S806-12

Design and construction of building structures with fibre-reinforced polymers

Legal Notice for Standards

Canadian Standards Association (CSA) standards are developed through a consensus standards development process approved by the Standards Council of Canada. This process brings together volunteers representing varied viewpoints and interests to achieve consensus and develop a standard. Although CSA administers the process and establishes rules to promote fairness in achieving consensus, it does not independently test, evaluate, or verify the content of standards.

Disclaimer and exclusion of liability

This document is provided without any representations, warranties, or conditions of any kind, express or implied, including, without limitation, implied warranties or conditions concerning this document's fitness for a particular purpose or use, its merchantability, or its non-infringement of any third party's intellectual property rights. CSA does not warrant the accuracy, completeness, or currency of any of the information published in this document. CSA makes no representations or warranties regarding this document's compliance with any applicable statute, rule, or regulation.

IN NO EVENT SHALL CSA, ITS VOLUNTEERS, MEMBERS, SUBSIDIARIES, OR AFFILIATED COMPANIES, OR THEIR EMPLOYEES, DIRECTORS, OR OFFICERS, BE LIABLE FOR ANY DIRECT, INDIRECT, OR INCIDENTAL DAMAGES, INJURY, LOSS, COSTS, OR EXPENSES, HOWSOEVER CAUSED, INCLUDING BUT NOT LIMITED TO SPECIAL OR CONSEQUENTIAL DAMAGES, LOST REVENUE, BUSINESS INTERRUPTION, LOST OR DAMAGED DATA, OR ANY OTHER COMMERCIAL OR ECONOMIC LOSS, WHETHER BASED IN CONTRACT, TORT (INCLUDING NEGLIGENCE), OR ANY OTHER THEORY OF LIABILITY, ARISING OUT OF OR RESULTING FROM ACCESS TO OR POSSESSION OR USE OF THIS DOCUMENT, EVEN IF CSA HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES, INJURY, LOSS, COSTS, OR EXPENSES.

In publishing and making this document available, CSA is not undertaking to render professional or other services for or on behalf of any person or entity or to perform any duty owed by any person or entity to another person or entity. The information in this document is directed to those who have the appropriate degree of experience to use and apply its contents, and CSA accepts no responsibility whatsoever arising in any way from any and all use of or reliance on the information contained in this document.

CSA is a private not-for-profit company that publishes voluntary standards and related documents. CSA has no power, nor does it undertake, to enforce compliance with the contents of the standards or other documents it publishes.

Intellectual property rights and ownership

As between CSA and the users of this document (whether it be in printed or electronic form), CSA is the owner, or the authorized licensee, of all works contained herein that are protected by copyright, all trade-marks (except as otherwise noted to the contrary), and all inventions and trade secrets that may be contained in this document, whether or not such inventions and trade secrets are protected by patents and applications for patents. Without limitation, the unauthorized use, modification, copying, or disclosure of this document may violate laws that protect CSA's and/or others' intellectual property and may give rise to a right in CSA and/or others to seek legal redress for such use, modification, copying, or disclosure. To the extent permitted by licence or by law, CSA reserves all intellectual property rights in this document.

Patent rights

Attention is drawn to the possibility that some of the elements of this standard may be the subject of patent rights. CSA shall not be held responsible for identifying any or all such patent rights. Users of this standard are expressly advised that determination of the validity of any such patent rights is entirely their own responsibility.

Authorized use of this document

This document is being provided by CSA for informational and non-commercial use only. The user of this document is authorized to do only the following:

If this document is in electronic form:
- load this document onto a computer for the sole purpose of reviewing it;
- search and browse this document; and
- print this document if it is in PDF format.

Limited copies of this document in print or paper form may be distributed only to persons who are authorized by CSA to have such copies, and only if this Legal Notice appears on each such copy.

In addition, users may not and may not permit others to
- alter this document in any way or remove this Legal Notice from the attached standard;
- sell this document without authorization from CSA; or
- make an electronic copy of this document.

If you do not agree with any of the terms and conditions contained in this Legal Notice, you may not load or use this document or make any copies of the contents hereof, and if you do make such copies, you are required to destroy them immediately. Use of this document constitutes your acceptance of the terms and conditions of this Legal Notice.

CANADIAN STANDARDS ASSOCIATION

CSA Standards Update Service

S806-12
March 2012

Title: *Design and construction of building structures with fibre-reinforced polymers*
Pagination: 198 pages (xi preliminary and 187 text), each dated **March 2012**

To register for e-mail notification about any updates to this publication

- go on-line to **shop.csa.ca**
- click on **E-mail Services** under **MY ACCOUNT**
- click on **CSA Standards Update Service**

The **List ID** that you will need to register for updates to this publication is **2421834**.

If you require assistance, please e-mail **techsupport@csa.ca** or call 416-747-2233.

Visit CSA's policy on privacy at **csagroup.org/legal** to find out how we protect your personal information.

CSA Standard

S806-12

Design and construction of building structures with fibre-reinforced polymers

CANADIAN STANDARDS ASSOCIATION

Published in March 2012 by Canadian Standards Association
A not-for-profit private sector organization
5060 Spectrum Way, Suite 100, Mississauga, Ontario, Canada L4W 5N6
1-800-463-6727 • 416-747-4044

100%

The Canadian Standards Association (CSA) prints its publications on Rolland Enviro100, which contains 100% recycled post-consumer fibre, is EcoLogo and Processed Chlorine Free certified, and was manufactured using biogas energy.

*To purchase CSA Standards and related publications, visit CSA's Online Store at **shop.csa.ca** or call toll-free 1-800-463-6727 or 416-747-4044.*

ISBN 978-1-55491-931-4

Contents

Tables

Figures

Technical Committee on Design and Construction of Building Structures with Fibre-Reinforced Polymers

G. Razaqpur	McMaster University, Hamilton, Ontario	*Chair*
A. Wiseman	Public Works & Government Services Canada, Gatineau, Québec	*Vice-Chair*
B. Benmokrane	Université de Sherbrooke, Sherbrooke, Québec	
L. Bisby	The University of Edinburgh, Edinburgh, Scotland	*Associate*
O. Chaallal	Université du Québec / ÉTS, Montréal, Québec	*Associate*
R. Cheng	University of Alberta, Edmonton, Alberta	
M. Cheung	University of Ottawa, Ottawa, Ontario	
B. Drouin	Pultrall, Thetford-Mines, Québec	
H. Dutrisac	Cement Association of Canada, Ottawa, Ontario	*Associate*
W. El-Dakhakhni	McMaster University, Hamilton, Ontario	*Associate*
N. Erakovic	Halcrow Yolles, Toronto, Ontario	
G. Fallis	Vector Construction Limited, Winnipeg, Manitoba	
W. Gold	BASF Construction Chemicals-Building Systems, Beachwood, Ohio, USA	
M. Green	Queen's University, Department of Civil Engineering, Kingston, Ontario	*Associate*
M. Hachborn	Res Precast Inc., Innisfil, Ontario	

R. Heere	Metro Testing Laboratories Ltd., Burnaby, British Columbia	
H. Hong	University of Western Ontario, London, Ontario	*Associate*
D. Lau	Carleton University, Department of Civil and Environmental Engineering, Ottawa, Ontario	*Associate*
R. McGrath	Cement Association of Canada, Ottawa, Ontario	
K. Neale	Université de Sherbrooke, Sherbrooke, Québec	*Associate*
M. Saatcioglu	University of Ottawa, Ottawa, Ontario	
S. Sheikh	University of Toronto Toronto, Ontario	*Associate*
R. Sherping	Sika Canada Inc., Pointe Claire, Québec	
N. Shrive	The University of Calgary, Calgary, Alberta	
D. Svecova	University of Manitoba, Winnipeg, Manitoba	*Associate*
C. Taraschuk	National Research Council Canada, Ottawa, Ontario	
A. Weber	Schöck Bauteile GmbH, Baden-Baden, Germany	
M. Tumkur	Canadian Standards Association, Mississauga, Ontario	*Project Manager*

Preface

This is the second edition of CSA S806, *Design and construction of building structures with fibre-reinforced polymers*. It supersedes the first edition published in 2002.

