dial. The displacement meter fitted to the free end of the FRP tendon shall also be a dial gauge or similar apparatus. The slippage of the free end shall be recorded in increments of 0.01 mm, together with the corresponding applied load.

H6.5
Loadings and readings shall be continued at appropriate intervals until
(a) rupture of the FRP rod occurs;
(b) the enclosing concrete splits; or
(c) slippage of at least 2.5 mm has occurred at the loaded end of the embedded length.

H7 Calculations

H7.1
In cases where a test specimen is judged to have undergone a tensile failure at an anchoring section, or to have slipped out of an anchoring section before the FRP tendon has slipped from the concrete or before the load is significantly reduced due to splitting or cracking of the concrete, the data shall be disregarded and additional tests shall be performed until the number of valid tests is not less than three.

H7.2
The average bond strength shall be calculated and reported with a precision to three significant digits, and the curves for the pullout or bond stress versus slippage at both free end and loaded end for each test specimen shall be plotted. The calculation of average bond strength shall be as follows:

$$\tau = \frac{P}{ul} \qquad \textbf{(H-1)}$$

H7.3
Average bond stress corresponding to slippage at the free end of 0.05 mm, 0.10 mm, and 0.25 mm, as well as the maximum bond stress at failure, shall be calculated.

H7.4
At any stage in the test, nominal average bond stress causing slippage at the loaded end may be calculated as the load on the bar divided by the nominal surface area of the entire embedded length of the bar. The slip shall be calculated as the average of the readings of the dial gauges, corrected for the elongation of the reinforcing bar in the distance between the bearing surface of the concrete cube and the point on the reinforcing bar where the measuring device was attached.

H8 Report
The test report shall include the following items:
(a) the name of the FRP rod;
(b) the type of fibre and fibre-binding material, volume ratio of fibre, and type of surface treatment of FRP;
(c) numbers or identification marks of test specimens;
(d) the designation, nominal diameter, and maximum cross-sectional area;
(e) the date of test, test temperature, and loading rate;
(f) dimensions of test specimens and the bonded length of the FRP rod;
(g) the concrete mix, slump, and compressive strength at time of testing;
(h) the average bond stress causing slippage at the free end of 0.05 mm, 0.10 mm, and 0.25 mm for each test specimen;
(i) the average bond stress causing slippage at the loaded end at intervals from 0 to 0.25 mm for each test specimen;
(j) the maximum bond stress, failure mode, and averages for each test specimen; and
(k) the bond stress-slippage displacement (free end and loaded end) curves for each test specimen.

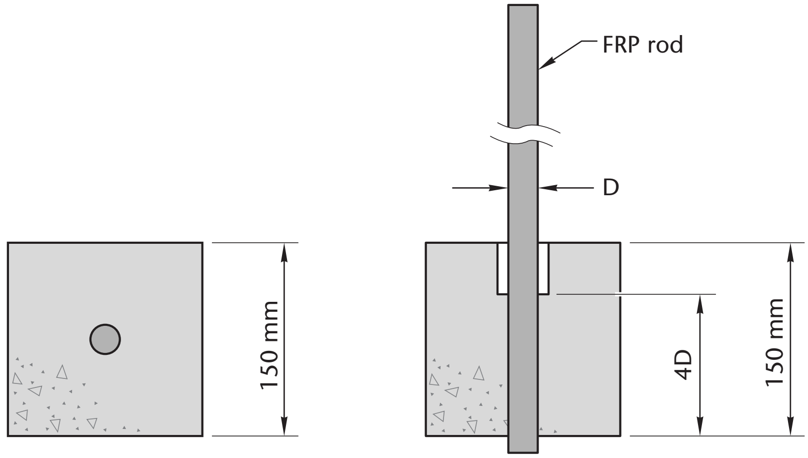


Figure H1
Vertical Bond Test Specimen
(See Clause H4.1.2.)

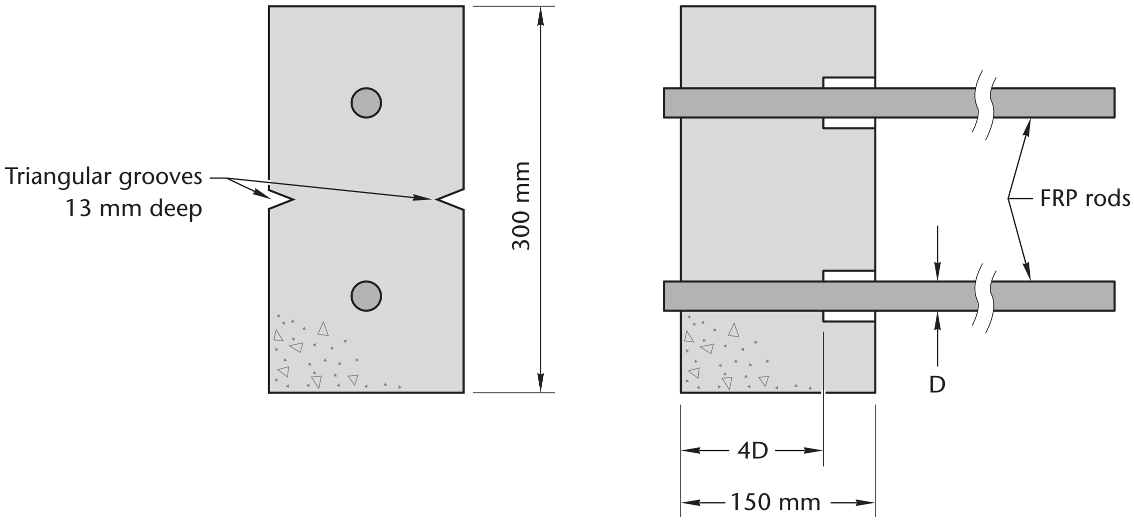
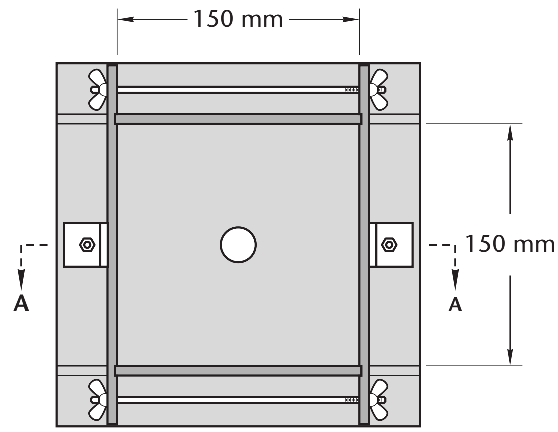
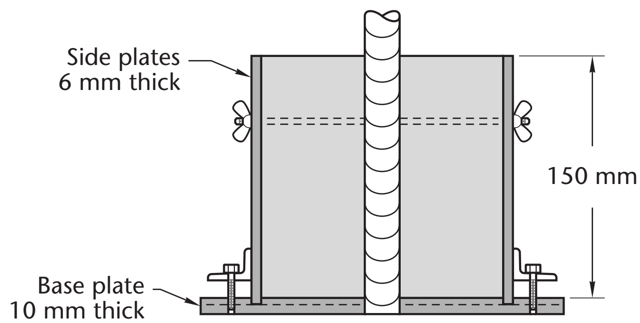


Figure H2
Horizontal Bond Test Specimen
(See Clause H4.1.3.)



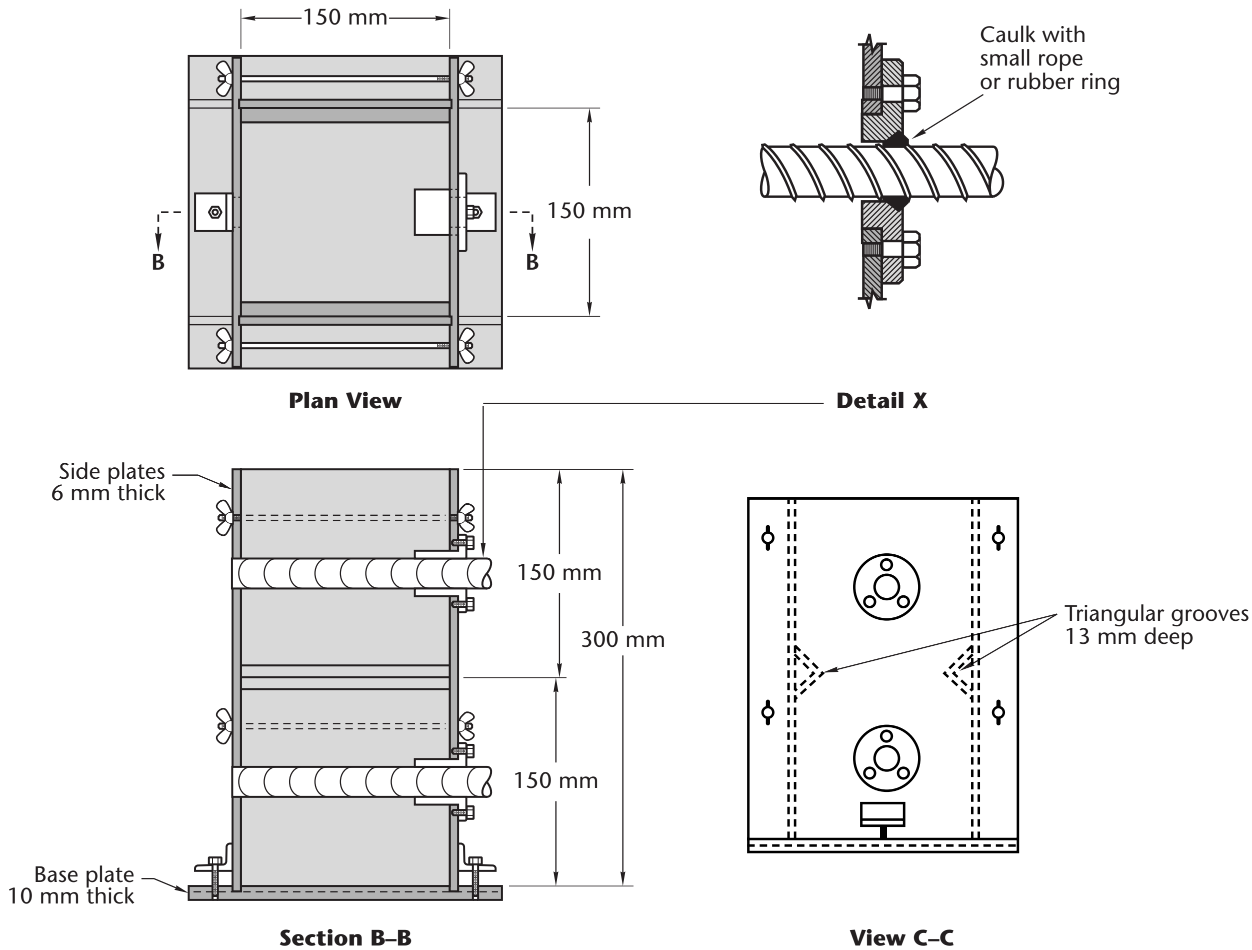
Plan View



Section A–A

Note: *This figure is based on a figure from ASTM Standard C 234.*

Figure H3
Mould for Bond Test Specimens for Vertical Bars
(See Clause H4.2.)



Note: *This figure is based on a figure from ASTM Standard C 234.*

Figure H4
Mould for Bond Test Specimens for Horizontal Bars
(See Clause H4.2.)

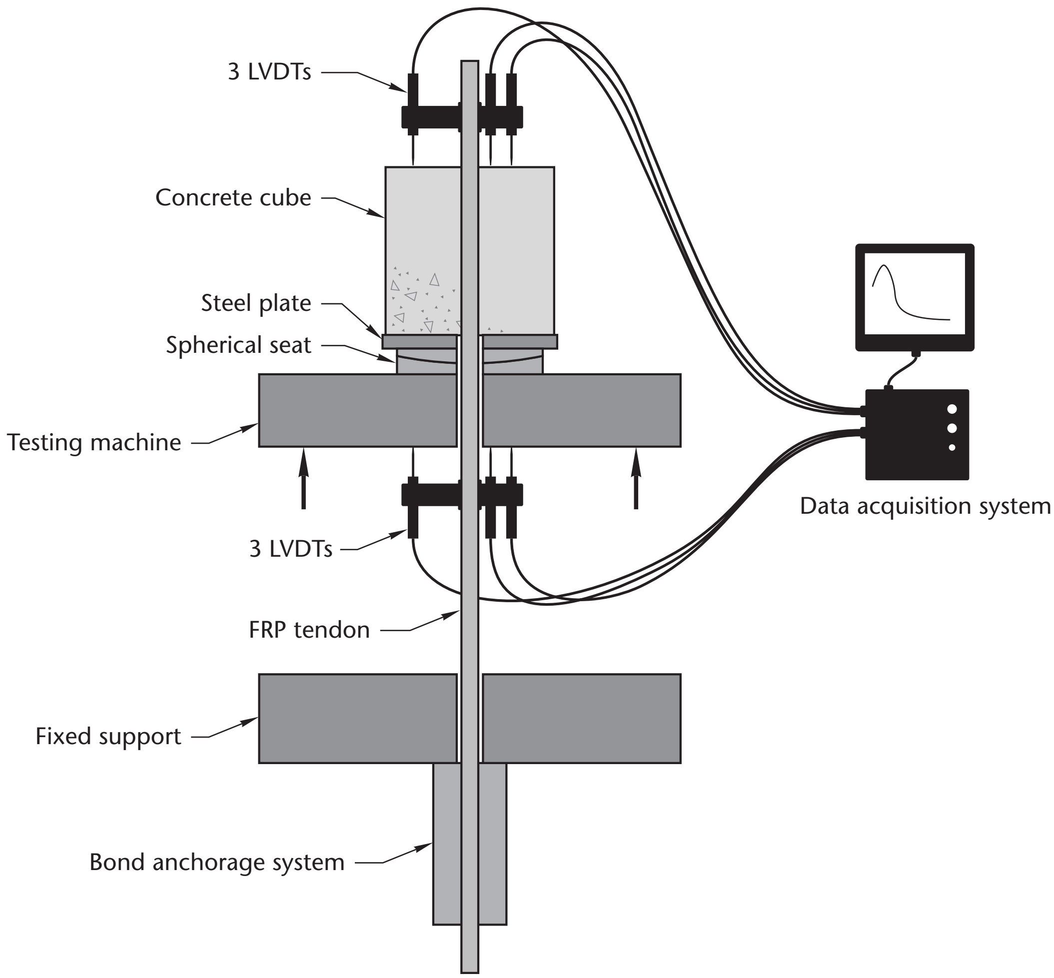


Figure H5
Bond Test Set-up
(See Clause H6.1.)

Annex J (Informative)
Test Method for Creep of FRP Rods

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

J1 Scope

This Annex specifies the test requirements to determine the creep properties of FRP rods used as reinforcing bars or prestressing tendons in concrete.

J2 Notation

The following symbols are used in this Annex:

A = nominal cross-sectional area of test specimen, mm^2
a, b = empirical constants
f_r = million-hour creep failure strength, MPa
F_r = million-hour creep failure capacity, N
T = time (hours)
Y = load ratio

J3 Significance and Use

J3.1

This test method for investigating creep failure is used to compare the creep behaviour of different FRP rods and is intended for use in laboratory tests in which the principal variable is the size or type of FRP rods.

J3.2

Unlike the creep failure of steel reinforcing bars or prestressing tendons subjected to significant sustained stress for long time periods, the creep failure of FRP rods may take place at levels below the static tensile strength; hence, the creep strength shall be evaluated when determining acceptable stress levels in FRP rods used as bars or tendons. Creep strength varies according to the type of FRP rods used.

J3.3

This test method measures the load-induced, time-dependent tensile strain at selected ages for FRP rods, under an arbitrary set of controlled environmental conditions and corresponding load rate.

J4 Terminology

The following definitions apply in this Annex:

Creep — the time-dependent, permanent deformation of an FRP rod subjected to a sustained load at a constant temperature.

Creep failure — the failure occurring in a test specimen due to a sustained load.

Creep failure capacity — the stress at which failure occurs after a specified period of time from initiation of a sustained load. In particular, the stress causing failure after one million hours is referred to as the million-hour creep failure capacity.

Creep failure strength — the stress causing failure after a specified period of time from initiation of a sustained load. In particular, the stress causing failure after one million hours is referred to as the million-hour creep failure strength.

Creep failure time — the lapsed time between the application of a sustained load and failure of the test specimen.

Creep strain — the differential change in length per unit length occurring in a test specimen due to creep.

Load ratio — the ratio of a constant sustained load applied to a test specimen to its tensile capacity.

J5 Specimen Preparation

J5.1
Test specimens shall be prepared and handled in accordance with Annex C of this Standard.

J5.2
The number of test specimens for each test condition shall not be less than five. If a test specimen fails at an anchoring section or slips out of an anchoring section, an additional test shall be performed on a separate test specimen taken from the same lot.

J6 Test Equipment and Requirements

J6.1
The testing machine shall be capable of maintaining constant, sustained loading during deformation of the test specimen.

J6.2
The anchorage shall be in accordance with Annex B of this Standard.

J6.3
The extensometer or strain gauge used shall be in accordance with Annex C of this Standard.

J6.4
The device for measuring the passage of time shall be accurate to within 1% of the elapsed time.

J6.5
The test temperature shall be 20 ± 2°C except for special circumstances.

J7 Test Method

J7.1
The mounting of the test specimen and the gauge length shall be in accordance with Annex C of this Standard.

J7.2
Test specimens shall not be subjected to any shock, vibration, or torsion.

J7.3
Creep test measurement shall begin at the moment that the test specimen has attained the prescribed load.

J7.4
Creep tests shall be conducted for not less than five values of load ratio. The load ratios chosen shall be between 0.2 and 0.8.

J7.5
For each value of load ratio, failure shall not occur in five test specimens after 1000 h of loading.