This Standard contains provisions for building structures composed of fibre-reinforced polymers (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.

CSA acknowledges that the development of this Standard was made possible, in part, by the financial support of the following: American Composites Manufacturers Association — FRP Rebar Manufacturers Council, BP Composites Ltd., Fibrewrap Construction Canada Inc., FIRep North America Inc., Hughes Brothers, Inc., ISIS Canada, Public Works Government Services Canada, Pultrall Inc., Schöck, Sika Canada, and Vector Construction.

This Standard was prepared by the Technical Committee on Design and Construction of Building Structures with Fibre-Reinforced Polymers, under the jurisdiction of the Strategic Steering Committee on Structures (Design), and has been formally approved by the Technical Committee.

March 2012

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) *To submit a request for interpretation of CSA Standards, please send the following information to* ***inquiries@csa.ca*** *and include "Request for interpretation" in the subject line:*
(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) where possible, phrase the request in such a way that a specific "yes" or "no" answer will address the issue.
Committee interpretations are processed in accordance with the CSA Directives and guidelines governing standardization *and are published in CSA's Current Standard Activities, which is available on the CSA website at* ***standardsactivities.csa.ca****.*

(5) *CSA Standards are subject to periodic review, and suggestions for their improvement will be referred to the appropriate committee. To submit a proposal for change to CSA Standards, please send the following information to* ***inquiries@csa.ca*** *and include "Proposal for change" in the subject line:*
(a) Standard designation (number);
(b) relevant clause, table, and/or figure number;
(c) wording of the proposed change; and
(d) rationale for the change.

S806-12
Design and construction of building structures 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 S.*

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.

1.5 Terminology

In CSA standards, "shall" is used to express a requirement, i.e., a provision that the user is obliged to satisfy in order to comply with the standard; "should" is used to express a recommendation or that which is advised but not required; and "may" is used to express an option or that which is permissible within the limits of the standard.

Notes accompanying clauses do not include requirements or alternative requirements; the purpose of a note accompanying a clause is to separate from the text explanatory or informative material.

Notes to tables and figures are considered part of the table or figure and may be written as requirements.

Annexes are designated normative (mandatory) or informative (nonmandatory) to define their application.

2 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 might exist. The user may find it more appropriate to refer to such editions.*

CSA (Canadian Standards Association)

A23.1-09/A23.2-09
Concrete materials and methods of concrete construction/ Test methods and standard practices for concrete

CAN/CSA-A23.3-04 (R2010)
Design of concrete structures

A23.4-09
Precast concrete — Materials and construction

CAN/CSA-A3000-08
Cementitious materials compendium

O86-09
Engineering design in wood

CAN/CSA-S6-06
Canadian Highway Bridge Design Code

S16-09
Design of steel structures

CAN/CSA-S136-07
North American Specification for the design of cold-formed steel structural members

CAN/CSA-S157-05/S157.1-05 (R2010)
Strength design in aluminum/Commentary on CSA S157-05, Strength Design in Aluminum

S304.1-04
Design of masonry structures

S413-07
Parking structures

S478-95 (R2007)
Guideline on durability in buildings

S807-10
Specification for fibre-reinforced polymers

ACI (American Concrete Institute)

440.1R-06
Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars

216R 1989 (Reapproved 2001)
Guide for Determining the Fire Endurance of Concrete Elements

ANSI (American National Standards Institute)
Z124
Plastic Fixture Standards

ASTM (American Society for Testing and Materials)
C39/C39M-11
Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

C138/C138M-10b
Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

C143/C143M-10a
Standard Test Method for Slump of Hydraulic-Cement Concrete

C144-11
Standard Specification for Aggregate for Masonry Mortar

C192/C192M-07
Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

C234-91a (withdrawn)
Standard Test Method for Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel

C260/C260-10a
Standard Specification for Air-Entraining Admixtures for Concrete

C293/C293M-10
Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading)

C330/C330M-09
Standard Specification for Lightweight Aggregates for Structural Concrete

C393/C393M-06
Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure

C494/C494M-11
Standard Specification for Chemical Admixtures for Concrete

C511-09
Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes

C518-10
Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Apparatus

C531-00(2005)
Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes

C581-03(2008)e1
Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service

C617/C617M-11a
Standard Practice for Capping Cylindrical Concrete Specimens

C1185-08
Standard Test Methods for Sampling and Testing Non-Asbestos Fiber-Cement Flat Sheet, Roofing and Siding, Shingles, and Clapboards

D149-09
Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies

D150-11
Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation

D256-10
Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics

D257-07
Standard Test Methods for DC Resistance or Conductance of Insulating Materials

D495-99 (2004)
Standard Test Method for High-Voltage, Low-Current, Dry Arc Resistance of Solid Electrical Insulation

D543-06
Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents

D570-98(2010)e1
Standard Test Method for Water Absorption of Plastics

D584-10
Standard Test Method for Wool Content of Raw Wool Laboratory Scale

D635-11
Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position

D638-10
Standard Test Method for Tensile Properties of Plastics

D648-07
Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position

D695-10
Standard Test Method for Compressive Properties of Rigid Plastics

D696-08
Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between –30°C and 30°C with a Vitreous Silica Dilatometer

D732-10
Standard Test Method for Shear Strength of Plastics by Punch Tool

D746-07
Standard Test Method for Brittleness Temperature of Plastics and Elastomers by Impact

D785-08
Standard Test Method for Rockwell Hardness of Plastics and Electrical Insulating Materials

D790-10
Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

D792-08
Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement

D953-10
Standard Test Method for Bearing Strength of Plastics

D1037-06a
Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials

D1141-98(2008)
Standard Practice for Substitute Ocean Water

D1602-58(1998) (withdrawn)
Method of Test for Bearing Load of Corrugated Reinforced Plastic Panels

D2247-11
Standard Practice for Testing Water Resistance of Coatings in 100% Relative Humidity

D2344/D 2344M-00(2006)
Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates

D2583-07
Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor

D2584-08
Standard Test Method for Ignition Loss of Cured Reinforced Resins

D2734-09
Standard Test Methods for Void Content of Reinforced Plastics

D2834-95(2008)
Standard Test Method for Nonvolatile Matter (Total Solids) in Water-Emulsion Floor Polishes, Solvent-Based Floor Polishes, and Polymer-Emulsion Floor Polishes

D2863-10
Standard Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index)

D2990-09
Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

D3039/D3039M-08
Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

D3045-92(2010)
Standard Practice for Heat Aging of Plastics Without Load

D3164-11
Standard Test Method for Strength Properties of Adhesively Bonded Plastic Lap-Shear Sandwich Joints in Shear by Tension Loading

D3165-07
Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies

D3171-09
Standard Test Method for Constituent Content of Composite Materials

D3410/D3410M-03(2008)
Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading

D3479/D3479M-96(2007)
Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials

D3528-96(2008)
Standard Test Method for Strength Properties of Double Lap Shear Adhesive Joints by Tension Loading

D3841-97(2008)e1
Standard Specification for Glass-Fiber-Reinforced Polyester Plastic Panels

D3846-08
Standard Test Method for In-Plane Shear Strength of Reinforced Plastics

D3914-02(2008)
Standard Test Method for In-Plane Shear Strength of Pultruded Glass-Reinforced Plastic Rod

D3916-08
Standard Test Method for Tensile Properties of Pultruded Glass-Fiber-Reinforced Plastic Rod

D4065-06
Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures

D4329-05
Standard Practice for Fluorescent UV Exposure of Plastics

D4541-09e1
Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers

D5028-09
Standard Test Method for Curing Properties of Pultrusion Resins by Thermal Analysis

D5229/D5229M–92
Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

D5379/D5379M-05
Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method

D5420-10
Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimen by Means of a Striker Impacted by a Falling Weight (Gardner Impact)

D7205/D7205M-06
Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars

E4-10
Standard Practices for Force Verification of Testing Machines

E84-11a
Standard Test Method for Surface Burning Characteristics of Building Materials

E104-02(2007)
Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions

E119-11a
Standard Test Methods for Fire Tests of Building Construction and Materials

E178-08
Standard Practice for Dealing With Outlying Observations

E662-09
Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials

E1142-11b
Standard Terminology Relating to Thermophysical Properties

G154-06
Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials

CEN (European Committee for Standardisation)
EN 1992-1-2:2004 – Eurocode 2 2004
Design of concrete structures; General rules; Structural fire design

CPCI (Canadian Precast/Prestressed Concrete Institute)
Design Manual, 4th edition, 2007

National Research Council Canada
National Building Code of Canada, 2010

PCI (Precast/Prestressed Concrete Institute Publication)
MNL-128-01
Recommended Practice for Glass Fiber Reinforced Concrete Panels, 4th edition, 2001

SAE (Society of Automotive Engineers)
J-400-2002
Test for Chip Resistance of Surface Coatings

ULC (Underwriters' Laboratories of Canada)
CAN/ULC-S101-07
Standard Methods of Fire Endurance Tests of Building Constructions and Materials

CAN4-S102-07
Methods of Test for Surface Burning Characteristics of Building Materials and Assemblies

CAN/ULC-S102.2-07
Method of Test for Surface Burning Characteristics of Flooring, Floor Covering, and Miscellaneous Materials and Assemblies

CAN4-S114-05
Standard Method of Test for Determination of Non-Combustibility in Building Materials

2010 *(UL Design No. N790 and UL Design No. X842)*
Fire Resistance Directory

3 Definitions, abbreviations, subscripts and symbols, and units of measurement

3.1 Definitions

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

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.

Characteristic tensile strength — equal to the mean tensile strength minus three times the standard deviation

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 CAN4-S114.

Composite — a combination of one or more materials differing in form or composition on a macro scale.
Note: *The constituents retain their identities, i.e., 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.*

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.

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) a family of glass with a calcium alumina borosilicate composition and a maximum alkali content of 2.0%;
(b) 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.
Note: *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.
Note: *As applied to elements of buildings, it is measured by the methods and criteria defined in ULC CAN/ULC-S101.*

Fire resistance — the property of a material or assemblage to withstand or give protection from fire.
Note: *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 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 midpoint of the temperature range over which an amorphous material changes from a brittle and vitreous state to a plastic state, or vice versa.

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.
Note: *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.

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.

Near surface mounted (NSM) — FRP rods or strips that are bonded into slots cut into the surface of the concrete.

Noncombustible — the property of a material that meets the acceptance criteria of ULC 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.

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:

Post-tensioning — a method of prestressing in which the tendons are tensioned after the concrete has hardened.

Pretensioning — a method of prestressing in which the tendons are tensioned before the concrete is placed.

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.

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 CSA A23.1 or CSA A23.4, as applicable.

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.
Note: *See also* ***Stirrup****.*

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 might be required to carry superimposed in-plane loads.

Yield strength — specified minimum yield strength of steel reinforcement.

3.2 Abbreviations

The following acronyms are used in this Standard:
AFRP — aramid fibre-reinforced polymer
CFRP — carbon fibre-reinforced polymer
FRC — fibre-reinforced concrete
FRP — fibre-reinforced polymer
GFRP — glass fibre-reinforced polymer
NSMR — near-surface mounted reinforcement

3.3 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.

3.4 Units of measurement

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.

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, may be used 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 Item (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 6.3.1 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 6.4.2, 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 a manner consistent with ULC 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 and concrete slabs, beams, and columns strengthened 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 strengthening of a structural assembly, then the original assembly shall be capable of supporting the full specified gravity load acting on the repaired or strengthened structure and 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 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 CAN/ULC-S102.2.

5.3.4 Noncombustibility

The noncombustibility of materials shall be determined in accordance with ULC 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 S478.

6 Limit states, loading, load combinations, and factored resistance

6.1 Symbols
The following symbols are used in Clause 6:

f'_c = specified compressive strength of concrete
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

6.2 Limit states

6.2.1 Durability
In addition to the requirements of this Standard, concrete structures shall satisfy the durability requirements of CSA A23.1, CSA A23.4, CSA S807, or CSA S413, as applicable, and for the intended use and exposure conditions

6.2.2 Fire resistance
In addition to the requirements of this Standard, concrete structures reinforced or retrofitted with FRP shall satisfy the fire resistance requirements of the applicable building code as applicable.

6.2.3 Ultimate limit state
Building components and connections shall be designed in such a way that factored resistance is equal to or greater than the 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.

6.2.4 Serviceability limit states

6.2.4.1 Deflections
Structures and structural components shall be designed to satisfy the deflection control requirements of Clause 8.3.2, with the loading as specified in Clause 6.4.2.

6.2.4.2 Local damage and cracking
Structural components and connections shall be designed to satisfy the minimum reinforcement area and maximum reinforcement spacing requirements of this Standard, as well as the requirements of Clauses 8.4 and 8.5.5, and the relevant clauses in Clause 10, with the loading as specified in Clause 6.4.2.

6.2.4.3 Vibrations
In the design of buildings and 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 and load factors

6.4.1 Load combinations and factor for ultimate limit state
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 specified in Part 4 of the *National Building Code of Canada* or other applicable building codes.

6.4.2 Load combination for serviceability limit states
A building and its components shall be checked for applicable serviceability limit states specified in Clause 6.2.4 under the effects of the service loads. The applicable load combination shall be taken as the one that results in the most unfavourable effect for the limit state under consideration.

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 CSA 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 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

6.5.3.1
The specified concrete strength used in design shall not exceed 80 MPa.

6.5.3.2
The factored concrete resistance used in checking ultimate limit states shall be taken as $\phi_c f_c'$ in compression and $0.48\phi_c\sqrt{f_c'}$ in tension where $\phi_c = 0.65$, except for precast concrete components unless they are produced in certified manufacturing plants in accordance with CAN/CSA-A23.3, in which case $\phi_c = 0.70$.

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 O86.1 for wood;
(b) CSA S16 for steel;
(c) CAN/CSA-S136 for cold-formed steel;
(d) CAN/CSA-S157 for aluminum; and
(e) CSA 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 according in accordance with CSA S807.

7.1.2.2
The maximum stress in FRP bars or grids under loads at serviceability limit state shall not exceed the following fraction of the characteristic tensile strength:
(a) for AFRP, 0.35;
(b) for CFRP, 0.65; and
(c) for GFRP, 0.25.

7.1.2.3
The maximum strain in GFRP tension reinforcement under sustained service loads shall not exceed 0.002.

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
The properties of non-prestressed FRP reinforcement shall be provided by the manufacturer in accordance with CSA S807.

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 properties of FRP prestressing tendons shall be provided by the manufacturer in accordance with CSA S807 when applicable.

7.1.5 Testing and acceptance

7.1.5.1
All of the design properties of FRP reinforcement listed in Table 1 shall be considered and the relevant design properties shall be obtained from tests conducted in accordance with CSA S807.

7.1.5.2
FRP reinforcement shall be tested for creep and creep rupture in accordance with CSA S807.

7.1.5.3
Preshaped FRP reinforcement such as ties, stirrups, grids, and cages for beams shall be tested for strength development in accordance with CSA S807.

7.1.5.4
The following acceptance limits shall apply to FRP reinforcement used in structural components:
(a) rupture tensile strain 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 strength for FRP reinforcement shall be the mean tensile strength determined in accordance with Annex C minus three times the standard deviation.

7.1.6.2
For the bent portions of FRP bars, the strength shall be determined in accordance with the relevant provisions of S807.

7.1.6.3
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 2.

7.1.6.4
For the purpose of design, FRP reinforcing elements in the concrete compression zone shall be deemed to have zero compressive strength and stiffness.

7.1.6.5
The design elastic modulus for FRP reinforcement, E_F, shall be the mean modulus determined in accordance with Annex C.

7.1.6.6
The characteristic rupture tensile strain for FRP reinforcement shall be the mean rupture tensile strain determined in accordance with Annex C minus three times the standard deviation.

7.2 Surface-bonded and near-surface-mounted FRP reinforcing materials

7.2.1 General
Surface-bonded and near-surface-mounted FRP reinforcing materials shall conform to Clauses 7.2.2 and 7.2.3. Their physical properties shall be determined by testing in accordance with Clause 7.2.4. The physical and mechanical properties of FRP composites shall be determined in accordance with Clause 7.2.5. Design strength and stiffness shall be based on characteristic properties determined in accordance with Clause 7.2.6.