J7.6
It is preferable that creep strain be recorded automatically by a recorder attached to the testing machine. If a recorder is not attached to the testing machine, creep strain shall be measured and recorded at the following times after the prescribed load is attained: 1, 3, 6, 9, 15, 30, and 45 min; and 1, 1.5, 2, 4, 10, 24, 48, 72, 96, and 120 h. Subsequent measurements shall be taken at least once every 120 h.

J8 Calculations

J8.1
The material properties of the FRP rod shall only be assessed on the basis of the test specimen undergoing failure in the test section. In cases where tensile failure or slippage occurs at an anchoring section, the data shall be disregarded and additional tests shall be performed until the number of test specimens failing in the test section is not less than five.

J8.2
Data for test specimens that break at the start of loading shall be disregarded. In this case, the applied load and creep failure time shall be recorded but shall be excluded from the data. No additional tests shall be performed.

J8.3
For each test specimen, the load ratio-creep failure time curve shall be plotted on a semi-logarithmic graph, where the load ratio is represented on an arithmetic scale along the vertical axis and creep failure time in hours is represented on a logarithmic scale along the horizontal axis.

J8.4
A creep failure line chart shall be prepared by calculating an approximation line from the graph data by means of the least-square method according to Equation J-1:

$$Y = a - b\log T \qquad \textbf{(J-1)}$$

J8.5
The load ratio at one million hours, as determined from the calculated approximation line, shall be the creep failure load ratio. The load and stress corresponding to this creep failure load ratio shall be the

million-hour creep failure capacity and the million-hour creep failure strength, respectively. The million-hour creep failure strength shall be calculated according to Equation J-2, to three significant digits:

$$f_r = \frac{F_r}{A} \qquad \textbf{(J-2)}$$

J9 Report

The test report shall include the following items:
(a) the name of FRP rod;
(b) the type of fibre and fibre-binding material and the volume ratio of fibre;
(c) numbers or identification marks of test specimens;
(d) the designation, nominal diameter, and maximum cross-sectional area;
(e) the date of test and test temperature;
(f) the type and name of the testing machine;
(g) the type and name of the anchorage;
(h) the tensile capacity, average tensile capacity, and tensile strength for each test specimen;
(i) the load ratios and the creep failure time curve for each test specimen;
(j) the formula for derivation of approximation line; and
(k) the creep failure load ratio, the million-hour creep failure capacity, and the million-hour creep failure strength.

Annex K (Informative)
Test Method for Long-Term Relaxation of FRP Rods

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

K1 Scope
This Annex specifies the test requirements for evaluating the long-term relaxation behaviour of FRP rods used as reinforcing bars or prestressing tendons in concrete under a given constant temperature and strain. Tendon relaxation in prestressed concrete structures is an important factor to be considered in the design.

K2 Notation
The following symbols are used in this Annex:

a, b = empirical constants
T = time (hours)
Y = relaxation rate, %

K3 Significance and Use

K3.1
This test method for investigating long-term relaxation of FRP rods is intended for use in laboratory tests in which the principal variable is the size or type of FRP rods.

K3.2
This test method measures the load-induced, time-dependent tensile strain at selected ages for FRP rods in an arbitrary set of controlled environmental conditions and corresponding load rates.

K4 Terminology
The following definitions apply in this Annex:

Relaxation — the time-dependent decrease in stress in an FRP rod held at a given constant temperature and strain under a prescribed initial load.

Relaxation rate — the absolute value of the slope of the relaxation curve at a given time. In particular, the relaxation value after one million hours is referred to as the million-hour relaxation rate.

Tensile capacity — the average of the tensile failure loads determined on the basis of tests conducted in accordance with Annex C of this Standard.

K5 Specimen Preparation

K5.1
Test specimens shall be prepared and handled in accordance with Annex C of this Standard.

K5.2
The number of test specimens for each test condition shall not be less than five. If a test specimen fails at an anchoring section, or slips out of an anchoring section, an additional test shall be performed on a separate test specimen taken from the same lot.

K6 Test Equipment and Requirements

K6.1
The testing machine shall be capable of loading at a rate of 200 ± 50 MPa per minute and of sustaining the load while maintaining constant strain.

K6.2
The anchorage shall be in accordance with Annex B of this Standard.

K6.3
The accuracy of the initial load applied to the test specimen shall be as follows:
(a) for testing machines with loading capacity equal to or less than 1 kN: ±1.0% of set load; and
(b) for testing machines with loading capacity of more than 1 kN: ± 2.0% of set load.

K6.4
The accuracy of readings or automatic recordings of loads shall be within 0.1% of the initial load.

K6.5
The testing machine shall limit strain fluctuations in the test specimen to no more than $\pm 25 \times 10^{-6}$ throughout the test period once the strain in the test specimen has been fixed. If the FRP rod slips from an anchoring section, the slippage distance shall be compensated for so as not to affect the test results.

K6.6
If an extensometer or strain gauge is to be fitted to the test specimen, it shall be in accordance with Annex C of this Standard.

K6.7
The device for measuring the passage of time shall be accurate to within 1% of the elapsed time.

K6.8
The test temperature shall normally be 20 ± 2°C. Where the test results are heavily dependent upon temperature, additional tests shall be performed at –30°C and 60°C. In every case, temperature fluctuation over the test period shall be not more than ±2°C.

K7 Test Method

K7.1
Mounting of the test specimen and the gauge length shall be in accordance with Annex C of this Standard.

K7.2
If a strain gauge is to be attached to the test specimen, the test specimen shall be preloaded by applying a load of 10 to 40% of the prescribed initial load, after which the strain gauge shall be attached and correctly calibrated.

K7.3
The initial load shall be either 70% of the guaranteed tensile capacity or 80% of the million-hour creep failure capacity, whichever is less. Because the purpose of the test is to determine the relaxation rates required for design purposes, the initial load shall be set to the rate in actual service conditions. In some cases, this may result in a load that falls within a range where creep failure occurs but not failure due to relaxation. In such cases, it shall be confirmed under actual loading conditions that the load does not result in creep failure of the FRP specimens (the initial load being increased as necessary). Also, the initial load may be 75 + 2% of the tensile strength.

K7.4
The initial load shall be applied without subjecting the test specimen to shock or vibration. The specified rate of loading shall be 200 ± 50 MPa per minute. The strain on the test specimen shall be fixed after the initial load has been applied and maintained for 120 ± 2 s. The end of this period of sustained load shall be deemed to be the test start time.

K7.5
Load reduction shall generally be measured over a period of at least 1000 h. Preferably, load reduction shall be recorded automatically by a recorder attached to the testing machine. If no recorder is attached to the testing machine, strain relaxation shall be measured and recorded at the following times: 1, 3, 6, 9, 15, 30, and 45 min; and 1, 1.5, 2, 4, 10, 24, 48, 72, 96, and 120 h. Subsequent measurements shall be taken at least once every 120 h.

K8 Calculations

K8.1
The relaxation value shall be calculated by dividing the load measured in the relaxation test by the initial load.

K8.2
The relaxation curve shall be plotted on a semi-logarithmic graph where the relaxation value (%) is represented on an arithmetic scale along the vertical axis, and test time in hours is represented on a logarithmic scale along the horizontal axis. An approximation line shall be derived from the graph data by means of the least-squares method according to Equation K-1:

$$Y = a - b\log T \quad \textbf{(K-1)}$$

K8.3
The relaxation rate after one million hours shall be evaluated from the approximation line. Where the service life of the structure in which the FRP rods are to be used is determined in advance, the relaxation rate for the number of years of service life (service-life relaxation rate) shall also be determined.

K9 Report

The test report shall include the following items:
(a) the name of FRP rod;
(b) the type of fibre and fibre-binding material, and the volume ratio of fibre;
(c) the numbers or identification marks of test specimens;
(d) the designation, nominal diameter and maximum cross-sectional area;
(e) the date of test, test temperature, and temperature fluctuations;
(f) the type and name of the testing machine;
(g) the initial load and loading rate of initial load;
(h) the guaranteed tensile capacity and the ratio of initial load to guaranteed tensile capacity;
(i) the relaxation curve for each test specimen;
(j) the average relaxation rates at 10, 120, and 1000 h;
(k) the formula for determining the approximation line;
(l) the million-hour relaxation rate; and
(m) the relaxation rate corresponding to design service life (service-life relaxation rate), where applicable.

Annex L (Informative)
Test Method for Tensile Fatigue of FRP Rods

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

L1 Scope

L1.1
This Annex specifies the test requirements to determine tensile fatigue under constant tensile loading for FRP rods used as reinforcing bars or prestressing tendons in concrete.

L1.2
The test specimens shall be linear or grid FRP formed from continuous fibres in such a manner as to act mechanically as a monolithic body.

L1.3
Various versions of fatigue testing, such as tension-tension, tension-compression, compression-compression, are permissible. The test method given here is generic for evaluating material characteristics. The intended usage of the material shall guide the choice of fatigue test.

L2 Significance and Use

L2.1
This test method for investigating tensile fatigue is intended for use in laboratory tests in which the principal variable is the size or type of FRP rods.

L2.2
Fatigue properties of reinforced or prestressed concrete structures are an important factor to be considered in design. For FRP rods used as reinforcing bars or tendons, the fatigue behaviour shall be measured according to the method given in this Annex, in keeping with the intended purposes.

L2.3
The test method shall be capable of measuring the stress range and relevant numbers of cycles for FRP rods so as to establish the S-N curve under an arbitrary set of controlled environmental conditions and corresponding load rates.

L3 Terminology
The following definitions apply in this Annex:

Fatigue strength — the maximum cyclical stress at which the test specimen does not fail at a prescribed number of cycles.

Frequency — the number of loading or stressing cycles per second.

Number of cycles — the number of times the repeated load or stress is applied to the test specimen.

Repeated load or **stress** — load or stress alternating simply and cyclically between fixed maximum and minimum values.

Average load or **stress** — the mean value of the maximum and minimum repeated loads or stresses.

Load or **stress amplitude** — one-half of the load or stress range.

Load or **stress range** — the difference between the maximum and minimum repeated loads or stresses.

Load or **stress ratio** — minimum load or stress divided by maximum load or stress.

Maximum repeated load or **stress** — the maximum load or stress during repeated loading or stressing.

Minimum repeated load or **stress** — the minimum load or stress during repeated loading or stressing.

S-N curve — the graphical plot of the repeated load or stress along a vertical axis versus the number of cycles to fatigue failure (horizontal axis).

L4 Specimen Preparation

L4.1

The test specimen shall be prepared and handled in accordance with Annex C of this Standard.

L4.2

There shall be a minimum of five test specimens for each of at least three loading (stressing) levels. If a test specimen fails at an anchoring section or slips out of an anchoring section, an additional test shall be performed on a separate test specimen taken from the same lot.

L4.3

The total length of the specimen shall be $40d + 2L_g$ or greater, where d is the nominal diameter of specimen in mm, and L_g is the length of grip in mm.

L5 Test Equipment and Requirements

L5.1

The testing machine shall be capable of maintaining constant load (stress) amplitude, maximum and minimum repeated load (stress), and frequency. The testing machine shall be fitted with a counter capable of recording the number of cycles to failure of the test specimen. The load indicator shall be capable of measuring loads with an accuracy of not less than 1% of the load range.

L5.2

Anchorages shall be in accordance with Annex B of this Standard. Preferably, the same type of anchorage shall be used for all specimens in a given series of tests.

L5.3
If strain measurements are required as results of the fatigue tests, an extensometer or strain gauge capable of maintaining an accuracy of ±1% of the indicated value shall be used.

L5.4
The test temperature shall be within the range of 5 to 35°C. The specified test temperature for test specimens sensitive to temperature variations shall be 20 ± 2°C.

L6 Test Method

L6.1
The mounting of test specimens shall be in accordance with Annex C of this Standard.

L6.2
The load may be set in one of two ways: by fixing the average load and varying the load amplitude or by fixing the minimum repeated load and varying the maximum repeated load. The method adopted shall be determined according to the purpose of the test. In either case, a minimum of three load levels shall be chosen such that the range of number of cycles to failure is between 10^3 to 4×10^6. Typical S-N curves for FRP are used for maximum-minimum stress ratio, R, fixed at certain value as 0.1. In actual concrete structures subject to variable loads, permanent loads such as dead load weight may be considered the minimum load and the design load may be considered the maximum load.

The following procedure may be employed where the maximum stress level for the initial test is difficult to determine:

(a) An appropriate stress level shall be selected in the range 20 to 60% of the static tensile strength, and the fatigue test shall commence using this value as the repeated maximum stress.

(b) If the test specimen does not fail after 10^4 cycles at this repeated maximum stress, 5% of the static tensile strength shall be added, and the test shall be performed uninterruptedly using the same test specimen.

(c) If failure does not occur after 10^4 cycles following the procedure outlined in Item (b), a further 5% shall be added to the repeated maximum stress.

(d) The procedure outlined in Item (c) shall be repeated until specimen fails.

(e) The initial tensile-tensile fatigue repeated maximum stress shall be set at the repeated maximum stress level at which the test specimen fails, minus 5% of the static tensile strength. For prestressed tendons, the stress level may be in the range of 50 to 75% of the static tensile strength. However, for reinforced concrete rods, the stress level may be 10 to 20%.

L6.3
The frequency shall be within the range of 1 to 10 Hz and preferably close to 4 Hz.

L6.4
Static load shall be applied up to the average load, after which repeated loading shall begin. The prescribed load shall be introduced rapidly and without shock. The maximum and minimum repeated loads shall remain constant for the duration of the test. Counting of the number of cycles shall, whenever practicable, commence when the load on the test specimen has reached the prescribed load.

L6.5
Complete separation (breaking) of the test specimen shall be deemed to constitute failure. The number of cycles to failure shall be recorded. If the test specimen does not fail after 4×10^6 cycles, the test may be discontinued. A test specimen that does not fail shall not be counted or reused.

L6.6
Tests for each test specimen shall, whenever practicable, be conducted without interruption from the start of the test to the end of the test. When a test is interrupted, the number of cycles up to the time of interruption and the period of the interruption shall be recorded.

L7 Calculations

L7.1
Data for test specimens that slip from an anchoring section shall be disregarded in assessing the fatigue properties of FRP rods. In cases where tensile failure or slippage has occurred at an anchoring section, the data shall be disregarded and additional tests shall be performed until the number of test specimens failing in the test section or exceeding 2×10^6 cycles is not less than five.

L7.2
The S-N curve shall be plotted with maximum repeated stress, stress range, or stress amplitude represented on an arithmetic scale on the vertical axis, and the number of cycles to failure represented on a logarithmic scale on the horizontal axis. Where measurement points coincide, the number of coinciding points shall be noted. Right-facing arrows shall be added to indicate points from test results for test specimens that do not fail.

L7.3
The fatigue strength after 2×10^6 cycles shall be derived from the S-N curve. The fatigue strength shall be reported with a precision to three significant digits.

L8 Report
The test report shall include the following items:
(a) the name of the FRP rod;
(b) the type of fibre and fibre-binding material, and the fibre volume content;
(c) the numbers or identification marks of the specimens;
(d) the designation, nominal diameter, and maximum cross-sectional area;
(e) the date of test, the test temperature, and the humidity (from the commencement to the conclusion of the test);
(f) the maximum load (stress), minimum load (stress), load (stress) range, number of cycles to failure, and the frequency for each test specimen;
(g) a record of observed failure mode for each test specimen;
(h) the S-N curve; and
(i) the fatigue strength at 2×10^6 cycles.

Annex M (Informative)
Test Method for Coefficient of Thermal Expansion of FRP Rods

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

M1 Scope

M1.1
This Annex specifies the test requirements for measuring the coefficient of thermal expansion by thermal mechanical analysis of FRP rods used as reinforcing bars or prestressing tendons in concrete.

M1.2
The test specimens shall be linear or grid FRP formed from continuous fibre, in such a manner as to act mechanically as a monolithic body.

M2 Notation
The following symbols are used in this Annex:

ΔL_{refm} = difference in the length of specified test specimen for length calibration between temperatures T_1 and T_2. For apparatus in which the test specimen and specified test specimen for length calibration are measured simultaneously, $\Delta L_{refm} = 0$

ΔL_{spm} = difference in length of specimen between temperatures T_1 and T_2, µm

L_o = length of test specimen at room temperature, µm

T_1 = minimum temperature for calibration of coefficient of thermal expansion, °C

T_2 = maximum temperature for calibration of coefficient of thermal expansion, °C

α_{set} = coefficient of thermal expansion calculated for the specified test specimen for length calibration between temperatures T_1 and T_2, °C

α_{sp} = coefficient of thermal expansion, °C

M3 Significance and Use

M3.1
This test method for investigating the coefficient of thermal expansion is intended for use in laboratory tests in which the principal variable is the type of FRP rods.

M3.2
This test method measures the changes in length of a test specimen caused by changes in temperature in order to calculate the coefficient of thermal expansion.

M4 Terminology
The following definitions apply in this Annex:

Coefficient of thermal expansion — the dimensional change in length per unit length of a specimen per degree of temperature change. The mean of the given temperatures is taken as the representative temperature.

Thermal mechanical analysis (TMA) — a method for measuring the deformation of a material as a function of either temperature or time by varying the temperature of the material according to a calibrated program under a nonvibrating load.

TMA curve — a graphical plot of deformation (vertical axis) and temperature or time (horizontal axis).

M5 Specimen Preparation

M5.1

Prior to testing, test specimens shall be kept for a minimum of 24 h at a temperature of 20 ± 2°C and relative humidity of 65 ± 5%. The test specimens shall then be kept for 48 h at the maximum test temperature for dehumidification, de-aeration, and the elimination of strain resulting from bending.

M5.2

The test specimens shall be 20 mm in length, with a diameter for round specimens or a breadth for square cross-sections of no more than 5 mm.

M5.3

The number of test specimens shall not be less than five.

M6 Test Equipment and Requirements

M6.1

The thermal mechanical analysis apparatus used for testing shall be capable of operating in compression, maintaining a constant atmosphere around the test specimen, and raising the temperature of the test specimen at a constant rate.