7.2.2 Materials and composition

7.2.2.1
Component materials and combination thereof in a strengthening system shall be compatible to each other and to the applied substrate. 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.
Note: *A typical surface mounted strengthening system and its components may be as shown in Figure 1a.*

7.2.2.2
Selection of protective coatings shall be based on the requirements of the composite repair including but not limited to resistance to environmental effects such as moisture, chemicals, temperature extremes, fire, impact, UV exposure, resistance to site-specific effects, and resistance to vandalism.

Protective coatings shall be selected from the general classes of epoxy, vinylester, urethane, polyester, and other suitable materials.

7.2.3 General properties of surface-bonded and near-surface-mounted FRP composites

7.2.3.1
The properties of surface-bonded FRP laminates shall be provided by the system manufacturer.

7.2.3.2
The properties of near-surface-mounted bars and strips shall comply with CSA S807.

7.2.4 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 D, F, N, and O.

7.2.5 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 3. Environmental durability of FRP composites shall be tested in accordance with the test methods and standards given in Table 4.

7.2.6 Characteristic values for design
The characteristic tensile strength of FRP composites used as surface-bonded and near-surface mounted reinforcement shall be the mean tensile strength determined in accordance with Annex F, minus three times the standard deviation.

7.2.7 Resistance factor
For surface-bonded and near-surface-mounted FRP reinforcing materials, a resistance factor, ϕ_F, of 0.65 shall be used for design for ultimate limit states.

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, Portland-limestone cement, fly ash, slag, or silica fume), fibre reinforcement, aggregate, admixtures, and water.

7.3.2.2
The Portland cement and Portland-limestone cement shall be in accordance with CSA A3000.

7.3.2.3
The sand shall be
(a) properly graded silica sand;
(b) washed and dried; and
(c) free of contaminants and lumps.

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

7.3.2.5
Mixing water shall be in accordance with 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 M, 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 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 A23.1 and CSA A23.4.

7.3.3 Determination of physical and mechanical properties

7.3.3.1
The physical and mechanical 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, toughness, shrinkage, creep, residual tensile strength, thermal expansion, transport properties, freeze-thaw resistance, and response to fire and high temperature.

7.3.3.2
When relevant, FRP cladding shall be tested in accordance with the ASTM standards listed in Table 5.

7.3.3.3
FRC cladding shall be tested in accordance with ASTM C518, C531, C1185, and D1037, and its flammability and combustibility shall be tested in accordance with ASTM E84 and UL 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 satisfies the requirements of 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

7.4.2.1

The materials of FRP composites, including thermoset resins, curing agents, fillers, additives, core materials, and fibres, shall be compatible with the environmental conditions and with the relevant provisions of Clauses 7.4.2.2 to 7.4.2.6.

7.4.2.2

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

7.4.2.3

If additives 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.

7.4.2.4

Fire-retardant agents shall be used as necessary to meet combustibility requirements and shall be in accordance with the recommendations of the resin manufacturer.

7.4.2.5

Ultraviolet absorbers, when needed, shall be used in accordance with the recommendations of the resin manufacturer.

7.4.2.6

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 and mechanical properties

The physical and mechanical 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, response to fire and high temperature, and thermal expansion. Other physical properties to be considered according to necessity shall be impact resistance, shrinkage, freeze-thaw resistance, density, and light transmission.

8 Design of concrete components with FRP reinforcement

8.1 Symbols

The following symbols are used in Clause 8:

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 is 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_{cs} = area of concrete in strips along exposed side faces of beams

A_F = area of FRP tension reinforcement

A_{FT} = area of longitudinal FRP reinforcement in the tension tie

A_{Ft} = area of one leg of transverse FRP torsional reinforcement

A_{Fv} = area of FRP shear reinforcement perpendicular to the axis of a member within the distance s

A_g = gross area of section

A_o = area enclosed by shear flow path, including area of holes (if any)

A_{oh} = area enclosed by centreline of exterior closed transverse torsion reinforcement, including area of holes (if any)

A_p = area of prestressing tendons

A_s = area of steel tension reinforcement

A_{st} = total area of longitudinal reinforcement

A_v = area of steel shear reinforcement perpendicular to the axis of a member within the distance s

A_{vF} = minimum area of transverse FRP shear reinforcement

a = shear span

b = width of compression face of member, corbel, or bracket

b_w = minimum effective web width

c = distance from extreme compression fibre to neutral axis

D = dead loads or related internal moments and forces

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_v = effective shear depth, taken as the greater of 0.9 d or 0.72 h

E = earthquake loads or related internal moments and forces

E_c = modulus of elasticity of concrete

E_F = modulus of elasticity of FRP reinforcement

E_p = modulus of elasticity of prestressing tendons

E_S = modulus of elasticity of steel reinforcement

$F_{\ell c}$ = required tension force in longitudinal reinforcement on flexural compression side of member

$F_{\ell t}$ = required tension force in longitudinal reinforcement on flexural tension side of member

f'_c = specified compressive strength of concrete

f_{cu} = limiting compressive stress in concrete strut

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 reinforcement

f_{po} = stress in prestresing tendon when strain in the surrounding concrete is zero

f_r = modulus of rupture of concrete

f_y = specified yield strength of reinforcement

h = overall thickness or height of a member

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 = effective length factor
k_a = coefficient taking into account the effect of arch action on member shear strength
k_b = coefficient dependent on the reinforcing bar bond characteristics
k_c = coefficient representing the efficiency of transverse reinforcement
k_m = coefficient taking into account the effect of moment at section on shear strength
k_s = coefficient taking into account the effect of member size on its shear strength
k_r = coefficient taking into account the effect of reinforcement rigidity on its shear strength
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
ℓ_d = development length of reinforcement
ℓ_u = clear span or unsupported length between floors or other effective horizontal lines of lateral support
M_1 = smaller factored end moment on a compression member associated with the same loading case as M_2 (positive if member is bent in single curvature, negative if bent in double curvature)
M_2 = larger factored end moment on a compression member (always positive)
M_{cr} = cracking moment
M_f = factored moment
M_r = factored moment resistance (M_f)
N_f = factored axial load normal to the cross-section occurring simultaneously with V_f, including effects of tension due to creep and shrinkage (taken as positive for tension and negative for compression)
P = applied concentrated load
P_f = factored axial load
P_o = nominal unconfined axial load capacity of column, taken as $\alpha_1 f'_c (A_g - A_{st}) + f_y A_{st}$, for columns with longitudinal steel reinforcement and $\alpha_1 f'_c (A_g - A_F)$ for columns with FRP longitudinal reinforcement
$P_{r,max}$ = maximum factored axial load resistance of compression members
P_{ro} = factored axial load resistance at zero eccentricity
q = uniformly distributed applied load
r = radius of gyration
S = factor for creep deflection under sustained loads
S_G = FRP grid spacing parallel to the bending direction of interest
s = spacing of shear reinforcement, measured parallel to the longitudinal axis of the member
s_ℓ = spacing of laterally supported longitudinal reinforcement
T = cumulative effects of temperature, creep, shrinkage, and differential settlement
T_{cr} = pure torsional cracking resistance
T_f = factored torsional moment
T_r = factored torsional resistance
t_w = wall thickness of box section or wall thickness of idealized hollow section under torsion
V_c = factored shear resistance provided by concrete
V_f = factored shear force
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_r = factored shear resistance
V_s = factored shear resistance provided by shear reinforcement
V_{sF} = factored shear resistance provided by FRP shear reinforcement
V_{ss} = factored shear resistance provided by steel shear reinforcement
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
β_1 = ratio of depth of rectangular compression block to depth of the neutral axis
γ_c = density of concrete
ε_{cs} = shrinkage strain of concrete
ε_F = strain in FRP reinforcement under specified loads
ε_{Fu} = ultimate strain of FRP reinforcement
ε_l = longitudinal strain at mid-depth of the section
ε_s = strain in steel reinforcement under specified loads
κ = curvature
λ = factor to account for concrete density
ρ_{Fw} = longitudinal FRP reinforcement ratio
ρ_{Fh} = ratio of volume of hoop or rectilinear transverse FRP reinforcement to total volume of core (out-to-out of hoop or transverse reinforcement)
ρ_{Fs} = ratio of volume of spiral FRP reinforcement to total volume of core (centre-to-centre of spirals) of a spirally reinforced compression member
ρ_w = longitudinal reinforcement ratio
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

8.2 Design requirements

8.2.1 General
Except as specified in Clause 8.2.2, 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 Failure initiated by FRP rupture
If the factored resistance of a section is greater than 1.6 times the effect of the factored loads, the requirements of Clause 8.2.1 may be waived.

8.2.3 Minimum cover
Minimum clear concrete cover in reinforced concrete members shall be $2d_b$ or 30 mm, whichever is greater.

8.2.4 Buildings other than parking structures
The design of concrete with FRP reinforcement shall be in accordance with the *National Building Code of Canada* and CAN/CSA-A23.3, except as specified in this Standard. In the event of conflict between this Standard and the referenced standards, this Standard shall take precedence.

8.2.5 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 S413. In the event of conflict between this Standard and CSA S413, this Standard shall take precedence.

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

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

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 the relevant limit stress specified in Clause 7.1.2.2 for the reinforcement layer closest to the extreme tension fibre. The value of k_b shall be determined in accordance with Annex S, but in the absence of test data it may be taken as 1.2 for deformed or sand coated 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 that can attack FRPs 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 6.

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 7.

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

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

where f_r is calculated in accordance with Clause 8.3.2.8.

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
= 1.5 for 12 months
= 1.3 for 6 months
= 1.1 for 3 months

8.3.2.8

The modulus of rupture, f_r, shall be taken as

$$f_r = 0.6\lambda\sqrt{f_c'} \quad \textbf{(8-3)}$$

where

λ = 1.0 for normal density concrete

λ = 0.85 for structural semi-low density concrete in which all the fine aggregate is natural sand

λ = 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.

8.3.3 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

$$(c/d) \geq 7/(7 + 2000\varepsilon_{Fu}) \quad \textbf{(8-4)}$$

8.4.1.5

When c/d satisfies the requirements of Clause 8.4.1.4, 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

$$\alpha_1 = 0.85 - 0.0015 f'_c \geq 0.67 \quad \textbf{(8-5)}$$

$$\beta_1 = 0.97 - 0.0025 f'_c \geq 0.67 \quad \textbf{(8-6)}$$

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

$$M_r > 1.5 M_{cr} \quad \textbf{(8-7)}$$

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

8.4.2.2

If every section where $M_{cr} \geq 1.5 M_f$, the minimum reinforcement requirements in Clause 8.4.2.1 may be waived.

8.4.2.3

In slabs, a minimum area of reinforcement of $(400/E_F)\,A_g$ shall be used in each of the two orthogonal directions. This reinforcement shall not be less than 0.0025 A_g and shall be spaced no farther apart than three times the slab thickness or 300 mm, whichever is less.

8.4.3 Members under flexure and axial load

8.4.3.1

Longitudinal FRP reinforcement may be used in members subjected to combined flexure and axial load. The FRP reinforcement in compression zones of such members shall be deemed to have zero compressive strength and stiffness as per Clause 7.1.6.4.

8.4.3.2

FRP reinforced columns shall be designed to have adequate factored resistance under the combinations of factored axial load and moment giving the maximum and minimum ratios of moment to axial load.

8.4.3.3

Slender columns that satisfy the following equations shall not be permitted to have FRP longitudinal reinforcement:

(a) for compression members braced against sidesway:

$$\frac{k\ell_u}{r} \geq 34 - 12\left(\frac{M_1}{M_2}\right) \geq 40 \qquad \textbf{(8-8)}$$

where $\left(\frac{M_1}{M_2}\right)$ is positive if the column is bent in single curvature and negative if the member is bent in double curvature.

(b) for compression members not braced against sidesway:

$$\frac{k\ell_u}{r} \geq 22 \qquad \textbf{(8-9)}$$

Compression members braced against sidesway may be considered when bracing elements have a total stiffness, resisting lateral movement of that storey, of at least 12 times the gross stiffness of the columns within the storey.

8.4.3.4

For compression members braced against sidesway, the effective length factor, k, shall be taken as 1.0, unless analysis shows that a lower value is justified. The calculation of k shall be based on cracked section properties of members.

8.4.3.5

Flexural resistance of compression members shall be computed in accordance with Clause 8.4.1, with the effects of axial force included in flexural analysis.

8.4.3.6

The maximum factored axial load resistance, $P_{r,max}$, of compression members shall be

(a) for spirally reinforced columns and for columns that conform to the requirements of Clause 12.7:

$$P_{r,max} = 0.85P_{ro} \qquad \textbf{(8-10)}$$

(b) for tied columns:

$$P_{r,max} = 0.80P_{ro} \qquad \textbf{(8-11)}$$

8.4.3.7

The area of longitudinal bars in compression members shall be not less than 0.01 times the gross area, A_g, of the section, except as permitted by Clause 8.4.3.8.

8.4.3.8
Columns with total longitudinal bar area smaller than 0.01 times the gross area, A_g, of the section may be used, provided that the bar area is not less than 0.005 times the gross area of the section and the factored axial and flexural resistances are multiplied by the ratio $0.5(1+\rho_t/0.01)$.

8.4.3.9
The area of longitudinal bars for compression members, including regions containing lap splices, shall not exceed 0.08 times the gross area of the section.

8.4.3.10
The minimum number of longitudinal reinforcing bars in compression members shall be four for bars within rectangular and circular ties, three for bars within triangular ties, and six for bars enclosed by spirals complying with Clause 8.4.3.13. The minimum FRP bar size for longitudinal FRP bars shall be not less than 15 mm in diameter.

8.4.3.11
In lieu of using the full gross area in resistance calculations, a compression member with a square, octagonal, or other regular polygonal cross-section may be considered a circular section with a diameter equal to the least lateral dimension of the actual shape. The gross area considered, the required percentage of reinforcement and the resistance shall be based on that circular section.

8.4.3.12
In cases where columns are reinforced longitudinally with steel and transversely with FRP reinforcement, the requirements of CAN/CSA-A23.3 shall apply to longitudinal steel reinforcement and Clauses 8.4.3.13 and 8.4.3.14 shall apply to the transverse FRP reinforcement.

8.4.3.13
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

$$\rho_{Fs} = \frac{f'_c}{f_{Fh}}\left(\frac{A_g}{A_c}-1\right)\left(\frac{P}{P_0}\right) \quad \textbf{(8-12)}$$

where

$$\frac{P}{P_0} \geq 0.2 \quad \textbf{(8-13)}$$

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

$f_{Fh} = \phi_F f_{Fu}$, or the stress corresponding to a strain of $0.006E_F$ in the FRP, or the stress corresponding to the failure of corners, hooks, bends, and laps, whichever is least.

8.4.3.14
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 comprehensive test results.

(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 relevant provisions of CAN/CSA-A23.3

8.4.3.15

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.

Note: *Bar number refers to the bar nominal diameter in mm.*

8.4.4 Design for shear and torsion in flexural regions

8.4.4.1 General

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

8.4.4.2 Sections near supports

Provided that the reaction force parallel to the direction of the applied shear introduces compression into a support region and provided that no concentrated load that causes a shear force greater than $0.30\lambda\phi_c\sqrt{f_c'}b_w d$ is applied within the distance d_v from the face of the support, the following shall apply:

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

8.4.4.3 Required shear resistance

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

8.4.4.4 Factored shear resistance

The factored shear resistance of members with longitudinal FRP reinforcement shall be determined by

(a) for members with FRP stirrups:

$$V_r = V_c + V_{sF} \quad \textbf{(8-14)}$$

(b) For members with steel stirrups

$$V_r = V_c + V_{ss} \quad \textbf{(8-15)}$$

However, V_r shall not exceed

$$V_{r,max} = 0.22\phi_c f_c' b_w d_v + 0.5V_p + [(M_{dc}V_f)/M_f] \quad \textbf{(8-16)}$$

8.4.4.5 Determination of V_c

For sections having an effective depth not exceeding 300 mm and with no axial load acting on them

$$V_c = 0.05\lambda\phi_c k_m k_r (f_c')^{\frac{1}{3}} b_w d_v \qquad \textbf{(8-17)}$$

where

$$k_m = \sqrt{\frac{V_f d}{M_f}} \leq 1.0 \qquad \textbf{(8-18)}$$

$$k_r = 1 + (E_F \rho_{Fw})^{\frac{1}{3}} \qquad \textbf{(8-19)}$$

but V_c calculated in accordance with Equation (8-17) shall not be taken greater than $0.22\phi_c \sqrt{f_c'} b_w d_v$ nor less than $0.11\phi_c \sqrt{f_c'} b_w d_v$. In the determination of V_c, f_c' shall not be taken greater than 60 MPa.