M6.2

Sensitivity calibration of the displacement gauge shall be performed periodically using either an external micrometer or a micrometer attached to the testing machine. Calibration of the temperature gauge shall be performed using a pure substance of known melting point.

M6.3

The thermal mechanical analysis apparatus shall be installed in a location where it is not subjected to vibration during testing.

M7 Test Method

M7.1

The test specimen, the gauge rod (which is a control test specimen of a pure substance of known melting point used for calibration of the temperature gauge), and the test platform shall be cleaned, and the test specimen placed upright and bonded to the platform, if possible.

M7.2

The gauge rod shall be placed in the centre of the test specimen, with no pressure applied.

M7.3
The atmosphere around the test specimen shall consist of dry air (water content not more than 0.1% w/w) or nitrogen (water content not more than 0.001% w/w, oxygen content not more than 0.001% w/w) maintained at a flow rate of 50 to 100 ml/min.

M7.4
Load shall be gently applied to the tip of the gauge rod at room temperature. The temperature shall first be lowered to –30°C then raised to 0°C, and the displacement of the test specimen shall be recorded throughout the testing process. The procedure shall be repeated for temperature ranges from 0 to 30°C and from 30 to 60°C.

M7.5
The rate of temperature increase shall not be more than 5°C per minute.

M7.6
The compressive stress acting on the test specimen shall be 4 ± 0.5 MPa.

M8 Calculations

M8.1
The coefficient of thermal expansion of the test specimen within the measured temperature range (T_1,T_2) shall be calculated according to Equation M-1:

$$\alpha_{sp} = \alpha_{set} + \left(\Delta L_{spm} - \Delta L_{refm}\right)/\left[L_o \times (T_2 - T_1)\right] \quad \textbf{(M-1)}$$

M8.2
Each coefficient of thermal expansion shall be calculated to six decimal places (10^{-7}) and the average value reported with a precision to five decimal places (10^{-6}). If the average value is less than 1, it shall be reported with a precision to six decimal places (10^{-7}).

M9 Report
The test report shall include the following items:
(a) the name of the FRP rod;
(b) the type of fibre and fibre-binding material, and the volume ratio of fibre;
(c) numbers or identification marks of test specimens;
(d) the designation, nominal diameter, and maximum cross-sectional area;
(e) the date of test;
(f) the dimensions of test specimens;
(g) the pretest curing method;
(h) the type of testing machine;
(i) the type of ambient atmosphere during test and flow rate;
(j) the name of the substance used for temperature calibration, and the measurements taken;
(k) the type of specified test specimens for length calibration;
(l) the temperature range for which the coefficient of thermal expansion was measured, the representative temperature, and the heating rate;
(m) the thermal mechanical analysis curve for each test specimen; and
(n) the coefficient of thermal expansion for each test specimen and the average coefficient of thermal expansion and standard deviation.

Annex N (Informative) ***Test Method for Shear Properties of FRP Rods***

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

N1 Scope

This Annex specifies the test requirements for determining the shear properties of FRP rods used as reinforcing bars or prestressing tendons in concrete by direct application of double shear.

N2 Notation

The following symbols are used in this Annex:

A = nominal cross-sectional area of test specimen, mm^2
P = shear failure load, N
t = distance between shear faces
δ = gap between the two parts of the testing machine
τ = shear strength, MPa

N3 Significance and Use

This test method for shear strength is intended for use in laboratory tests in which the principal variable is the size or type of FRP rods. This test method establishes values of shear strength for comparison and may also be used for structural design purposes. It measures the shear capacity in FRP tendons in an arbitrary set of controlled environmental conditions.

N4 Specimen Preparation

N4.1

Whenever practicable, test specimens shall not be subjected to any processing. For grid-type FRP rods, linear test specimens may be prepared by cutting away extraneous material in such a way that it does not affect the performance of the part to be tested. Test specimens shall be as straight as possible; severely bent pieces shall not be used.

N4.2

During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, or other conditions capable of causing changes to material properties of the test specimen shall be avoided.

N4.3

Test specimens shall be of constant length, regardless of the nominal diameter of the FRP rods. Specimen length shall not be less than 5 times the shear plane interval and shall not be greater than 30 cm.

N4.4

The number of test specimens shall not be less than five. If a test specimen shows significant pull-out of fibres, indicating that failure was not due to shear, an additional test shall be performed on a separate test specimen taken from the same lot.

N5 Test Equipment and Requirements

N5.1
The testing machine shall have a loading capacity in excess of the tensile capacity of the test specimen and shall be capable of applying load at the required loading rate. The testing machine shall also be capable of accurately displaying load to within less than 1% error throughout the test.

N5.2
The two parts of the machine are the push-in cutting device and a test specimen holder.

N5.3
The shear testing apparatus shall be constructed so that a rod-shaped test specimen is sheared on two planes more or less simultaneously by two blades (edges) converging along faces perpendicular to the axis of the test specimen. The discrepancy in the axis direction between the upper and lower blades (δ) shall be within the range of 0 to 0.5 mm and shall be made as small as possible. The specification distance between shear planes, t, shall be 50 mm (see Figure N1).

N5.4
The test temperature shall be within the range of 5 to 35°C. The test temperature for test specimens sensitive to temperature variations shall be 20 ± 2°C.

N6 Test Method

N6.1
The test specimen shall be mounted in the centre of the shear apparatus, touching the upper loading device. No gap shall be visible between the contact surface of the loading device and the test specimen.

N6.2
The specified loading rate shall be such that the shearing stress increases at a rate of 30 to 60 MPa per minute. The load shall be applied uniformly without subjecting the test specimen to shock.

N6.3
Loading shall be continued until the test specimen fails. The failure load shall be recorded, with a precision of three significant digits. It should be noted that loading may decrease temporarily due to the presence of two rupture faces.

N7 Calculations

N7.1
Failure, whether it is due to shear or not, shall be determined by visual inspection. If pull-out of fibres, etc, is obvious, the data shall be disregarded and additional tests shall be performed until the number of test specimens failing due to shear is not less than three.

N7.2
Shear strength shall be calculated with a precision to three significant digits according to Equation N-1:

$$\tau = \frac{P}{2A} \qquad \textbf{(N-1)}$$

N8 Report

The test report shall include the following items:
(a) the name of the FRP rod;
(b) the type of fibre and fibre-binding material, and the volume ratio of fibre;
(c) the number or identification mark of test specimens;
(d) the designation, nominal diameter, and maximum cross-sectional area;
(e) the date of test, test temperature, and the loading rate;
(f) the interval between double shear faces;
(g) the shear failure load for each test specimen, average shear failure load, and shear strength; and
(h) the failure mode of each test specimen.

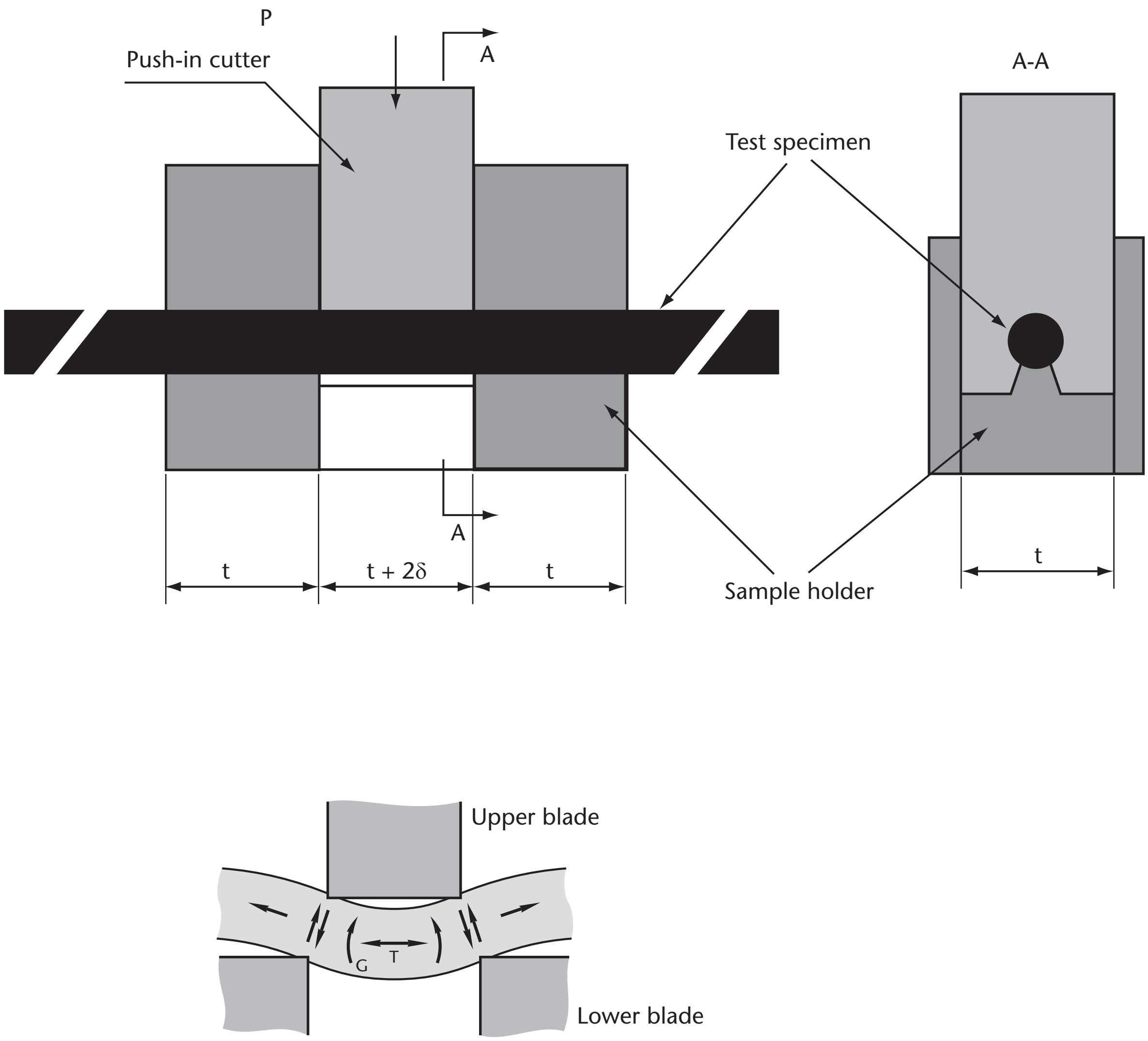


Figure N1
Double Shear Testing Machine
(See Clause N5.3.)

Annex O (Informative) **Test Method for Alkali Resistance of FRP Rods**

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

O1 Scope

This Annex specifies the test requirements for evaluating the alkali resistance of FRP rods used as reinforcing bars or prestressing tendons in concrete by immersion in an aqueous alkaline solution.

O2 Notation

The following symbols are used in this Annex:

F_{u1} = tensile capacity before immersion, N
F_{u2} = tensile capacity after immersion, N
Ret = tensile capacity retention rate, %

O3 Significance and Use

O3.1

This test method for investigating the alkali resistance of FRP rod is intended for use in laboratory tests in which the principal variables are the concentration of alkaline solution and the size or type of FRP rods.

O3.2

This test method measures tensile capacity retention by measuring the tensile capacity and the weight before and after immersion of an FRP rod.

O4 Specimen Preparation

O4.1

Bars 10 mm in diameter shall be used. Test specimens shall, whenever practicable, not be subjected to any processing. For grid-type FRP rods, linear test specimens may be prepared by cutting away extraneous material in such a way that does not affect the performance of the part being tested.

O4.2

During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, and other conditions capable of causing changes to material properties of the test specimen shall be avoided.

O4.3

The length of the test section for tensile testing shall not be less than 100 mm nor more than 40 times the nominal diameter of the FRP rod. For FRP rod in strand form, the length shall also not be less than two times the strand pitch. For the weight change test, the length of the test section shall be such that the outer surface area is not less than 45.6 cm^2, in accordance with ASTM Standard D 543.

O4.4
The number of test specimens for pre- and post-immersion tensile testing shall not be less than five. If a test specimen is found to have failed at an anchoring section or to have slipped out of an anchoring section, an additional test shall be performed on a separate test specimen taken from the same lot.

O4.5
The alkaline solution used for immersion shall have the same composition as the pore solution found in concrete. The recommended composition of alkaline solution is 118.5 g of $Ca(OH)_2$, 0.9g of NaOH, and 4.2 g of KOH in 1 L of deionized water.

O4.6
The test may also be performed on specimens embedded in concrete. The concrete mix and the curing procedure shall be in accordance with ASTM Standard C 511. Specimens shall be embedded in concrete for 28 days before testing. Dimensions of the concrete cylinder shall be as shown in Figure O1.

O4.7
In order to prevent the infiltration of solution via the ends of test specimens during immersion, both ends of a test specimen shall be coated with epoxy resin.

O4.8
The test specimen shall be mounted in the immersion apparatus. A tensioning load may be applied to the test specimen. The alkaline solution shall be prevented from absorbing CO_2 from the air and from the evaporation of water during immersion.

O5 Test Equipment and Requirements

O5.1
The testing machine and devices shall be in accordance with Annex C of this Standard.

O5.2
The test temperature shall be in accordance with Annex C of this Standard.

O6 Test Method

O6.1
The pH value of the alkaline solution shall be measured before and after the alkali resistance test.

O6.2
The specified temperature for immersion shall be 60°C.

O6.3
The test specimen shall be washed in water after removal from the immersion solution.

O6.4
The external appearance of the test specimen shall be examined before and after the alkali-resistance test, for comparison of colour, surface condition, and change of shape. If necessary, the test specimen may be sectioned and polished, and the condition of the cross-section examined with a microscope or other suitable instrument.

O6.5
For the weight-change test, the test specimen shall be dried at 105 ± 1°C before immersion and the mass shall be measured until unchanged (W_0). After immersion, the specimen shall be quickly washed with water, dried with tissue paper, and then immediately weighed (W_1). The specimen shall then be dried at 105 ± 1°C and the mass shall be measured until unchanged (W_2).

O6.6
For the tensile test, the test method shall be in accordance with Annex C of this Standard.

O6.7
The samples shall have one-month, three-month, and six-month tests. The samples shall be stressed during the test to a level of 1.1 times the design allowable strength at 60°C.

O7 Calculations

O7.1
The mass change of FRP rods shall be calculated according to Equation O-1 or O-2:

$$\text{Mass gain (\%)} = \frac{W_1 - W_0}{W_0} \times 100 \qquad \textbf{(O-1)}$$

$$\text{Mass gain (\%)} = \frac{W_0 - W_1}{W_0} \times 100 \qquad \textbf{(O-2)}$$

O7.2
The material properties of FRP rods shall be assessed only on the basis of test specimens undergoing failure in the test section. In cases where tensile failure or slippage has occurred at an anchoring section, the data shall be disregarded and additional tests shall be performed until the number of test specimens failing in the test section is not less than five.

O7.3
The tensile capacity retention rate shall be calculated according to Equation O-3, with a precision to two significant digits:

$$\text{Ret} = \frac{F_{u1}}{F_{u2}} \times 100 \qquad \textbf{(O-3)}$$

O8 Report
The test report shall include the following items:
(a) General items:
  (i) the name of the FRP rod;
  (ii) the type of fibre and fibre-binding material, and the volume ratio of fibre;
  (iii) the numbers or identification marks of test specimens;
  (iv) the designation, nominal diameter, and maximum cross-sectional area; and
  (v) the date of the commencement and conclusion of immersion;
(b) Items related to alkaline-solution immersion:
  (i) the composition of alkaline solution, pH, temperature, immersion period, and time;
  (ii) the tensile load and ratio of tensile load to nominal tensile capacity (if tension is not applied, this factor should be noted); and

(iii) the record of observation of external appearance and mass change; and

(c) Items related to tensile testing:
   (i) the test temperature and loading rate;
   (ii) the tensile capacities for immersed and non-immersed test specimens at the one-month, three-month, and six-month intervals, with averages and standard deviations of tensile capacities and tensile strength;
   (iii) the tensile rigidity, modulus of elasticity, and their averages for all immersed and non-immersed test specimens;
   (iv) the ultimate strain for all immersed and non-immersed test specimens and the average ultimate strain;
   (v) the tensile-capacity retention rate; and
   (vi) stress-strain curves for all immersed and non-immersed test specimens.

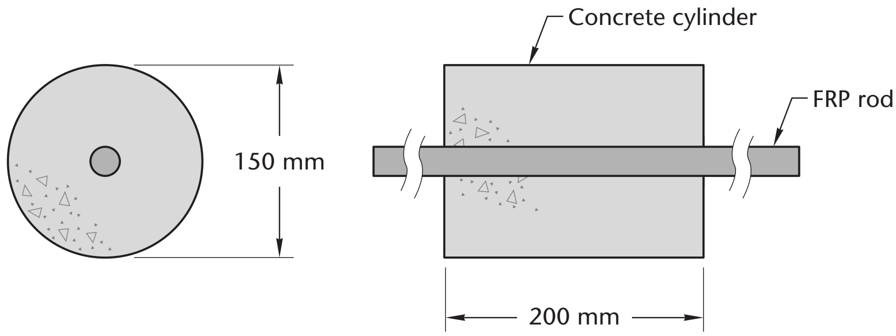


Figure O1
Dimensions of the Concrete Cylinder
(See Clause O4.6.)

Annex P (Informative)
Test Methods for Bond Strength of FRP Sheet Bonded to Concrete

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

P1 Scope

This Annex specifies two test methods for determining the bond strength of FRP sheets bonded to concrete. One is designed for use with a testing machine and the other for use without a testing machine.

P2 Notation

The following symbols are used in this Annex:

E_F = modulus of elasticity of FRP sheet
k = effective length multiplier
L = bond length
L_{cp} = concrete prism length
L_e = effective bond length
L_{ea} = anticipated effective bond length
P = measured ultimate load
t_F = FRP thickness
w = bond width

P3 Test Method A

P3.1 Apparatus

P3.1.1 Testing Machine

The machine shall generally conform to ASTM Standard E 4. The machine shall have a greater loading capacity than the expected strength of the specimen and shall preferably be equipped with either strain-rate or load-rate control.