8.4.4.6 Shear modification due to arch effect V_c

For sections located within a distance of 2.5 d from the face of a support where the support reaction causes compression in the beam parallel to the direction of the shear force at the section, the value of V_c shall be calculated as the value determined according to Clause 8.4.4.5 multiplied by the factor k_a as given in Equation (8-20)

$$k_a = \frac{2.5}{\frac{M_f}{V_f d}} \geq 1.0 \qquad \textbf{(8-20)}$$

but k_a shall not exceed 2.5.

8.4.4.7 Shear modification due to member size

For members with effective depth greater than 300 mm and with less transverse shear reinforcement than required by Equation (8-28), the value of V_c shall be calculated as the value determined according to Clause 8.4.4.5 multiplied by the factor k_s as given in Equation (8-21).

$$k_s = \frac{750}{450 + d} \leq 1.0 \qquad \textbf{(8-21)}$$

8.4.4.8 Neglecting size effect

For members with effective depth greater than 300 mm and with transverse shear reinforcements equal to or greater than that required by Equation (8-28), the value of V_c shall be calculated as the value determined according to Clause 8.4.4.5.

8.4.4.9 Determination of V_{sF} and V_{ss}

For members with transverse reinforcement perpendicular to the longitudinal axis, V_{sF} shall be computed as

$$V_{sF} = \frac{0.4\phi_F A_{Fv} f_{Fu} d_v}{s} \cot\theta \qquad \textbf{(8-22)}$$

$$V_{ss} = \frac{\phi_s A_v f_y d_v}{s} \cot\theta \qquad \textbf{(8-23)}$$

f_{Fu} shall not be greater than 0.005 E_F and the angle θ of the diagonal compressive stress shall be calculated as

$$\theta = 30^\circ + 7000\ \varepsilon_l \qquad \textbf{(8-24)}$$

where the longitudinal strain ε_t at mid-depth of the section shall be calculated as

$$\varepsilon_l = \frac{\frac{M_f}{d_v} + \left(V_f - V_p\right) + 0.5N_f - A_p f_{po}}{2\left(E_F A_F + E_p A_p\right)} \quad \textbf{(8-25)}$$

In evaluating Equation (8-25), the following conditions apply:
(a) V_f and M_f shall be taken as positive quantities and M_f shall not be taken less than $(V_f - V_p)d_v$.
(b) The value of ε_l calculated in accordance with Equation (8-25) shall not be taken less than zero.
(c) For sections closer than d to the face of the support, the value of ε_l calculated at d from the face of the support may be used to calculate θ.
(d) The angle θ shall not be taken greater than 60° nor less than 30°.

8.4.4.10 Members subjected to axial tension

For members subjected to axial tension, V_c shall be computed as

$$V_c = \left[0.05\ \lambda\phi_c k_m k_r (f_c')^{\frac{1}{3}}\ b_w d_v\right] k_s k_a \left(1 - \frac{0.3N_f}{A_g}\right) \geq 0.0 \quad \textbf{(8-26)}$$

where the term within the first bracket in Equation (8-26) shall not be taken less than $0.1\lambda\varphi_c\sqrt{f_c'}b_w d$ and the factor k_s is given in Clauses 8.4.4.7. The force N_f shall be positive for tension.

8.4.4.11 Members subjected to axial compression

For members subjected to axial compression, V_c shall be computed as

$$V_c = \left[0.05\ \lambda\phi_c k_m k_r (f_c')^{\frac{1}{3}}\ b_w d_v\right] k_s k_a \left(1 - \frac{N_f}{14A_g}\right) \quad \textbf{(8-27)}$$

but the product $k_a\left(1 - \frac{N_f}{14A_g}\right)$ shall not be taken greater than 3, and the quantity in the first bracket on the right-hand side of Equation (8-27) shall not be taken less than $0.11\sqrt{f_c'}b_w d_v$. The force N_f shall be negative for compression.

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 FRP shear reinforcement shall be such that

$$A_{vF} = 0.07\sqrt{f_c'}\,\frac{b_w s}{0.4\ f_{Fu}} \quad \textbf{(8-28)}$$

but f_{Fu} shall not be taken greater than 1200 MPa or $0.005E_F$.

Near locations where the spacing, s, of the transverse reinforcement changes, the quantity $\frac{A_{vF}}{s}$ may be assumed to vary linearly over a length h centred on the location where the spacing changes.

8.4.6 Maximum spacing of transverse reinforcement

8.4.6.1

The spacing of transverse reinforcement, s, placed perpendicular to the axis of the member shall not exceed $0.6d_v \cot\theta$ or 400 mm.

8.4.6.2

If V_f exceeds $0.11\lambda\phi_c f_c' b_w d_v + V_p$ or if T_f exceeds $0.25T_{cr}$, the maximum spacings specified in Clauses 8.4.6.1 shall be reduced by one-half.

8.4.7 Proportioning of longitudinal reinforcement

8.4.7.1 Extension of longitudinal reinforcement

At every section, the longitudinal reinforcement shall be designed to resist the additional tension forces caused by shear as specified in Clauses 8.4.7.2 and 8.4.7.3. Alternatively, for members not subjected to significant tension or significant torsion, these requirements may be satisfied by extending the flexural tension reinforcement by the larger of distance $1.3d$ or $d \cot\theta$ beyond the location needed by flexure alone.

8.4.7.2 Flexural tension side

Longitudinal reinforcement on the flexural tension side shall be proportioned so that the factored resistance of the reinforcement at all sections, taking account of the stress that can develop in this reinforcement, shall be greater than or equal to the force $F_{\ell t}$, as follows:

$$F_{\ell t} = \frac{M_f}{d_v} + 0.5N_f + 1.3\left(V_f - 0.5V_{sF} - V_p\right) \qquad \textbf{(8-29)}$$

where M_f and V_f are taken as positive quantities and N_f is positive for axial tension and negative for axial compression. In Equation (8-29), d_v is the flexural lever arm corresponding to the factored moment resistance.

8.4.7.3 Flexural compression side

At sections where the moment term, M_f/d_v, in Equation (8-29) is less than the sum of the terms accounting for axial load and shear, longitudinal reinforcement on the flexural compression side of the section shall be proportioned so that the factored tensile resistance of this reinforcement, taking account of the stress that can be developed in this reinforcement, shall be greater than or equal to the force $F_{\ell c}$, as follows:

$$F_{\ell c} = 0.5N_f + 1.3\left(V_f - 0.5V_{sF} - V_p\right) - \frac{M_f}{d_v} \qquad \textbf{(8-30)}$$

where M_f and V_f are taken as positive quantities and N_f is positive for axial tension and negative for axial compression.

8.4.7.4 Compression fan regions

In regions adjacent to maximum moment locations, the area of longitudinal reinforcement on the flexural tension side of the member need not exceed the area required to resist the maximum moment acting alone. This provision shall apply only if the support or the load at the maximum moment location introduces direct compression into the flexural compression face of the member and the member is not subject to significant torsion.

8.4.7.5 Anchorage of longitudinal reinforcement at end supports

At exterior direct bearing supports, the longitudinal reinforcement on the flexural tension side of the member shall be capable of resisting a tensile force of $(V_f - 0.5V_{sF} - V_p)\ cot\ \theta + 0.5N_f$, with V_{sF} being based on the transverse reinforcement provided within a length of $d_v\ cot\ \theta$ from the face of the support. However, V_{sF} shall not be taken as greater than V_f. The tension force in the reinforcement shall be developed at the point where a line inclined at angle θ to the longitudinal axis and extending from the inside edge of the bearing area intersects the centroid of the reinforcement. Figure 3(b).

8.4.8 Sections subjected to combined shear and torsion

8.4.8.1 Transverse reinforcement for combined shear and torsion

The transverse reinforcement for combined shear and torsion shall be equal to the sum of that required for shear and that required for the coexisting torsion.

8.4.8.2 Transverse reinforcement for torsion

The amount of transverse reinforcement required for torsion shall be such that

$$T_r \geq T_f \qquad \textbf{(8-31)}$$

8.4.8.3 Factored torsional resistance

The value of T_r shall be calculated from

$$T_r = \frac{2A_o \phi_F A_{Ft} f_{Ft}}{s} \cot\theta \qquad \textbf{(8-32)}$$

where

$A_o = 0.85A_{oh}$

θ = specified in Clause 8.4.4.9.

The quantity f_{Ft} in Equation (8-32) shall not be greater than $0.4f_{Fu}$ or 1200 MPa, where f_{Fu} is the ultimate strength of a FRP bar.

8.4.8.4 Cross-sectional dimensions to avoid crushing

The cross-sectional dimensions to avoid crushing shall be as follows:

(a) for box sections:

$$\frac{V_f - V_p}{b_w d_v} + \frac{T_f}{1.7A_{oh}t_w} \leq 0.2\phi_c f_c' \qquad \textbf{(8-33)}$$

where

t_w = the wall thickness of box section or wall thickness of an idealized hollow section that is assumed to be not greater than either the ratio A_{oh}/p_h or two times the minimum clear cover to the closed transverse torsion reinforcement; and

(b) for other sections:

$$\sqrt{\left(\frac{V_f - V_p}{b_w d_v}\right)^2 + \left(\frac{T_f}{1.7A_{oh}t_w}\right)^2} \leq 0.2\phi_c f_c' \qquad \textbf{(8-34)}$$

8.4.8.5 Determination of ε_l

The value ε_l for a section subjected to torsion and shear should be determined by replacing the term $(V_f - V_p)$ in Equation (8-25) by the following:

$$\sqrt{(V_f - V_p)^2 + \left(\frac{0.9p_h T_f}{2A_o}\right)^2} \qquad \textbf{(8-35)}$$

In evaluating the Equations (8-22) and (8-32), the angle θ shall not be taken greater than 60° nor less than 30°.

8.4.8.6 Proportioning longitudinal reinforcement

The longitudinal reinforcement shall be proportioned to satisfy the requirements of Clause 8.4.7, except that the term ($V_f - 0.5V_{sF} - V_p$) shall be replaced by the following expression:

$$\sqrt{\left(V_f - 0.5V_{sF} - V_p\right)^2 + \left(\frac{0.45 p_h T_f}{2A_o}\right)^2} \quad \textbf{(8-36)}$$

8.5 Strut-and-tie model

8.5.1 Structural idealization

The strength of reinforced concrete structures, members, or regions may be investigated by idealizing the reinforced concrete as a series of reinforcing FRP tensile ties and concrete compressive struts interconnected at nodes to form a truss capable of carrying all of the factored loads to the supports. In determining the geometry of the truss, account shall be taken of the required dimensions of the struts and ties.

8.5.2 Proportioning of strut

8.5.2.1 Strength of strut

The dimensions of a strut shall be large enough to ensure that the calculated compressive force in the strut does not exceed $\phi_c f_{cu} A_{cs}$ where f_{cu} and A_{cs} are determined in accordance with Clauses 8.5.2.2 and 8.5.2.4.

8.5.2.2 Effective cross-sectional area of strut

The value of A_{cs} shall be calculated by considering both the available net concrete area and the anchorage conditions at the ends of the strut, as shown in Figure 3.

8.5.2.3 Net cross sectional area of strut

The net concrete area in Clause 8.5.2.2 shall be determined by considering only the area of concrete in the strut cross-section being investigated.

8.5.2.4 Limiting compressive stress in struts

The value of f_{cu} shall be calculated from

$$f_{cu} = \frac{f'_c}{0.8 + 170\varepsilon_1} \le 0.85 f'_c \quad \textbf{(8-37)}$$

where

$$\varepsilon_1 = \varepsilon_F + \left(\varepsilon_F + 0.002\right)\cot^2\theta_s \quad \textbf{(8-38)}$$

θ_s = the smallest angle between the strut and the adjoining ties
ε_F = the tensile strain in the tie bar located closest to the tension face of the beam and inclined at θ_s to the strut

If the tensile strain in the tie changes as the tie crosses the width of the strut, θ_s may be taken as the strain in the tie at the centreline of the strut.

8.5.3 Proportioning of ties

8.5.3.1 Strength of ties
The area of reinforcement in the tie, A_{FT}, shall be large enough to ensure that the calculated tensile force in the tie does not exceed $0.65\phi_F A_{FT} f_{Fu}$.

8.5.3.2 Anchorage of ties in node regions
The tie reinforcement shall have appropriate development length so that it is capable of resisting the calculated tension in the reinforcement at the location where the centroid of this reinforcement crosses the edge of the adjoining strut. For straight bars extending a distance beyond the critical location where $x < \ell_d$, the calculated stress shall not exceed $0.65\phi_F A_{FT} f_{Fu} (x/\ell_d)$, where ℓ_d is the required development of the bar.

8.5.4 Proportioning of node regions

8.5.4.1 Stress limits in node regions
Unless special confinement is provided, the calculated concrete compressive stress in the node regions shall not exceed the following:
(a) $0.85\phi_c f_c'$ in node regions bounded by struts and bearing areas;
(b) $0.75\phi_c f_c'$ in node regions anchoring a tie in only one direction; and
(c) $0.65\phi_c f_c'$ in node regions anchoring ties in more than one direction.

8.5.4.2 Satisfying stress limits in node regions
The stress limits in node regions may be considered satisfied if
(a) the bearing stress on the node regions based on net concrete area produced by concentrated loads or reactions does not exceed the stress limits specified in Clause 8.5.4.1; and
(b) the tie reinforcement is uniformly distributed over an effective area of concrete at least equal to the tie force divided by the stress limits specified in Clause 8.5.4.1.

8.5.5 Crack control reinforcement
Structures, members, or regions (other than slabs or footings) that have been designed in accordance with Clause 8.5 shall contain an orthogonal grid of reinforcing bars near each face. The ratio of reinforcement area to gross concrete area shall be not less than 0.004 for GFRP and AFRP, and 0.003 for CFRP in each direction. The spacing of this reinforcement shall not exceed 200 mm for GFRP and AFRP and 300 mm for CFRP bars. If located within the tie, the crack control reinforcement may also be considered as tie reinforcement.

8.6 Special provisions for brackets and corbels

8.6.1
Brackets and corbels shall be designed in accordance with Clause 8.5 and Clauses 8.6.2 to 8.6.8

8.6.2
The depth, d, at the face of a support shall be not less than the distance between the load and the face of the support.

8.6.3
The depth at the outside edge of the bearing area shall be not less than one-half of the depth at the face of the support.

8.6.4
The external tensile force, N_f, acting on the bearing area shall not be taken as less than $0.2V_f$ unless special provisions are made to avoid tensile forces.

8.6.5
In lieu of the crack control reinforcement specified in Clause 8.5.5, closed stirrups or ties parallel to the primary tensile tie reinforcement, A_{FT}, and having a total area of not less than $0.65A_{FT}$, shall be distributed within two-thirds of the effective depth adjacent to A_{FT}.

8.6.6
The ratio A_{FT}/bd calculated at the face of the support shall be not less than $0.04\ (f'_c/0.01E_F)$.

8.6.7
At the front face of the bracket or corbel, the primary tensile tie reinforcement, A_{FT}, shall be anchored to develop the required force in the tension tie.

8.6.8
The bearing area of the load on the bracket or corbel shall not project beyond the straight portion of the tension tie bars or beyond the interior face of the transverse anchor bar, if one is provided.

8.7 Punching shear

8.7.1 General
Unless specified otherwise in this standard, FRP reinforced concrete members shall be designed for punching shear using the relevant provisions of CAN/CSA-A23.3 and Clause 8.7.2 of this standard.