Note: *Universal testing machines may not have enough clearance to accommodate the relatively long anchors required by specimens of high load capacity. Special testing frames may be required in such cases.*

P3.1.2 Specimen-Anchoring Devices

Any anchoring device may be used provided that it satisfies the following conditions:

(a) The load shall be transmitted to the specimen without any eccentricity or torsion.
(b) Failure shall occur in the bond of the specimen, not in the anchor.

P3.1.3 Load-Measuring Device

A built-in load cell in the testing machine shall be used. The load cell shall be compatible with the data acquisition system.

P3.1.4 Data Acquisition System

The system shall be capable of continuously logging load, strain, and displacement at a minimum rate of two readings per second. The minimum resolutions shall be 100 N for load, one microstrain for strain, and 0.01 mm for displacement.

P3.2 Specimens

P3.2.1 General

The test specimen shall be as shown in Figure P1. One end of the steel bar on each side shall be embedded in a concrete prism and the other end shall be gripped in a testing machine. The bars shall be embedded in spiral reinforcement with a diameter equal to 3 times the diameter of the bar. A metal sheet shall be placed in the centre of the prism, 25 mm away from the two faces that do not have the bonded sheets, as shown in section A-A in Figure P1. The FRP sheets are bonded on two opposite sides of the prism.

P3.2.2 Number of Specimens

A total of six specimens, one for each bond length, shall be prepared.

P3.2.3 FRP Reinforcement

FRP reinforcement shall be representative of the roll or batch being tested.

P3.2.4 Precautions

Throughout the process of specimen preparation and handling until testing, care shall be taken to prevent the cracking of the concrete at the metal sheet.

P3.2.5 Cross-Sectional Area

The cross-sectional area of the FRP sheet shall be taken as the width of the sheet multiplied by its thickness.

P3.2.6 Tensile Strength

The tensile strength of the FRP sheet shall be determined in accordance with Annex G of this Standard.

P3.2.7 FRP Sheet Dimension

The FRP sheet width shall be taken as 100 mm. The length shall be taken as kL_{ea}. The anticipated effective length, L_{ea}, shall be estimated using the following equation:

$$L_{ea} = \frac{25\ 350}{(t_F \times E_F)^{0.58}} \quad \textbf{(P-1)}$$

The six values of k for the different sheet lengths may be taken in increments of 0.2, from 0.6 to 1.6.

P3.2.8 Specimen Length

The total concrete prism length shall be taken as

$$L_{cp} = 3.2\,L_{ea} + 50\text{ mm} \quad \textbf{(P-2)}$$

P3.2.9 Concrete

The concrete shall have a 28 day cylinder strength of 30 to 35 MPa and shall be batched and mixed in accordance with the applicable portions of ASTM Standard C 192. The slump shall be measured and its ultimate strength determined after 28 days.

P3.2.10 Casting Specimens
The prism shall be cast with the steel bars in the horizontal position. Spirals, bars, and metal sheets shall be supported during casting so as to maintain a straight profile.

P3.2.11 Curing Specimens
One day after moulding, the prism shall be demoulded and transferred to a curing environment in accordance with ASTM Standard C 192.

P3.2.12 Bonding the FRP Sheets
On the 28th day after moulding, the FRP sheets shall be bonded according to the manufacturer's installation procedures. A minimum of 7 days of curing after the installation of the FRP sheets shall be required. The curing normally is carried out at a room temperature of around 20°C, unless otherwise specified by the FRP system provider.

P3.2.13 Anchoring Free End of Steel Bar
After curing, the specimens shall be anchored in the testing machine at the free end of the steel bar using an appropriate gripping system.

P3.3 Test Environment
Tests shall be carried out with the room temperature maintained at 20 ± 5°C and relative humidity at 50 ± 25%.

P3.4 Order of Testing Specimens
The specimen with an FRP sheet length of $0.6L_{ea}$ shall be tested first. Thereafter, specimens with longer sheet lengths shall be tested in sequence.

P3.5 Test Procedure

P3.5.1 Mounting Specimen
The specimen shall be carefully transported, lifted, and mounted on the testing machine in the position shown in Figure P1. Axial alignment of the anchor with the machine grips shall be checked and necessary adjustments to the position of the specimen made before the mortar bed sets.

Note: *Alternatively, the prism may be supported on a spherically seated bearing block.*

P3.5.2 Rate of Loading
The load shall be applied at a bond stressing rate of 0.5 MPa/min. For machines with displacement control only, a strain rate of 0.5 mm/min shall be used. If the testing machine is equipped with neither load nor displacement control, a timing device may be used to observe the time taken to apply a known increment of stress.

P3.5.3 Data Recording
If a data acquisition system is used, it shall be started a few seconds before the commencement of the loading.

P3.5.4 Safety Measure
Because some specimens may fail suddenly with the release of a substantial amount of energy, protective eyeglasses shall be worn by all testing personnel. Caution shall be used to prevent dropping of the specimen after failure.

P3.5.5 Test Termination

The test shall be terminated when either the FRP sheet ruptures or the FRP sheet debonds from the concrete.

P3.5.6 Rejection

If any test specimen shows partial debonding before testing, the specimen shall be discarded. If a specimen fails at the bonding surface instead of in the concrete, the test shall be rejected and the next specimen tested. If such rejection leads to uncertainty about the effective length, a new series of specimens shall be tested. The number of specimens in the new series may be reduced in accordance with the trend shown by the tests already completed.

P4 Test Method B

P4.1 Apparatus

P4.1.1 Hydraulic Jack Testing

The hydraulic jack shall have a loading capacity exceeding the expected strength of the specimen and preferably shall be equipped with strain-rate or load-rate control. The load shall be transmitted to the specimen without any eccentricity or torsion.

P4.1.2 Load-Measuring Device

Either a built-in device in the hydraulic jack or a load cell with adequate capacity shall be used. The device shall be compatible with the data acquisition system.

P4.1.3 Data Acquisition System

The system shall be capable of continuously logging load, strain, and displacement at a minimum rate of two readings per second. The minimum resolutions shall be 100 N for load, one microstrain for strain, and 0.01 mm for displacement.

P4.2 Specimens

P4.2.1 General

The isometric view of a test specimen and the set-up is shown in Figure P2. The specimen shall be a rectangular concrete block with a rectangular empty core. Metal sheets shall be placed in the centre along the width, 25 mm away from the inner side face of the specimen. A hydraulic jack placed in the centre of the empty core applies the load through a rigid steel plate fixed to the inner face of the specimen. The FRP sheets are bonded to the sides of the two arms of the specimen.

P4.2.2 Specimen Dimensions

The specimen dimensions shall be as shown in Figure P3.

P4.2.3 Number of Specimens

A total of 6 specimens, one for each bond length, shall be prepared.

P4.2.4 FRP Reinforcement

FRP reinforcement shall be representative of the roll or batch being tested.

P4.2.5 Precautions

Throughout the process of specimen preparation and handling until testing, care shall be taken to prevent cracking of the concrete at the metal sheets.

P4.2.6 Cross-Sectional Area
The cross-sectional area of the FRP sheet shall be taken as the width of the sheet multiplied by its thickness.

P4.2.7 Tensile Strength
The tensile strength of the FRP sheet shall be determined in accordance with Annex G of this Standard.

P4.2.8 FRP Sheet Length
The length of the FRP sheet shall be taken as kL_{ea}. The anticipated effective length, L_{ea}, shall be estimated using Equation P-1. The 6 values of k for the different sheet lengths shall be taken in increments of 0.2, from 0.6 to 1.6.

P4.2.9 Concrete
The concrete shall have a 28 day cylinder strength of 30 to 35 MPa. It shall be batched and mixed in accordance with the applicable portions of ASTM Standard C 192. Slump of fresh concrete shall be measured and its ultimate strength determined 28 days.

P4.2.10 Casting Specimens
The specimen shall be cast with the metal sheets in the vertical position. Bars and metal sheets shall be supported during casting so as to maintain a straight profile.

P4.2.11 Curing Specimens
One day after moulding, the specimen shall be demoulded and transferred to a curing environment as stipulated in ASTM Standard C 192.

P4.2.12 Bonding the FRP Sheets
On the 28th day after moulding, the FRP sheets shall be bonded according to the manufacturer's installation procedures. A minimum of 7 days of curing after the installation of the FRP sheets shall be required. The curing normally is carried out at a room temperature of around 20°C, unless otherwise specified by the FRP system provider.

P4.3 Test Environment
Tests shall be carried out with the room temperature maintained at 20 ± 5°C and relative humidity at 50 ± 25%.

P4.4 Order of Testing Specimens
The specimen with a FRP sheet length of $0.6L_{ea}$ shall be tested first. Thereafter, specimens with longer sheet lengths shall be tested in sequence.

P4.5 Test Procedure

P4.5.1 Mounting the Specimen
The specimen shall be carefully transported, lifted, and mounted on a flat smooth surface.

P4.5.2 Rate of Loading
The load shall be applied at a bond stressing rate of 0.5 MPa/min.

P4.5.3 Data Recording
If a data acquisition system is used, it shall be started a few seconds before the commencement of loading.

P4.5.4 Safety Measure
Because some specimens may fail suddenly with the release of a substantial amount of energy, protective eyeglasses shall be worn by all testing personnel.

P4.5.5 Test Termination
The test shall be terminated when either the FRP sheet ruptures or the FRP sheet debonds from the concrete.

P4.5.6 Rejection
If any test specimen shows partial debonding before testing, the specimen shall be discarded. If a specimen fails at the bonding surface instead of in the concrete, the test shall be rejected and the next specimen tested. If such rejection leads to uncertainty about the effective length, a new series of specimens shall be tested. The number of specimens in the new series may be reduced by utilizing the trend shown by the tests already completed.

P5 Calculations

P5.1 Effective Length
The effective length, L_e, of the FRP sheet shall be taken as the average of the bonded lengths of three consecutively tested specimens that failed at the same load capacity, within a tolerance of 10%.

P5.2 Bond Stress
The average bond stress shall be calculated as the load on the sheet divided by the effective bonded surface area of the FRP sheet as follows:

$$f_b = \frac{P}{L(w)} \qquad \textbf{(P-3)}$$

where
$L = L_e$ if $L \geq L_e$
$= L$ if $L < L_e$

P6 Report
The report shall include the following:
(a) properties of the concrete:
  (i) the mix proportions of cement, fine and coarse aggregates, and admixtures (if any used), and the water-cement ratio;
  (ii) the slump of freshly mixed concrete as determined in accordance with ASTM Standard C 143;
  (iii) the 28 day strength of control cylinders as determined in accordance with ASTM Standard C 138; and
  (iv) any deviation from the stipulated standards in such aspects as mixing, curing, dates of demoulding, and testing control cylinders;
(b) properties of the FRP sheet:
  (i) the product name, batch, and designation;
  (ii) a description of fabrication method and laying sequence;
  (iii) the test specimen dimensions and the number of specimens tested; and
  (iv) the modulus of elasticity and ultimate tensile strength determined in accordance with Annex G of this Standard;
(c) bond test results:
  (i) the type of test method used;

(ii) the test specimen dimensions;
(iii) the conditioning procedure used for specimens;
(iv) a description of the FRP fabrication method and laying sequence;
(v) the number of specimens tested;
(vi) the loading rate or strain rate of the tests;
(vii) the effective length and bond stresses;
(viii) the date of the test including specimen preparation dates; and
(xi) the test operator; and

(d) plots for each specimen tested, which shall include
(i) applied loads as the ordinate and the stroke of the jack as abscissa;
(ii) the maximum applied load from each specimen as the ordinate and the bond length of each specimen as abscissa;
(iii) a sketch and description of failure surface; and
(iv) a close-up photograph of the debonding surface.

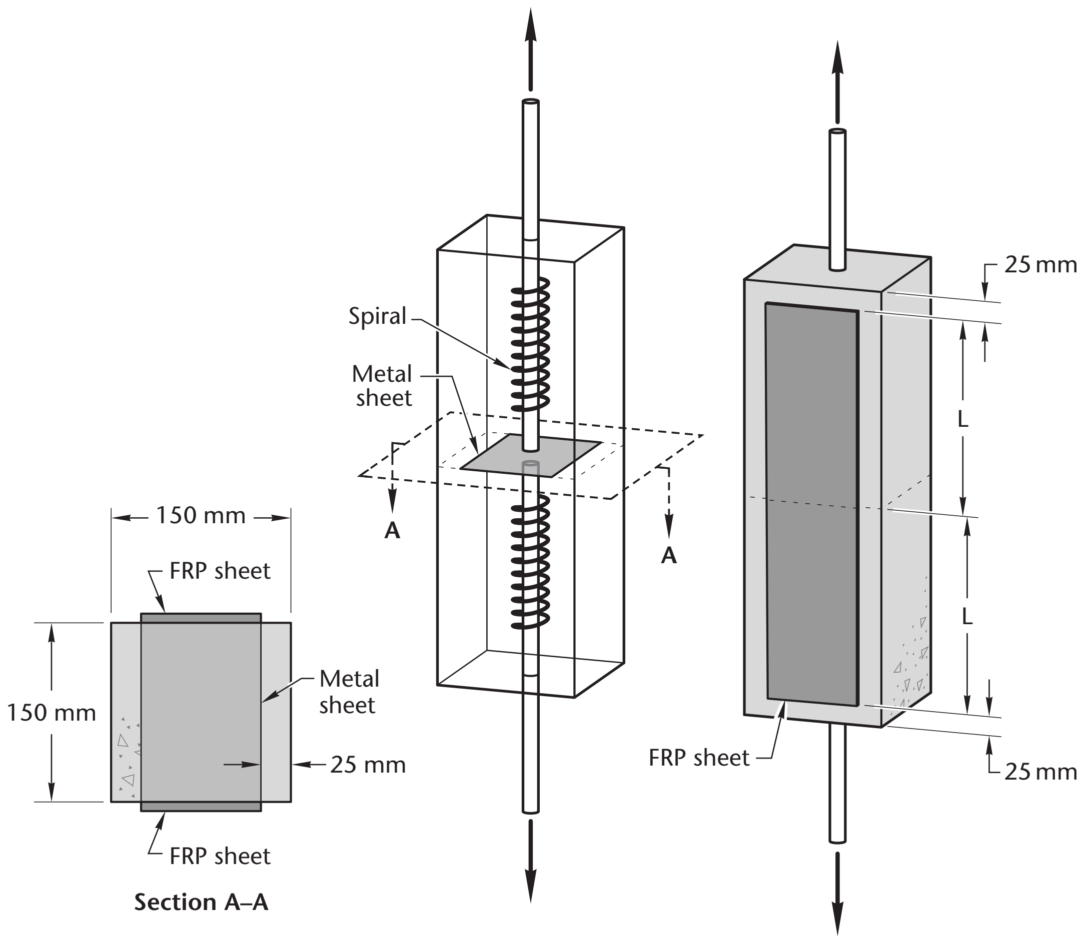


Figure P1
Pull Bond Test
(See Clauses P3.2.1 and P3.5.1.)

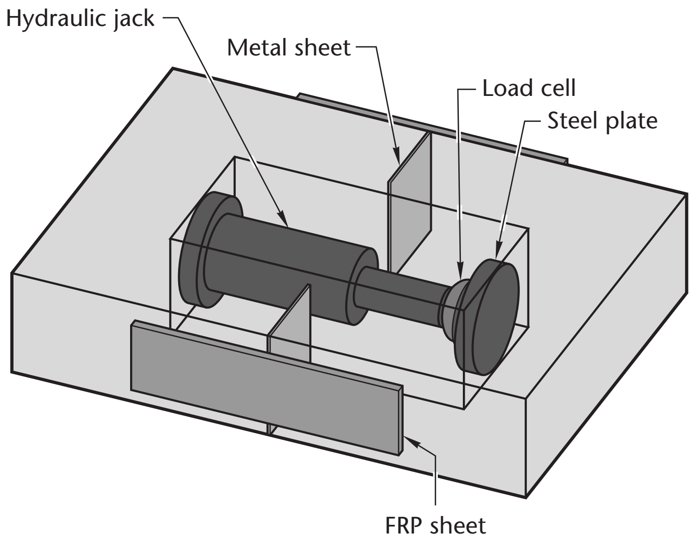


Figure P2
Push Apart Bond Test — Isometric View
(See Clause P4.2.1.)

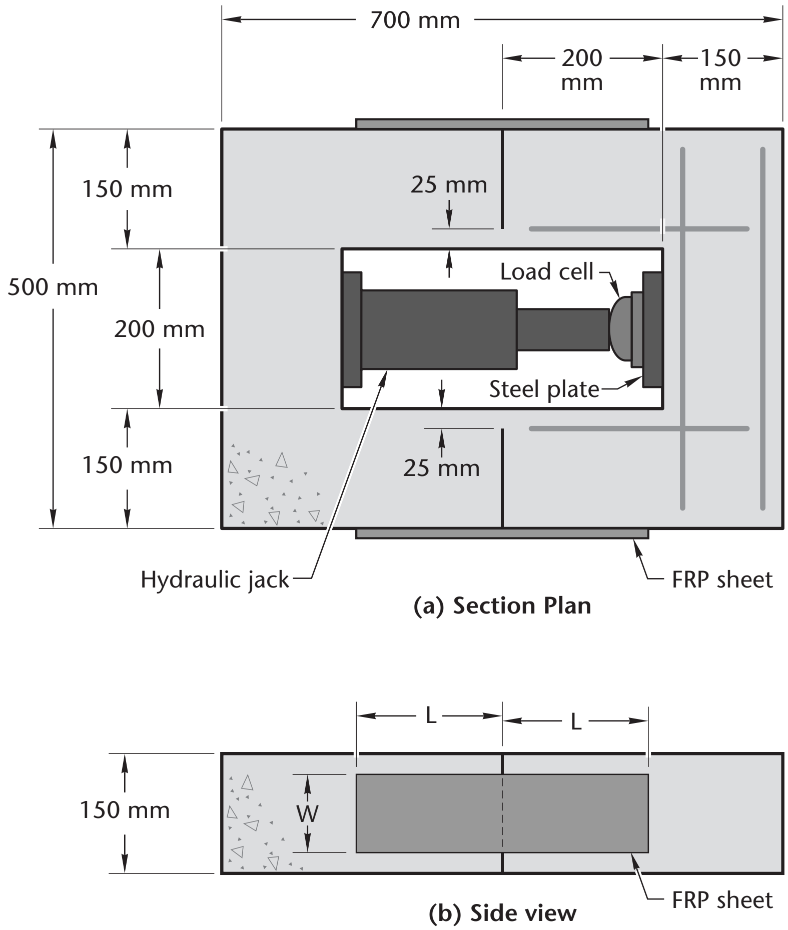


Figure P3
Push Apart Bond Test
(See Clause P4.2.2.)

Annex Q (Informative) **Test Method for Overlap Splice Tension Test**

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

Q1 Scope

This test method specifies the requirements for sample preparation and testing of overlap splices to determine splice tensile properties of unidirectional and bidirectional FRP materials used for external concrete reinforcement. It covers the determination of the overlap tensile (tensile shear) properties of resin matrix composites, reinforced by oriented continuous high-modulus (>69 GPa) fibres, to be used as external tensile reinforcement for concrete structures, and includes requirements for continuous reinforcing fibres at 0 degrees and continuous bidirectional fabrics at 0/90º.

Q2 Notation

The following symbols are used in this Annex:

f_{su} = average tensile shear strength
l = overlap length
P = failure load
w = specimen width

Q3 Referenced Documents

ASTM Standards D 3039, D 3165, and D 3528 provide standard test methods.

Q4 Summary of Test Method

The tension specimen shown in Figure Q1 shall be mounted in the grips of a self-aligning testing machine. A constant loading rate shall be applied to the specimen until failure. Strength of the overlap joint and mode of failure shall be noted.

Q5 Test Apparatus

The test apparatus shall be in accordance with ASTM D 3039.

Q6 Specimen Preparation

Q6.1 Field Preparation of Wet Layup Materials

Field specimens shall be made in a manner similar to the material used in actual field installation. A plastic sheet shall be placed on a smooth, flat, horizontal surface. The specified number of plies at the specified angles should be sequentially resin-coated and stacked on the plastic surface using the same amount of resin per unit area as will be applied in the actual installation. The overlap splice shall be constructed by carefully measuring the specified overlap length and placing the material accordingly. Grooved rollers or flat spatulas may be used to work out the trapped air in the laminate. Care shall be taken to ensure that the overlap ply does not slide during the rolling or screeding process. A second plastic sheet shall then be placed over the laminate, a smooth rigid flat plate placed on top of the plastic, and a weight placed on top of the plate. The weight shall be sufficient to produce a smooth surface upon cure but shall not cause significant flow of resin. After cure, the panel shall be cut and tabbed. For FRP systems requiring heat, pressure, or other mechanical/physical processing for cure, the engineer and material supplier shall agree on a representative specimen fabrication process.

Q6.2 Laboratory Preparation of Wet Layup Materials

A plastic sheet shall be placed on a smooth, flat, horizontal surface; resin shall be coated onto the film and the FRP fabric or sheet material placed in the resin. The overlap splice shall be constructed by carefully measuring the specified overlap length and placing the material accordingly. Additional resin shall then be overcoated. The process shall be repeated for multiple plies, if needed. A grooved roller may be used to work out trapped air. A second plastic sheet shall then be placed over the assembly. The flat edge of a small paddle excess resin shall be used to forcibly push out of the laminate with a screeding action in the fibre direction. Care shall be taken to ensure that the overlap ply does not slide during the rolling or screeding process. The laminate shall be cured without removing the plastic. Specimens shall be cut and tabbed after cure. Alternatively, specimens may be cut with a steel rule and utility knife after gelation but before full cure. For FRP systems requiring heat, pressure, or other mechanical/physical processing for cure, the engineer and material supplier shall agree on a representative specimen fabrication process.

Q6.3 Field/Laboratory Preparation of Precured FRP Laminates

Laminates shall be cut to size using an appropriate table saw. The mating surfaces of the lap joint shall be cleaned in accordance with the FRP manufacturer's directions. Resin/adhesive shall be applied to the mating surfaces, and the lap joint shall be measured, formed, and cured. Because laminate thickness is predetermined, specimen width and length may be altered by agreement between the engineer and laminate manufacturer. Care shall be taken to ensure that the specimen is flat because testing of nonflat specimens may result in lower tensile values due to induced moments.

Q6.4 Geometry

The test specimen shall be as shown in Figure Q1, with tabs bonded to the ends. Single-lap and double-lap geometry shall be permitted. Chamfering of the lap ends shall not be permitted unless similar configurations are used in the field. Table Q1 shows nominal specimen geometry for various overlap lengths. Variations in specimen width and thickness shall not be greater than ±1%.

Q6.5 Tabs

Moulded fibreglass and aluminum tabs shall be acceptable. The tabs shall be strain-compatible with the composite being tested. The tabs shall be bonded to the surface of the test specimen using a high-elongation (tough) adhesive system that will meet the temperature requirements of the test. The width of the tab shall be the same as the width of the specimen. The length of the tabs shall be determined by the shear strength of the adhesive, the specimen, or the tabs (whichever is lower), the thickness of the specimen, and the estimated strength of the composite. If a significant proportion of failures occur within one specimen width of the tab, there shall be a re-examination of the tab material and configuration, gripping method, and adhesive, and necessary adjustments shall be made in order to promote failure within the gauge section.

Q7 Conditioning

The test specimens shall be stored in an enclosed space maintained at a temperature of 23 ± 5°C and a relative humidity of 50 ± 10% and shall be tested in a room maintained at the same conditions.

Q8 Test Procedure

Q8.1

Measure the width and length of the overlap joint. Record the surface area of the joint.

Q8.2

Record the maximum load sustained by the specimen during the test and the failure mode of the specimen, according to the following definitions:

(a) Delamination/debond: the failure is a generally clean separation at the overlap interface;
(b) Tension failure: specimen fails outside of overlap splice at representative single laminate strength;
(c) Splitting: specimen fails along entire length, leaving portions of overlap bond intact;
(d) Tab failure: specimen fails in or close to tabs, usually at strength below single laminate strength; and
(e) any combination of the above failure modes.

Q8.3

The average tensile shear strength shall be calculated using the following equations, and the results reported with a precision of two significant figures:

For single lap

$$f_{su} = \frac{P}{wl} \quad \textbf{(Q-1)}$$

For double lap

$$f_{su} = \frac{P}{2wl} \quad \textbf{(Q-2)}$$

Q8.4

For each series of tests, the average value, standard deviation, and coefficient of variation shall be calculated.

Q9 Report

The report shall include the following:

(a) identification of the material tested;
(b) a description of the fabrication method and stacking sequence;
(c) the test specimen dimensions and overlap length;
(d) the conditioning procedure used;
(e) the number of specimens tested;
(f) the speed of testing if other than specified;
(g) the tensile shear strength, including the average value, standard deviation, and coefficient of variation;
(h) the date of the test; and
(i) the test operator.

Table Q1
Width and Gauge Lengths of Specimens

(See Clause Q6.4.)

Overlap length, mm	Specimen length, mm	Specimen width, mm
25	230	25
50	>254	25
76	>279	25
102	>305	25
152	>356	25
203	>406	25

Note: *Specimen orientation 0° or 0/90°.*

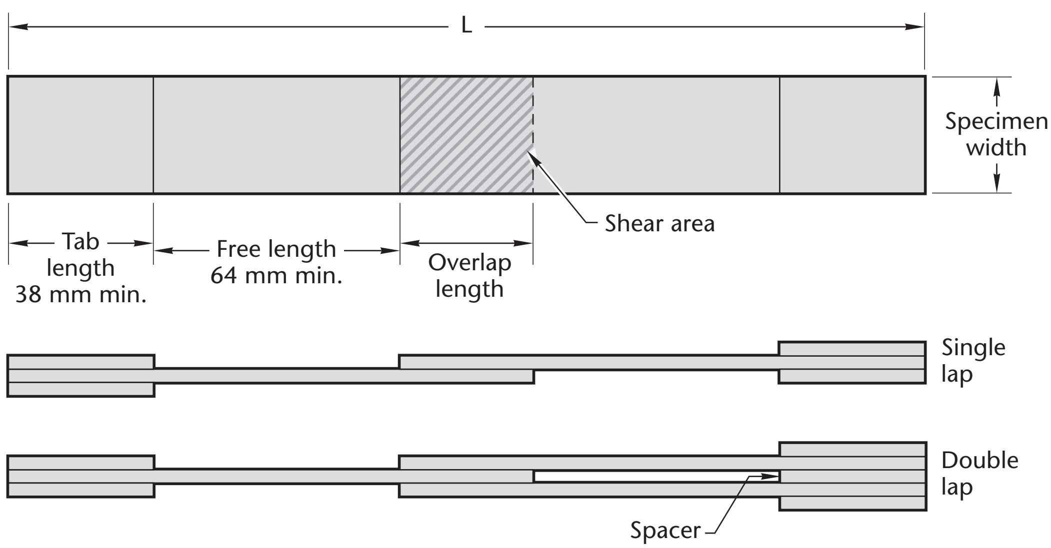


Figure Q1
Overlap Tension Specimen

(See Clauses Q4 and Q6.4.)

Annex R (Informative)
Fibre-Reinforced Concrete Cladding

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

R1 Fibre-Reinforced Concrete (FRC)

FRC substrate is produced by combining cementitious materials, granular materials, and water with additives and fibre reinforcement. This composite is referred to as fibre-reinforced concrete (FRC). If the reinforcement is a glass fibre, the combination is referred to as glass-fibre-reinforced concrete (GFRC). The general reference to FRC will be used throughout this Annex. Fibre reinforced concrete shall conform to the requirements of Clauses 7.3.2 and 7.3.3. Physical properties shall be tested in accordance with Clause 7.3.3.2 to determine compliance with the physical properties outlined in Clause 7.3.3 and this Annex.

R2 Materials and Composition of FRC

R2.1 General

The cementitious matrix shall consist of Portland cement, fibre reinforcement, sand, admixtures, and water, in accordance with the material requirements outlined in Clause 7.3.2.

Reinforcement used with cementitious formulations is required to increase the performance of these groups of composites. The physical properties required, such as high tensile and impact strength, will dictate the orientation of the reinforcing materials.

R2.2 Concrete Materials

R2.2.1 Cement

Portland cements and cementitious material conforming to CSA Standard CAN/CSA-A3000 are recommended for use in FRC. The producer shall have a choice of the type and kind of cement to use to achieve the specified properties of the product. Cements shall be selected to provide predictable strength and durability as well as proper colour. Cement performance can be influenced by atmospheric conditions, and the choice of cement has an influence on finishing techniques, mix design requirements, and spray-up procedures.

Cement used in face mixes or mist coats shall be controlled for colour uniformity. Cement shall be provided from one manufacturer using one colour, brand, and type, preferably from one production batch, throughout a given project. The use of white Portland cement will provide the most colour uniformity.

New cements are coming on the market that have been developed specifically for FRC. They have unique properties for the enhancement of FRC's long-term properties.

R2.2.2 Facing Materials

With FRC, any change in face mix materials or proportions will affect the surface appearance. If the face mix is exposed by sandblasting, retarders, or other means, the colour becomes increasingly dependent on the fine and coarse aggregates. A change in aggregate proportions, colour, or gradation will affect the uniformity of the finish, particularly where the aggregate is exposed.

Where fine and coarse aggregates are used for exposed finishes on the face of FRC panels, they should be clean, hard, strong, durable, inert, and free of staining or deleterious material. Aggregates shall conform to CSA Standards A23.1 and A23.4. Facing aggregate shall not exceed 10 mm. Aggregates shall be nonreactive with cement and available in particle shapes required for FRC. The method used to expose the aggregate in the finished product may influence the final appearance. Weathering of certain aggregates may influence their appearance over time.

Differential movements of facing materials may cause the FRC to reach critical strains beyond which the material will fail. Compatibility of the facing material to the backing shall be considered when developing mix designs. Veneers such as natural stone, thin brick, ceramic tile, or terra cotta may be used with care and particular attention as facing materials. A bond breaker with flexible mechanical anchors is recommended for use with natural stone in order to minimize panel bowing or high stresses in the FRC skin.

R2.2.3 Sand for FRC Backing

The use of properly graded silica sand in the FRC slurry reduces drying and shrinkage, thereby reducing the possibility of cracking and bowing due to shrinkage. Sands shall be washed and dried, shall be free of contaminants and lumps, and shall meet the compositional requirements of ASTM C 144.

A typical acceptable silica sand composition is:

(a) silica: 6–98%;
(b) soluble salts: 1% maximum;
(c) loss on ignition: 0.5% maximum; and
(d) clay and organic matter: 0.5% maximum.

R2.2.4 Admixtures and Curing Agents

Standard commercially available admixtures such as water reducers, accelerators, retarders, and air-entraining agents may be used to impart specific properties to FRC. Chemical admixtures shall conform generally to the requirements of ASTM Standard C 494, Types A, B, D, F and G, and air-entraining admixtures to ASTM Standard C 260. In addition, the use of a combination of admixtures shall be evaluated with the cement intended for use on the job.

R2.2.5 Mixing Water

Potable water free from deleterious matter that may interfere with the colour, setting, or strength of the FRC backing or face mix is recommended. (See CSA Standard A23.1, Clause 4.)

R2.3 Reinforcements

R2.3.1 General

Initial research on glass-fibre-reinforced cement or concrete (GFRC) took place in the early 1960s, and although the glass fibres lost their strength quickly due to the strong alkalinity of the cement-based matrix, continued research resulted in the development of the alkali-resistant (AR) glass fibre that is used today.

The chemical properties and composition of this AR glass are shown in Tables R1 and R2. It is noted that alkali-resistant glass fibre-reinforced concrete is by far the most widely used system for the manufacture of GFRC products.

R2.3.2 Alkali-Resistant Glass Fibre

Only high zirconia (minimum 16%) alkali-resistant glass fibres specifically designed for alkali resistance and use in concrete shall be used. Specifically, unprotected “E” glass, the type designed for use in reinforced plastic, shall not be used.

Alkali-resistant glass fibre reinforcement is available in roving, chopped strand, and scrim forms. The use of roving for spray-up and chopped strands for premix is most common, with scrim being used for selective reinforcement in areas of high stress concentrations.

Glass fibre lengths of 25 to 51 mm are most common in GFRC production. Lengths less than 25 mm are used for special situations (see Tables R1 and R2).

R2.3.3 Aramid Fibres
Aramid (aromatic polyamide) is a high-modulus synthetic polymeric material. In the form of a fibre, it has high tensile strength and high tensile modulus. Available data indicate that aramid FRC composites exhibit many desirable material properties but are more expensive than other fibres used in a similar application. However, where applications require strength, durability, and resistance characteristics, the additional cost may be justified.

The most common trade name for these fibres is Kevlar®. Mechanical properties of aramid fibres are shown in Table R3.

R2.3.4 Polypropylene Fibres
Polypropylene fibres have been incorporated into concrete in several forms and using several methods. The fibres can be incorporated into concrete as short, discrete chopped fibres (either monofilament or fibrillated tape), as a continuous network of fibrillated film, or as a woven mesh. The method of fabrication is obviously very much dependent on the form of the fibre. Typical properties of polypropylene fibres are shown in Table R4.

R2.3.5 Polyethylene Fibres
The only known technique to produce polyethylene-fibre-reinforced concrete has been one of adding the fibres during the concrete mixing operations. It was reported that polyethylene fibres could be easily dispersed in the concrete matrix in volume percentages up to 4% using conventional mixing techniques. Typical properties of polyethylene fibres are shown in Table R5.

R2.3.6 Polyester Fibres
Polyester fibres are generally added after all other concrete ingredients have been combined. Typically, these fibres are simply dumped into the concrete truck mixer at the batch plant or job site. The typical fibre dosage recommended by the manufacture is 0.89 kg/m^3, which is approximately 0.07% by volume. Typical properties of polyester fibres are shown in Table R6.

R3 Testing

R3.1 General
The manufacture of FRC products requires a greater degree of craftsmanship than that of conventional precast concrete. Therefore, it is important for manufacturers to implement an active quality control program that conforms to recognized standards.

The quality control program shall include inspections, tests of raw materials, and tests of the cured FRC. These tests are required to ensure a consistent and uniform manufacturing process. Properties of all materials used in the manufacture of FRC panels shall be verified by appropriate tests performed both in house and by an accredited testing laboratory.

In order to establish evidence of proper manufacture and conformance with plant standards and project specifications, a system of records shall be kept to provide full information on material tests, mix designs, FRC tests, inspections, and any other information specified for the project.

Each FRC panel shall be marked with an identification number referenced to the production and erection drawings and testing records. The date of manufacture shall be included. In the absence of specification requirements, records shall be kept for a minimum of two years after the structure has been completed and put into use.

R3.2 Acceptance Testing of Materials

R3.2.1 Cement
Plant testing of cementitious materials is not required if mill certificates are supplied with each shipment. All cementitious material shall meet the requirements of CSA Standard CAN/CSA-A3000.

R3.2.2 Glass Fibre

Plant testing of glass fibre is not required if the glass fibre strand is certified as being manufactured with an alkali-resistant glass produced using a minimum of 16% zirconia and conforms to the specification requirements contained in Table R1. Certificates shall be kept on file.

R3.2.3 Sand

Sieve analyses shall be conducted in accordance with CSA Standard A23.2, Method A23.2-2A, on samples taken from each shipment received at the plant.

R3.2.4 Facing Aggregates

Fine and coarse aggregates shall be regarded as separate ingredients, and each shall conform to the requirements for facing aggregates.

R3.2.5 Water

Water for use in precast concrete shall conform to the requirements of CSA Standard A23.1, Clause 4.

R3.2.6 Admixtures

Plant testing of admixtures is not required if certificates of compliance with appropriate requirements are supplied with each shipment. Instructions for admixture use shall be kept on file at the plant with the mill certificates. Admixtures for use in precast concrete shall conform to the requirements of CSA Standard A23.1, Clause 6.

R3.2.7 Curing Agent

Plant testing of curing agents is not required if curing agents are certified to conform to specification requirements. Curing agents are sensitive to freezing and shall be visually inspected for colour changes and/or coagulation upon delivery and prior to use. Certificates of compliance shall be maintained on file.

R3.2.8 Form Release Agents, Surface Retarders, and Sealers

Instructions for proper use and application shall be obtained from suppliers and kept on file at the plant for all such materials.

R3.2.9 Structural Shapes, Cold-Formed Steel, Hardware, and Inserts

Mill certificates for all of these items shall be obtained from the manufacturers and maintained at the plant. Hardware and miscellaneous materials for use in precast concrete shall conform to Clause 8 of CSA Standard A23.1 and Clause 8 of CSA Standard A23.4. Precast connection hardware shall be identified and located on the shop drawings. The owner shall specify corrosion protection adequate for the type of exposure and the design service.

R3.3 Production Testing

R3.3.1 Face Mixes

All face mixes shall be developed using the brand and type of cement, the type and gradation of aggregates, and the type of admixtures appropriate for use in production mixes. Face mixes shall be tested to determine volumetric changes due to moisture variation.

In addition, acceptance tests for face mixes shall include compressive strength, absorption, unit weight, and air content.

R3.3.2 GFRC Backing

Prior to design and production, a minimum of 20 unaged flexural strength tests (of six specimens each) produced on 20 separate days shall be conducted.

R3.3.3 Flex Anchor and Gravity Anchor Pull-off and Shear Tests

Prior to design and production, a minimum of 20 unaged strength tests of each type and size of anchor shall be conducted. The specimens and test procedures shall accurately simulate the various service conditions that are expected to be encountered during the life of the project.

R3.4 Production Testing of Aggregates

Aggregates for use in precast concrete shall conform to the requirements of CSA Standard A23.1, Clause 5; CSA Standard A23.4, Clause 5; and Clause R3 of this Standard.

R3.5 Production Testing — Wet

R3.5.1 Slurry Consistency Slump Test

Slurry consistency slump tests for each mixer shall be performed at the beginning of each shift. Alternatively, each mixer shall be equipped with an ammeter that indicates the relative resistance of the mixer motor. This is an advisory test performed at the discretion of the manufacturer.

R3.5.2 Slurry Unit Weight

The unit weight test (see ASTM Standard C 138) shall be performed once per day before starting production. The unit weight shall not vary more than 48 kg/m^3 from the established unit weight for the particular mix design in use. This is an advisory test performed at the discretion of the manufacturer.

R3.5.3 Slurry Temperature

Temperature shall be measured and recorded when test specimens are made, at frequent intervals in hot or cold weather, and at the start of operations each day. An armoured thermometer accurate to +1C° shall remain in the sample until the reading becomes stable. This is an advisory test performed at the discretion of the manufacturer.

R3.5.4 Spray Rate

The slurry flow rate (bucket test) and the fibre roving chopping rate (bag test) shall be used to determine if the fibre content being delivered by the spray equipment is within limits. The ratio of the fibre roving chopping rate to the slurry flow rate gives an indication of the fibre content. These tests shall be performed for each spray machine before starting production each day and after any extended shutdown. After the final setting of the fibre roving chopping rate, the length of any three fibres from the bag test shall be measured and shall be within 15% of the required length.

R3.5.5 Test Boards

Test boards shall be sprayed alongside of and in exactly the same way as the panel. The test board shall be lightly trowelled and be appropriately sized to provide two wash-out test specimens, six flexural test specimens, and anchor connection test specimens as required. As a minimum, one test shall be sprayed at least once per work shift per operator per spray machine per backing mix design. Each test board shall be marked with a unique identification number. The test boards shall be fabricated at a different time each day so that they represent the full range of production conditions and do not become part of a routine sequence of events.

Test boards manufactured with the panels shall be cured and stored in an environment similar to that of the panels until they are removed for testing. The elapsed time between removal of test board from this environment and testing shall be kept as short as possible.

The test board for a panel having a surface finish such as a mist coat or exposed aggregate shall be made without that surface finish but shall in all other respects duplicate the production panel.

R3.5.6 Washout Tests

The washout test is used to determine the glass fibre content of the backing. The average glass content determined by the washout test shall be recorded and be within the control limits of –0.5, +1.0% by weight of the mix. If either the spray gun calibration or spraying technique is modified, an additional washout test shall be performed.

The uniformity of glass distribution through the thickness (top to bottom) is important and can be checked by means of the washout test with split samples. This is an advisory test performed at the discretion of the manufacturer. If a dual head (rather than a concentric) spray gun is used (where the glass is sprayed into the slurry stream from one side), this test shall be performed weekly.

R3.5.7 Thickness

The skin thickness specified is the minimum for all points on the skin. Thickness of both the face mix and GFRC backing shall be checked with a suitable depth/thickness gauge, preferably a simple penetration gauge. A minimum of one thickness measurement per 0.5 m^2 of panel surface shall be made, with at least six measurements per panel. Bonding pad size, thickness, and compaction over anchors shall be visually checked. Bonding pad thickness over gravity anchors shall be checked with a penetration gauge at one-half or more of the anchor locations.

Additional thickness measurements shall be made at sensitive areas of the panel such as corners, reveals (false joints) and other breaks in plane surfaces, and attachment inserts. Inside corners shall be given special attention to ensure that thin areas, voids, and nonreinforced areas are not present. Thin areas shall be built-up by spraying fresh material into the area and not by transferring sprayed material from one part of the mould to another.

R3.5.8 Face Mix

Air content tests shall be conducted daily on mixes containing air-entraining admixtures.

R3.6 Production Testing — After Curing

R3.6.1 Backing Strength Tests

Flexural tests of the GFRC backing shall be performed at 28 to 30 days. Tests shall be performed each day for each operator, spray machine, and backing mix design. As variability in these factors decreases, as demonstrated by plotted test result data, the frequency of testing may be reduced to not less than one test per backing mix design per day. These reduced frequency tests shall be selected to check all operators and machines on a rotating basis, and the results of these tests shall be plotted daily to verify consistency of test results.

The strength level shall be considered satisfactory if both the following requirements are met:

(a) the average of all sets of three consecutive yield strength tests equals or exceeds the flexural yield strength, f_{yr}, and the average of all sets of three consecutive ultimate strength tests equal or exceed the flexural ultimate strength, f_{ur}, used in design; and

(b) no individual yield strength test is less than 90% of the f_{yr} used in design and no individual ultimate strength test is less than 90% of the f_{ur} used in design.

If any strength test falls below these requirements, the FRC design engineer shall take steps to ensure that the FRC panels represented by the test coupons are not jeopardized. The design engineer may request additional coupon testing from the same test board, have the panel load tested, have coupons cut and tested from suspect FRC panels, or take other appropriate action.

R3.6.2 Face Mix Strength Tests

Compressive strength tests of the face mix shall be conducted weekly in accordance with ASTM Standard C 39.

R3.6.3 Bulk Density and Absorption

These measurements shall be used to establish the level of compaction of the FRC and shall be performed weekly for each operator, spray machine, and backing mix design. A test sample (two specimens) shall be prepared from the test boards. Specimens may be taken from portions of actual flexural specimens.

R3.6.4 Flex Anchor and Gravity Anchor Pull-off or Shear Tests

Anchor connection tests shall be conducted on 300 x 300 mm minimum specimens cut from test boards. In order to confirm production values, two test specimens of one type and size of anchor shall be made from the test boards produced during a week. During the following weeks, additional types and sizes of anchors shall be tested so that all types and size of anchors are evaluated. Of the specimens produced during one week, two test specimens of an anchor type and size shall be randomly selected and tested at an age of approximately 28 days after the spray-up date. Manufacturers may develop alternate equivalent sampling procedures.

The anchor strength level shall be considered satisfactory if both of the following requirements are met:

(a) the average of all sets of three consecutive anchor strength tests equals or exceeds 1-2/3 times the P_u used in design; and

(b) no individual anchor strength test is less than 1-1/2 times the P_u used in design.

Bonding pad repair methods shall be evaluated and documented by test data.

R3.7 Design

The physical properties of GFRC depend greatly on the mix composition, glass fibre content, its length or orientation in the composite, and the overall quality of work during the manufacturing process.

The thickness of GFRC required in the design is determined by the panel design engineer. Because GFRC is a relatively thin material, even small thickness variations will have significant effects on skin stresses. Therefore GFRC thicknesses shall always be within the thickness tolerances specified.

In the design of GFRC cladding panels, the change over time of material properties and their performance in installations in a variety of climates shall be considered. A major aspect of the design of GFRC that shall be considered, in addition to external loads such as wind or gravity, is the reduction of restraint due to volume change, resulting from changes in moisture or temperature.

Determination of the design strength shall be based on test data provided by the manufacturer. The procedure for determining the ratio of test data to strength used in design is similar to the procedure for concrete.

For a full discussion on design, see Precast/Prestressed Concrete Institute (PCI) publication "Recommended Practice for Glass Fiber Reinforced Concrete Panels" and the Canadian Precast/Prestressed Concrete Institute (CPCI) *Design Manual*.

R3.8 Fabrication and Placement of Reinforcement

Fabrication and placement of reinforcement and prestressing tendons shall conform to the requirements of Clause 12 of CSA Standard A23.1 and Clause 12 of CSA Standard A23.4.

R3.9 Tolerances

R3.9.1

The tolerances of precast concrete work shall conform to the requirements of Clause 1 of CSA Standard A23.4.

R3.9.2 Wall Panels

For wall panels, refer to Clause 10.3 in CSA Standard A23.4.

R3.9.3 Joints

For tolerances in joints, Clause 10.6 in CSA Standard A23.4 shall be consulted. The design of the joints between GFRC cladding panels is an integral part of the total wall design. Requirements for joints shall be assessed with respect to both performance and cost. A joint width shall not be chosen for reasons of appearance alone: it shall relate to panel size, structure tolerance, anticipated movement, storey drift, joint materials, and adjacent surfaces. The joint can be expected to expand and contract up to 3 mm per 3 m of panel width (1:1000) as a result of moisture and thermal effects.

Movement capability is expressed as a function of the joint width when installed. Joint width shall be four times the anticipated movement unless a low modulus sealant is used, in which case joint width may be as narrow as twice the anticipated movement.

GFRC panels shall be designed to provide one and two-hour fire ratings as defined in ASTM Standard E 119. Joint details can be found in Chapter 4 of the CPCI *Design Manual.*

R3.10 Alternative Products

Other cementitious products are available as exterior cladding in the form of panels manufactured in flat or corrugated shapes.

The manufacturing technology uses asbestos-free fibre cement that consists of Portland cement, cellulose fibres, admixtures, and water. The fibres reinforce the cement, which allows for the manufacturing of large-size durable building panels that are formed, pressed, cut, and high-pressure cured in autoclave ovens. These panels are stabilized, moisture-resistant, noncombustible, rot-proof, rodent-proof, and maintenance free.

These panels are manufactured according to the following Standards:
(a) ULC Standard CAN/ULC-S102.2M;
(b) ASTM Standard E 84;
(c) ASTM Standard C 518;
(d) ASTM Standard C 531;
(e) ASTM Standard C 1185; and
(f) ASTM Standard D 1037.

Information on panel sizes, thicknesses, shapes, and colours, as well as installation instructions, are available from the manufacturers.

R3.11 Forms

Forms for precast concrete shall conform to the requirements of Clause 11 of CSA Standard A23.4.

Table R1
Chemical Composition of Selected Glasses, %
(See Clauses R2.3.1, R2.3.2, and R3.2.2.)

Component	A-glass	E-glass	AR-glass (Cem-FIL)
SiO_2	73	54	62
Na_2O	13	—	14.8
CaO	8	22	5.6
MgO	4	0.5	—
K_2O	0.5	0.8	—
Al_2O_3	1	15	0.8
Fe_2O_3	0.1	0.3	—
B_2O_3	—	7	—
ZrO_2	—	—	16.7
TiO_2	—	—	0.1

Table R2
Properties of Selected Glasses
(See Clauses R2.3.1 and R2.3.2.)

Property	A-glass	E-glass	AR-glass (Cem-FIL)
Specific gravity	2.46	2.54	2.70
Tensile strength, MPa	3 100	3 450	2 480
Modulus of elasticity, MPa	64 800	71 700	80 000
Strain at break, %	4.7	4.8	3.6

Table R3
Mechanical Properties of Aramid Fibres
(See Clause R2.3.3.)

Fibre	Tensile strength, MPa	Modulus of elasticity, MPa	Elongation at break, %
DuPont™ Kevlar® 29	3620	62 000	3.6
DuPont™ Kevlar® 49	3620	117 200	2.5
Teijin Technora®	3030	70 300	4.4

Table R4
Typical Properties of Polypropylene Fibre
(See Clause R2.3.4.)

Fibre	Specific gravity	Tensile strength, MPa	Modulus of elasticity, MPa
Polypropylene	0.9	550–690	3540

Table R5
Typical Properties of Polyethylene Fibre
(See Clause R2.3.5.)

Fibre	Specific gravity	Tensile strength, MPa	Modulus of elasticity, MPa
Polyethylene	0.96	200	5000

Table R6
Typical Properties of Polyester Fibre
(See Clause R2.3.6.)

Fibre	Specific gravity	Tensile strength, MPa	Modulus of elasticity, MPa
Polyester	1.34	900–1100	17 200

Annex S (Informative)
Fibre-Reinforced Polymer (FRP) Nonstructural Components

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

S1 Fibre-Reinforced Polymer Nonstructural Components

S1.1 General

The term "fibre-reinforced polymer composites" refers to thermoset resins, additives, catalysts, and reinforcements for strength. Most reinforcements are fibres, and most fibres are fibreglass. When the reinforcement is fibreglass, the finished product is referred to as fibreglass-reinforced polymers (FRP) or, in more general terms, reinforced plastic polymers composites (RP/C).

Additives are used to control the cure time, the viscosity, and other processing requirements. Other additives may be used to increase characteristics such as fire retardation, ultraviolet inhibition, and colour.

S2 Materials and Composition of Reinforced Polymer Composites

S2.1 Resin Paste

A resin paste may be prepared by using the specified resin and appropriate fillers to ensure that the finished paste will not flow out of the spaces being filled by the resin paste and that proper bonding to the surfaces in contact with the paste takes place.

S2.2 Fillers

Depending on the product being manufactured, the specified resin may be filled with ground-up laminates, gravel, chopped-up circuit boards, ground-up glass, and other material that does not dissolve in the unsaturated polyester/vinyl ester resin.

FRP is composed of two distinct materials: the matrix or resin and the reinforcement or glass fibre. The matrix used in architectural FRP consists primarily of thermosetting resin, but it may also contain functional fillers, flame retardants, colorants, or other performance-enhancing additives. The reinforcement generally consists of randomly dispersed chopped glass fibre or woven glass fabrics.

Most designers assume that FRP is an isotropic material and proceed accordingly, using primary mechanical properties, which for thin laminates in bending, are flexural strength and modulus of elasticity. For thin laminates in bending conditions, flexural strength and modulus are used. However, the assumption of isotropy is true at best only in the plane of the laminate, because the reinforcing fibres lie substantially in that plane. Out-of-plane properties may vary by an order of magnitude or more. The amount and orientation of the reinforcement fibre principally determine the mechanical properties.

Quasi-isotropic laminates containing randomly or multi-axially oriented fibres are the lowest cost and easiest to produce and hence most commonly used in FRP. The reinforcement is in the form of random chopped strands and/or fabrics. In these forms, the glass fibre content typically ranges from 20 to 40% by weight. In addition to providing mechanical strength, the fibre reinforcement also serves as a crack inhibitor. Hence, FRP exhibits very little notch sensitivity to either sustained or sudden impact loads.

S3 Physical Properties

S3.1 Tensile and Flexural Strength

Fibre content and orientation are the major factors that influence tensile and flexural strength. Orientation of some plies may be specified to deal with unidirectional loads. Quasi-isotropic laminates shall be deemed to exhibit up to 20% variation in mechanical properties when tested along different in-plane axes.

FRP laminates when stressed in plane shall be treated as linear elastic up to a brittle failure, and laminates that are repeatedly stressed shall be deemed to have 90% of the static strength.

S3.2 Modulus of Elasticity

The tangent of the tensile stress/strain curve shall normally be used as the modulus of elasticity for design purposes. For thin skins in bending, the flexural modulus may be used (it being noted that flexural modulus generally decreases with increasing temperature). Compressive modulus may be assumed equal to tensile modulus.

S3.3 Compressive Strength

Two compressive strengths shall be considered: in-plane and cross-plane. It should be noted that cored laminates sometimes fail in the in-plane compression mode when experiencing very large deflection and that both cross-plane and in-plane compression may be of concern in clamped joint designs.

S3.4 Shear Strength

In-plane, cross-plane, and interlaminar shear shall be considered. The following points shall be noted:
(a) in-plane shear measurements vary greatly with the test method;
(b) in-plane shear is usually considered with bolted joints, where tensile domain stress riser models are usually employed;
(c) cross-plane or punch shear is very dependent on reinforcement type and content;
(d) interlaminar shear is primarily dependent on the matrix; this type of shear is encountered in FRP joints and bonded structures; and
(e) although the interlaminar shear strength of FRP is very good, care should be taken to ensure that shear limited designs do not actually impose peel stresses.

S3.5 Volumetric Shrinkage

Because thermosetting resins shrink volumetrically upon curing, resulting in a linear shrinkage component, dimensional changes caused by shrinkage shall be allowed for in the mould.

S3.6 Moisture Absorption

Normally, dimensional change and stress due to moisture absorption need not be considered in design. Because of the low-moisture absorption and high strain at failure of FRP, its freeze-thaw performance is excellent; nevertheless, exterior parts shall be provided with drainage to eliminate standing water and thus prevent ice damage.

S3.7 Coefficient of Thermal Expansion

The coefficient of thermal expansion of FRP is comparable to that of aluminum and is influenced by the resin content. Allowances shall be made for differences between the thermal expansion of the FRP and that of adjoining or attached materials in order to avoid distortion or differential movement between components.

S3.8 Creep

Large-scale structural applications such as pressure vessels and radomes have demonstrated the capability of FRP to sustain loads over prolonged periods. Creep studies with composites have shown that these properties are controlled largely by the matrix. Normally polyester resins, which are crystalline polymers whose glass transition temperatures are usually well above the environmental temperature, shall be used so that creep will be much less than with many other building materials. Creep shall be carefully considered when the design includes bolted clamp joints in which the clamping force is a large fraction of compressive strength.

S3.9 Fatigue

Having been proven in service for automotive springs, helicopter rotors, pressure vessels, boat hulls, and aircraft structures, FRP is known to have an excellent life in cyclic and steady-state loading conditions and fatigue need not normally be considered. It is noted that tensile fatigue shows very little change in tensile strength except for a change in modulus of elasticity that is proportional to fatigue stress. Constant stress also reduces mechanical properties. The rate of reduction is related to the amount and type of stress, but in all cases the rate decreases and the stress reduction curve becomes asymptotic.

S3.10 Fire Performance

Because the organic portion of the matrix is a hydrocarbon, which under the proper conditions supports and maintains combustion, fire performance shall be considered. Several techniques are available to improve the flammability characteristics of FRP. The most common technique is to incorporate a halogen and synergist into the matrix. During ignition, the halogen and synergist smother the flame by eliminating oxygen from the combustion surface. Another technique involves the incorporation of hydrated fillers into the matrix. On heating, these fillers give up their water, thus quenching the combustion by heat removal and suffocation.

S3.11 Weathering

Weathering of FRP is related to degradation of the polymeric portion of the matrix by ultraviolet (UV) exposure. In some cases, UV exposure can cause embrittlement and micro-cracking in an unprotected laminate surface. The early stages of UV attack can cause colour shift or yellowing and gloss changes. FRP shall be protected from UV by an opaque gel coat surface, by painting the exposed surfaces, or by incorporating UV screens into the matrix. Of these techniques, gel coating is the most common because it provides the best surface finish and a deep 10 to 20 mm thick protective surface.

Gel coating is used by the marine industry to provide a durable, long-life finish on boat hulls. Factors influencing the weatherability of a gel-coated surface are the type of gel coat resin, the amount and type of fillers and colorants in the gel coat, and the coating thickness.

S3.12 Acoustical Properties

Being a composite of both low and high-modulus materials, FRP provides very good damping and attenuation of low- to mid-frequency sound waves. High-frequency sound waves are more likely to be reflected than absorbed.

S3.13 Density

The density of FRP shall be calculated by the rule of mixtures. The specific gravity for mixture components may be taken as follows:
(a) polyester resin: 1.2;
(b) glass fibre: 2.5; and
(c) typical filler: 2.3.

The typical density range for composites is 13.5 to 19.6 kN/m^3.

S3.14 Thermal Conductivity

The typical range of thermal conductivity is from 1.7 x 10^{-3} to 2.3 x 10^{-3} (W/cm•K). It is noted that low-density cores in FRP laminates can greatly reduce thermal conductivity.

S3.15 Electrical Properties
FRP is an excellent electrical insulator with good dielectric strength and a low loss factor. FRP is transparent to most electromagnetic fields. EMI shielding and reflectance can be provided by incorporating metallic fillers or fibres into the laminate.

S3.16 Bonding Properties
The bond strength between two FRP components or between an FRP component and metal, wood, or other attaching materials shall be determined using the lap shear criteria in ASTM Standard D 3164.

S3.17 Test Methods for FRP Materials
The test methods outlined in Table S1 shall be used, as needed.

S4 Exterior Cladding

S4.1 General
Many systems are used as exterior cladding, including composite panels, which are available as single panels or as completely installed systems. Exterior cladding may be used in both retrofit and new construction.

S4.2 Panels

S4.2.1 FRP Sheets
FRP panels shall be manufactured and tested according to ASTM Standard D 3841, which covers the classification, materials of construction, quality of work, physical requirements, and methods of testing glass-fibre-reinforced polyester plastic polymer panels intended for use in construction.

Installation of these FRP panels shall be as outlined in the manufacturer's instructions, depending on their use. The instructions specify the proper span lengths, gaskets, fasteners, and closure strips.

In general, corrugated FRP panels shall be installed in the same manner as other types of corrugated sheeting, with some precautions required in the cutting, drilling, laying, and fastening of these panels. The following points may be noted for guidance:

(a) FRP panels can be fabricated into virtually any desired configuration, from simple to complex, in various lengths, widths, and thicknesses, and in smooth or textured surface finishes with a variety of built-in colours available.

(b) Panels can be specially formulated to meet the flame-retardant requirements designated by various building codes, using test procedures developed by private organizations such as Underwriters Laboratories of Canada (ULC), to prove compliance with specific standards.

(c) Panels can be engineered to meet aesthetic requirements in architectural designs. They are weather-resistant and shatterproof, yet they can be opaque or translucent so as to permit the transmission of soft, nonglaring light as well as to provide excellent energy efficiencies.

S4.2.2 Composite Panels
A variation of the FRP panel involves a process where the finished product has an exposed aggregate facade. This product is usually composed of natural stone aggregate embedded in an integral glass-fibre-reinforced composite substrate material, made up of polyester resin and inorganic fillers in combination with a core material.

When such panels are used, the design framing requirements, fastening details, caulking, etc, shall be in accordance with the manufacturer's instructions.

Table S1
Test Methods for FRP Materials

(See Clause S3.17.)

Test description	ASTM Standard or other method
Mechanical properties	
Tensile strength	ASTM Standard D 638
Tensile modulus	ASTM Standard D 638
% elongation	ASTM Standard D 638
Flexural strength	ASTM Standard D 790
Flexural modulus	ASTM Standard D 790
Flexural strength-cored laminate	ASTM Standard C 393
Compressive strength	ASTM Standard D 695
Bearing load test	ASTM Standard D 1602
Punch shear test	ASTM Standard D 732
In-plane shear	ASTM Standard D 3846 or D 3914
Short beam shear	ASTM Standard D 2344
Izod impact	ASTM Standard D 256
Charpy impact	ASTM Standard D 256
Environmental	
Accelerated weathering test	ASTM Standard G 154 or D 4329
Humidity exposure	ASTM Standard D 2247
Corrosion testing	ASTM Standard C 581
Fire	
Surface burning characteristics	ASTM Standard E 84
Oxygen index	ASTM Standard D 2863
NBS smoke test	ASTM Standard E 662
Surface testing	
Gravelometer	SAE Standard J-400
Gardner gloss meter	Gardner
Stain resistance	ANSI Standard Z124
Physical properties	
Specific gravity	ASTM Standard D 792
Water absorption	ASTM Standard D 570
Barcol hardness	ASTM Standard D 2583
Materials properties	
Resin viscosity	Brookfield
Ignition loss of cured reinforced resin	ASTM Standard D 2584
Gel time	Room Temp./Cup
Weight per gallon	Gardner

Annex T (Informative) ***Procedure for the Determination of Concrete Cover for a Required Fire-Resistance Rating***

Note: *This Annex is not a mandatory part of this Standard. However, it has been written in mandatory terms to facilitate adoption where users of the Standard or regulatory authorities wish to formally adopt it as additional requirements to this Standard.*

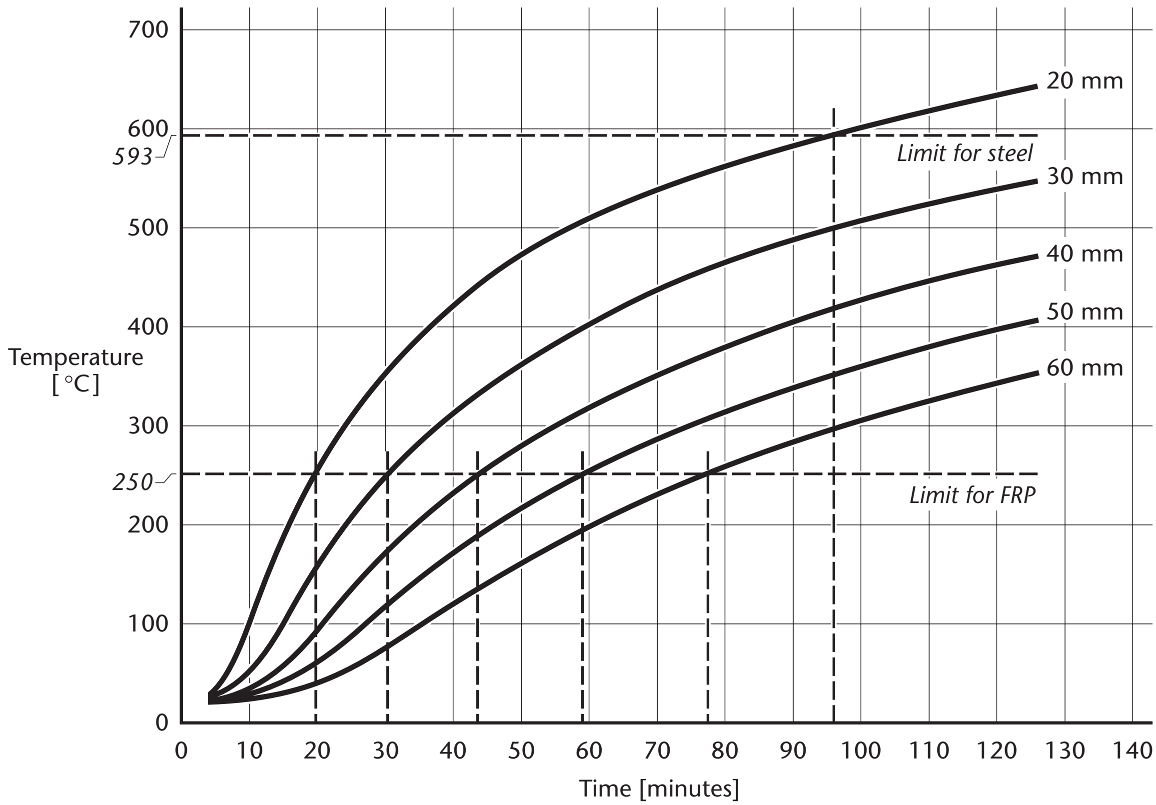
T1 Fire Resistance

The fire resistance of FRP reinforced concrete slabs can be determined in a similar way as that of steel-reinforced concrete slabs (see Appendix D of *National Building Code of Canada*). The methods of fire endurance tests given in UL Standard CAN/ULC-S101 are recommended. A parametric study conducted by Kodur and Baingo (1998) found that the fire resistance of FRP reinforced concrete slabs depends on the critical temperature of FRP reinforcement, the thickness of the concrete cover, and the type of aggregate in the concrete mix. The critical temperature is defined as the temperature at which the reinforcement loses enough of its strength (typically 50%) that the applied load can no longer be supported. T.T. Lie (1978) found that for reinforcing steel, the critical temperature is 593°C. For FRP reinforcement, however, the critical temperature depends on the type and composition of FRP, and hence it shall be obtained from the manufacturer's data.

Kodur and Baingo found that FRP reinforced concrete slabs made of carbonate aggregate concrete have about 10% higher resistance than those made with siliceous aggregate concrete. The definitions for the types of aggregate are provided in the *National Building Code of Canada*.

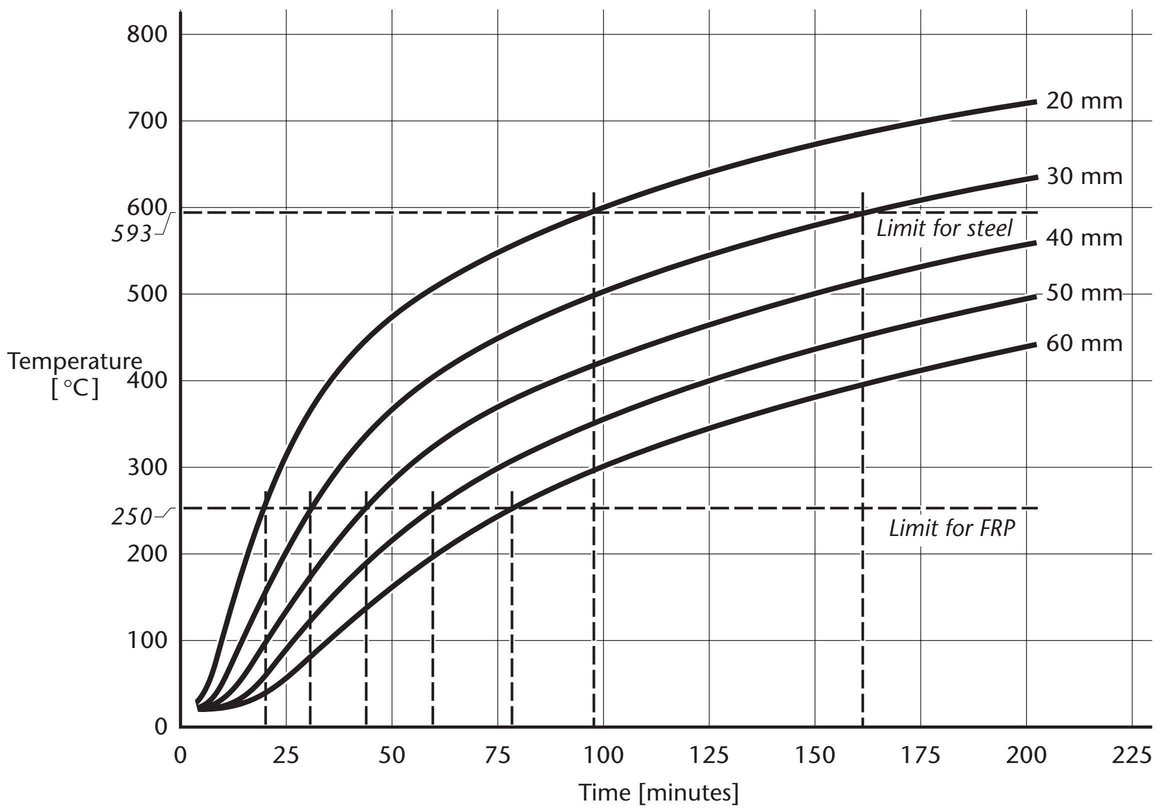
In lieu of actual test data, the fire resistance of FRP-reinforced concrete slabs can be established using the figures provided by Kodur and Baingo (see Figures T1 to T8) for a given critical temperature specified by the FRP manufacturers (in this case 250°C).

Alternatively, these figures can be used to obtain the relevant concrete cover thickness of FRP reinforcement for a required fire resistance rating. As an illustration, the required cover of reinforcement to obtain a fire resistance of 1 h in a 250 mm FRP reinforced concrete slab, made of carbonate aggregate concrete and with the critical temperature of FRP as 250°C, is 50 mm (see Figure T4). If the slab is made of siliceous aggregate, Kodur and Baingo's parametric study showed that the fire resistance would be about 54 min. Hence, a higher concrete cover thickness would be required to obtain a 1 h fire resistance rating. T.T. Lie is recommended reading for the calculation of fire resistance.



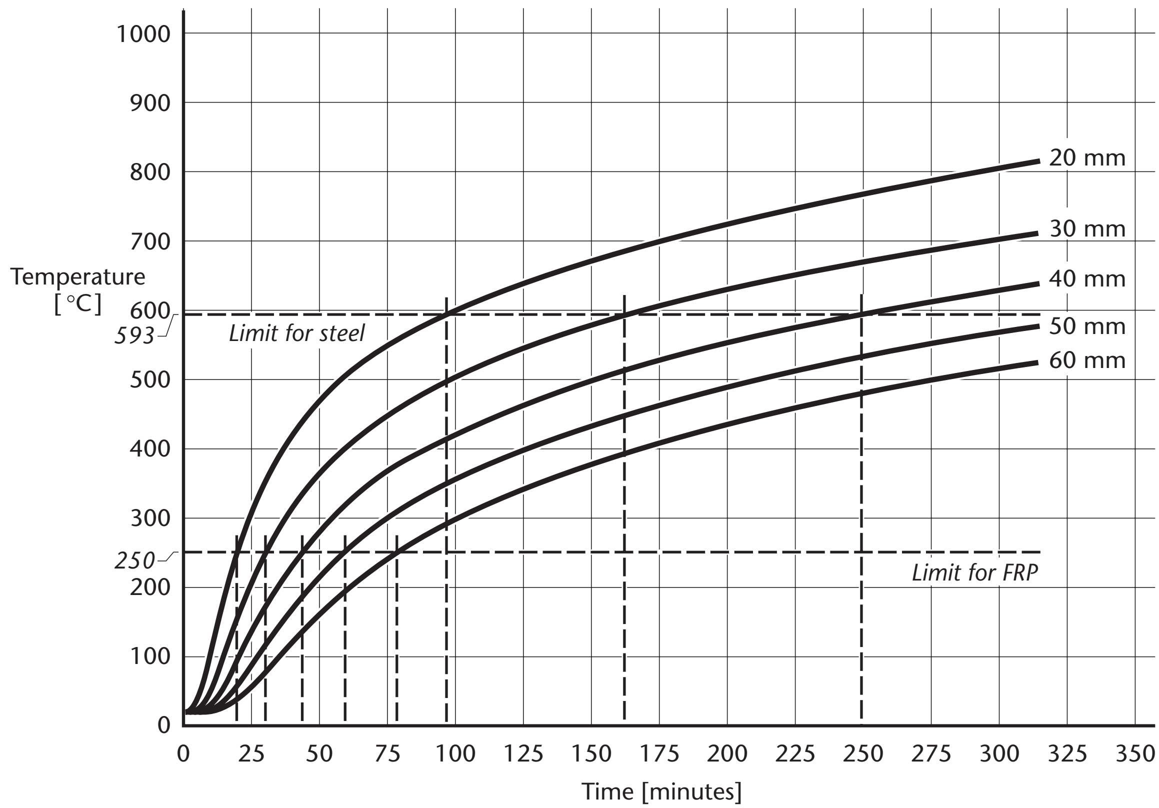
Note: *This figure is based on a figure from Kodur and Baingo (1998).*

Figure T1
Fire Resistance of 120 mm Concrete Slabs
(Carbonate Aggregate)
(See Clause T1.)



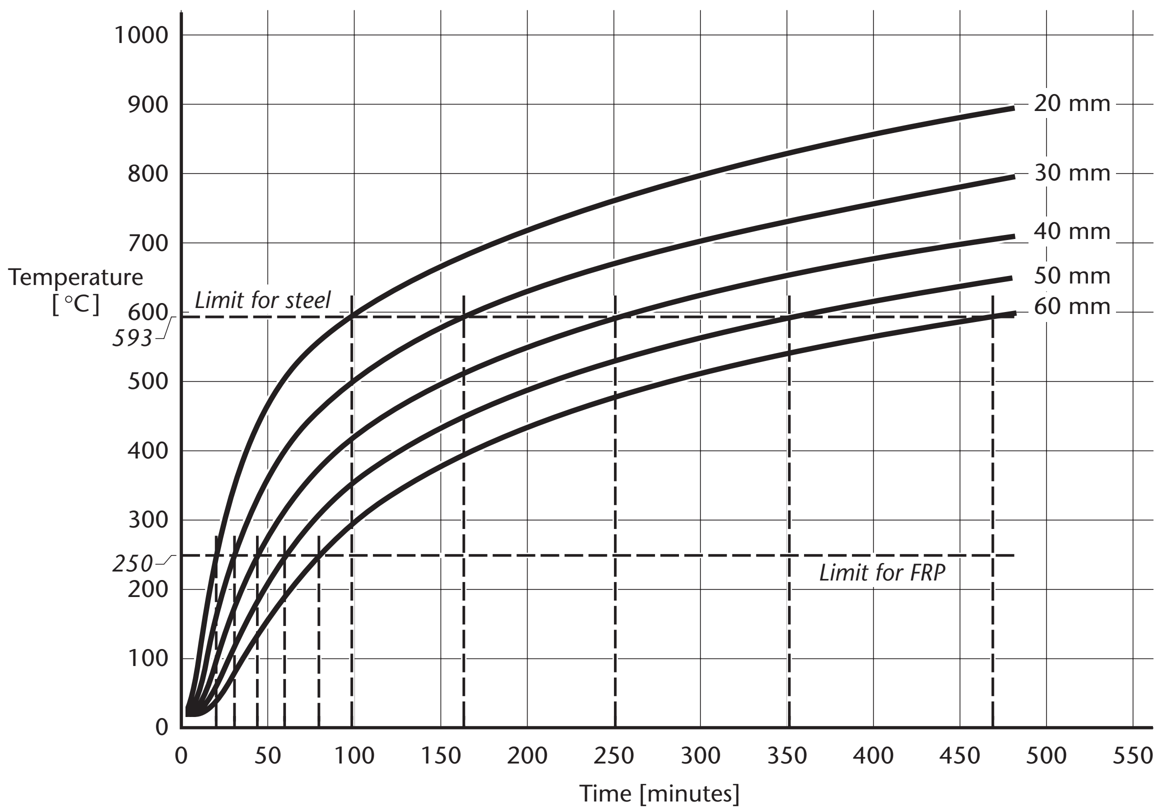
Note: *This figure is based on a figure from Kodur and Baingo (1998).*

Figure T2
Fire Resistance of 150 mm Concrete Slabs
(Carbonate Aggregate)
(See Clause T1.)



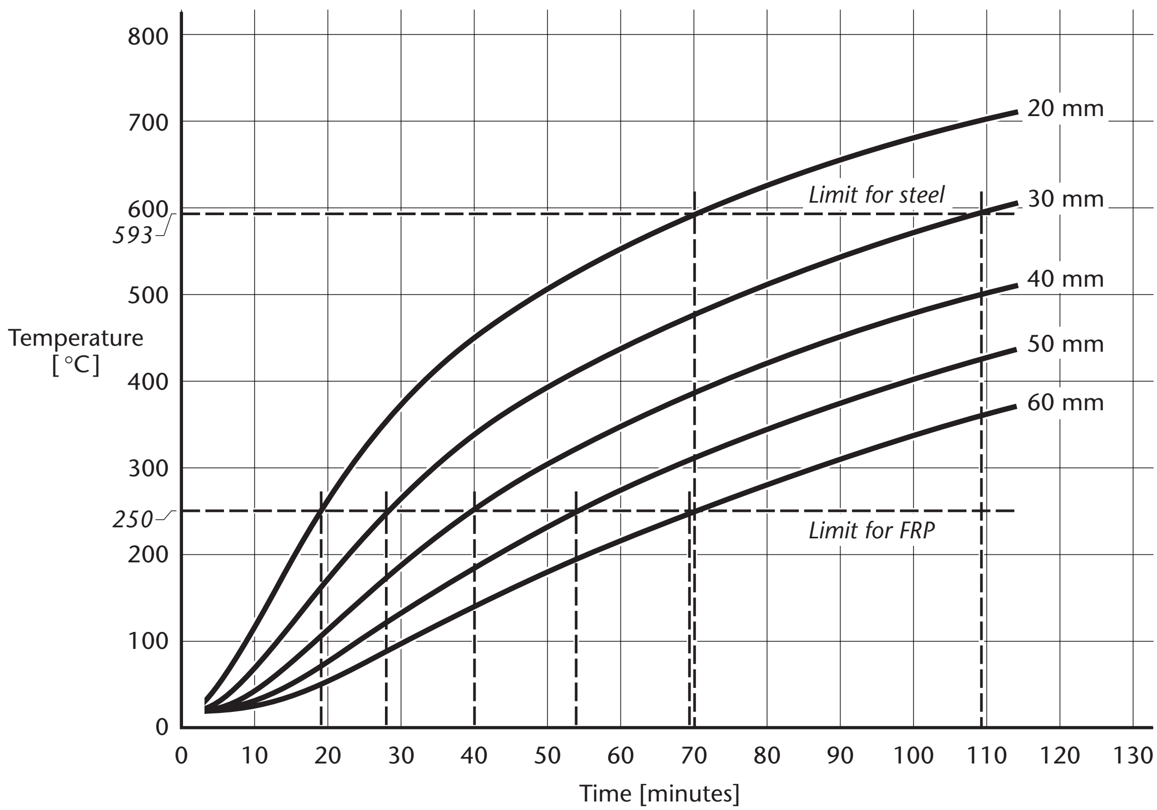
Note: *This figure is based on a figure from Kodur and Baingo (1998).*

Figure T3
Fire Resistance of 180 mm Concrete Slabs
(Carbonate Aggregate)
(See Clause T1.)



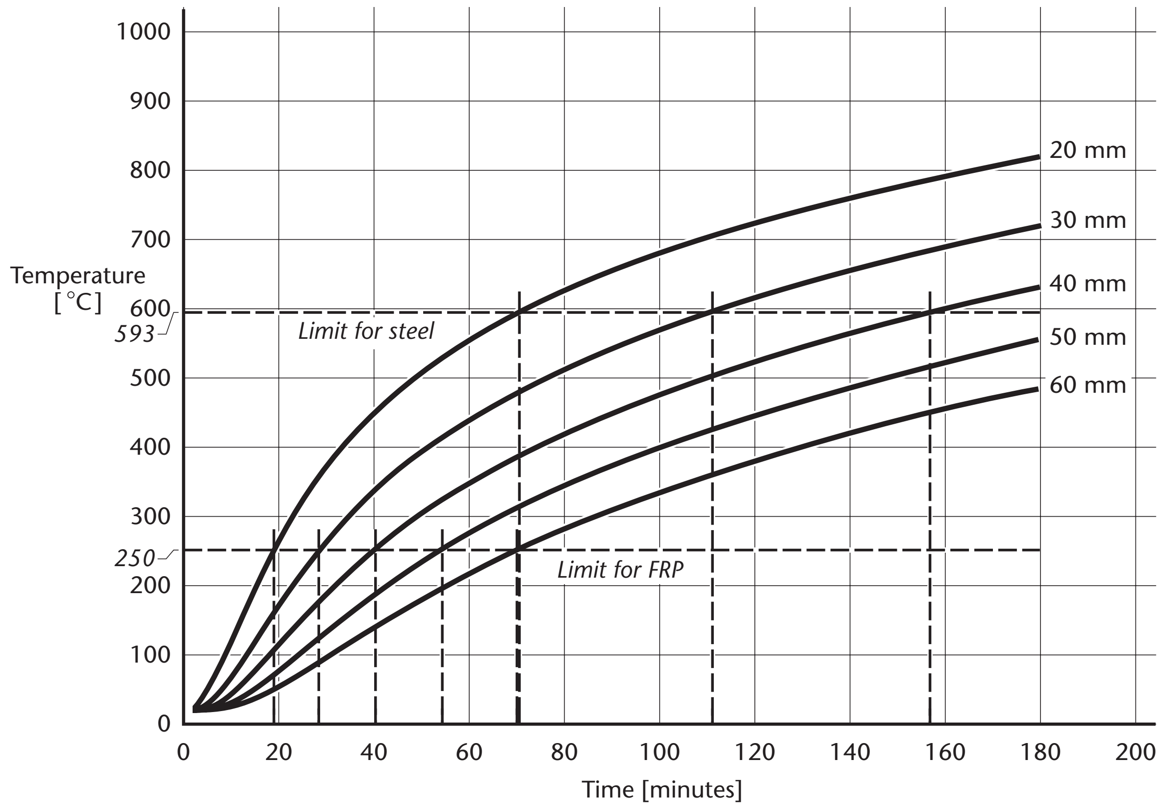
Note: *This figure is based on a figure from Kodur and Baingo (1998).*

Figure T4
Fire Resistance of 250 mm Concrete Slabs
(Carbonate Aggregate)
(See Clause T1.)



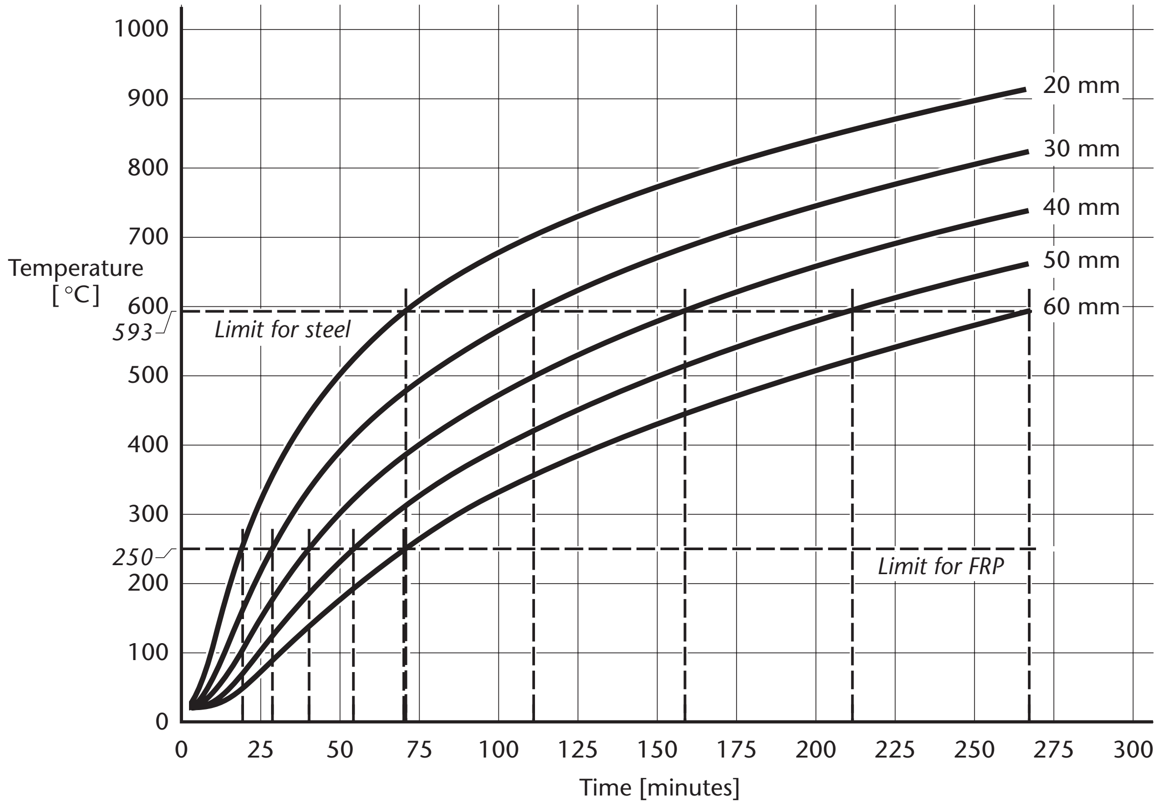
Note: *This figure is based on a figure from Kodur and Baingo (1998).*

Figure T5
Fire Resistance of 120 mm Concrete Slabs
(Siliceous Aggregate)
(See Clause T1.)



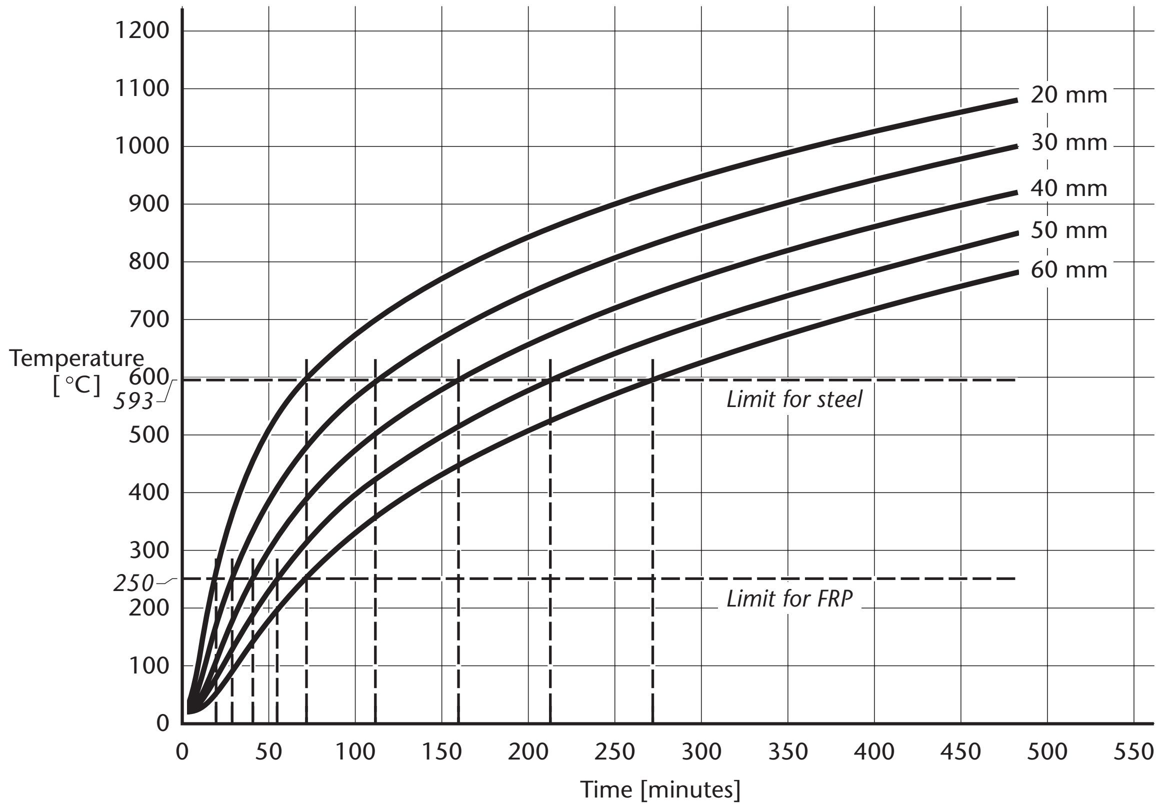
Note: *This figure is based on a figure from Kodur and Baingo (1998).*

Figure T6
Fire Resistance of 150 mm Concrete Slabs (Siliceous Aggregate)
(See Clause T1.)



Note: *This figure is based on a figure from Kodur and Baingo (1998).*

Figure T7
Fire Resistance of 180 mm Concrete Slabs
(Siliceous Aggregate)
(See Clause T1.)



Note: *This figure is based on a figure from Kodur and Baingo (1998).*

Figure T8
Fire Resistance of 250 mm Concrete Slabs
(Siliceous Aggregate)
(See Clause T1.)

Proposition de modification

N'hésitez pas à nous faire part de vos suggestions et de vos commentaires. Au moment de soumettre des propositions de modification aux normes CSA et autres publications CSA prière de fournir les renseignements demandés ci-dessous et de formuler les propositions sur une feuille volante. Il est recommandé d'inclure

- le numéro de la norme/publication
- le numéro de l'article, du tableau ou de la figure visé
- la formulation proposée
- la raison de cette modification.

Proposal for change

CSA welcomes your suggestions and comments. To submit your proposals for changes to CSA Standards and other CSA publications, please supply the information requested below and attach your proposal for change on a separate page(s). Be sure to include the

- Standard/publication number
- relevant Clause, Table, and/or Figure number(s)
- wording of the proposed change
- rationale for the change.

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