8.7.2 Punching shear resistance
The factored shear stress resistance of concrete due to punching shall not exceed the limits specified in CAN/CSA-A23.3 and in this clause

(a) $$v_r = v_c = \left(1 + \frac{2}{\beta_c}\right)\left[0.028\ \lambda\phi_c\left(E_F\rho_F f'_c\right)^{\frac{1}{3}}\right] \quad \textbf{(8-39)}$$

where

β_c = the ratio of the long side to short side of the column, concentrated load , or reaction area

(b) $$v_r = v_c = \left[\left(\frac{\alpha_s d}{b_o}\right) + 0.19\right]\ 0.147\lambda\phi_c\left(E_F\rho_F f'_c\right)^{\frac{1}{3}} \quad \textbf{(8-40)}$$

where

α_s = 4 for interior columns, 3 for edge columns, and 2 for corner columns

(c) $$v_r = v_c = 0.056\ \lambda\phi_c\left(E_F\rho_F f'_c\right)^{\frac{1}{3}} \quad \textbf{(8-41)}$$

8.7.3 Maximum value of f'_c
When calculating V_c by Equations (8-39), (8-40), and (8-41), the value of f'_c used in these equations shall not exceed 60 MPa.

8.7.4 Size effect on punching shear resistance
If the effective depth d of the structural slab systems exceeds 300 mm, the value of V_r obtained from Equations (8-39), (8-40), and (8-41) shall be multiplied by $(300/d)^{0.25}$.

9 Development and splices of reinforcement

9.1 Symbols

The following symbols are used in Clause 9:

A_b = area of an individual bar
A_F = area of FRP reinforcement
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_F = design stress in FRP tension reinforcement at ultimate limit state
f_{Fu} = ultimate strength of FRP shear reinforcement
f'_c = specified compressive strength of concrete
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_a = length of effective bearing for strut anchored by reinforcement; additional embedment length at support or at point of inflection (see Clause 9.7.3.)
ℓ_d = the development length of bars in tension
M_f = factored moment resistance
S_G = FRP grid spacing parallel to the bending direction under investigation
V_f = factored shear force

9.2 Development of reinforcement — General

9.2.1

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.

9.2.2

Mechanical devices and hooks shall not be used to develop bars in tension unless it has been demonstrated by proper testing that closely simulate field conditions that they can develop at least 1.67 times at least the required level of tension in the bar.

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 or shall be calculated in accordance with Clauses 9.3.2 , but it shall not be less than 300 mm.

9.3.2 Development length

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

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

but d_{cs} shall not be greater than $2.5d_b$ and $\sqrt{f'_c}$ shall not be greater than 5 MPa.

9.3.3 Modification factors

The following modification factors shall be used in calculating the development length in Clauses 9.3.2:

(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 $A_b \leq 300\text{mm}^2$
= 1.0 for $A_b > 300\text{mm}^2$

(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 tests. In the absence of direct test 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

For other surface treatments or combinations of surface profiles and treatment, k_5 shall be obtained from bond tests in accordance with CSA S807.

9.3.4 Development length of bundled bars

The development length of individual bars within a bundle shall be provided by the manufacturer. The number of bars in a single bundle shall not be greater than three bars.

9.3.5

GFRP bars larger than 25 mm in diameter and AFRP and CFRP bars larger than 20 mm in diameter shall not be bundled in beams or girders.

9.3.6

Individual bars in a bundle cut off within the span of flexural members shall terminate at different points at least 45 bar diameter apart.

9.3.7

Where spacing limitation and clear concrete cover are based on bar size, a unit of bundled bars shall be treated as a single bar with a diameter giving an area equal to the total area of the bundle under consideration.

9.3.8

The development length, ℓ_d, may be multiplied by the factor (A_F required)/(A_F provided) where reinforcement in a flexural member exceeds that required by analysis, except where anchorage or development for design strength is specifically required for the reinforcement.

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

$$\ell_d = 3.3 k_2 k_4 \frac{A_G}{S_G} \frac{f_F}{\sqrt{f'_c}} \qquad \textbf{(9-2)}$$

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

9.5 Development length of bent bar

The development length of the bent bar should be taken as:

$$\begin{cases} 165 k_2 \dfrac{d_b}{\sqrt{f'_c}} \text{ for } f_F \le 520 \text{ MPa} & \textbf{(9-3)} \\ \dfrac{f_F}{3.1} k_2 \dfrac{d_b}{\sqrt{f'_c}} \text{ for } 520 < f_F \le 1040 \text{ MPa} & \textbf{(9-4)} \\ 330 k_2 \dfrac{d_b}{\sqrt{f'_c}} \text{ for } f_F > 1040 \text{ MPa} & \textbf{(9-5)} \end{cases}$$

provided that the calculated development length is not less than $12d_b$ or 230 mm.

The tail length of a bent bar, ℓ_t, should not be less than $12d_b$. The bend radius, r_b, should not be less than $3d_b$.

9.6 Development of flexural reinforcement — General

9.6.1

Critical sections for development of reinforcement in flexural members are located 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.

9.6.2

Reinforcement shall extend beyond the point at which it is no longer required to resist flexure as specified in Clause 8.4.7.

9.6.3

Continuing reinforcement shall have an embedment length of not less than the development length, ℓ_d, plus the longer of the effective depth of the member or $12d_b$ beyond the point where terminated tension reinforcement is no longer required to resist flexure.

9.6.4

Special attention shall be given to providing 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.

9.7 Development of positive moment reinforcement

9.7.1

At least one-third of the positive moment reinforcement in simply supported members and one-quarter of the positive moment reinforcement in continuous members shall extend along the same face of the member into the support. In beams constructed monolithically with the support, such reinforcement shall extend into the support at least 150 mm, but not less than required by Clause 8.4.7.

9.7.2

When a flexural member is part of a primary lateral load resisting system, the positive moment reinforcement required by Clause 9.7.1 to be extended into the support shall be able to develop its design strength in tension at the face of the support by embedment length or proven mechanical system.

9.7.3

At simple supports and at points of inflection, the positive moment tension reinforcement shall be limited to a diameter such that ℓ_d calculated for the design strength by the method specified in Clause 9.3.2 shall satisfy the following equation:

$$\ell_d \leq \frac{M_r}{V_f} + \ell_a \qquad \textbf{(9-6)}$$

where, at a support, ℓ_d shall be the embedment length beyond the centre of the support, and at a point of inflection, ℓ_a shall be limited to the effective depth of the member or $12d_b$, whichever is greater.

The value of M_r/V_f may be increased by 15% when the ends of the reinforcement are confined by a compressive reaction.

9.8 Development of negative moment reinforcement

9.8.1

Negative moment reinforcement in a continuous, restrained, or cantilever member, or in any member of a rigid frame, shall be anchored in or through the supporting member by embedment length, hooks, or mechanical anchorage. The anchorage ability of the hooks and mechanical anchorages shall be demonstrated by suitable test results.

9.8.2

At least one-third of the total tension reinforcement provided for negative moment at a support shall have an embedment length beyond the point of inflection of not less than the effective depth of the member, $12d_b$, or 1/16 of the clear span, whichever is greater.

9.9 Anchorage of shear reinforcement

9.9.1

Web reinforcement shall be carried as close to the compression and tension surfaces of a member as practically feasible.

9.9.2

Unless it is determined that the shear reinforcement can develop its design strength at mid-height of the beam or column cross-section, FRP web reinforcement shall consist of closed loops or spiral reinforcement.

9.9.3

The web reinforcement shall have sufficient development length to develop its design stress at mid-height of the member.

9.10 Splices of reinforcement — General

9.10.1

Splices of reinforcement shall be made only as required or permitted by design drawings or specifications, or as authorized by the designer.

9.10.2
Unless demonstrated by proper testing that closely simulates field conditions and as per Clause 5.1.2, lap splices shall not be used for bars larger than 30 mm in diameter.

9.10.3
The lap splice length shall be 1.3 ℓ_d, where ℓ_d is the basic development length of the bar.

9.10.4
Lap splices of bundled bars shall be based on the lap splice length required for individual bars within a bundle, increased by 20% for a two-bar bundle and 30% for a three-bar bundle. Individual bar splices within a bundle shall not overlap.

9.10.5
Spliced bars in flexural members shall have a transverse spacing not exceeding the lesser of one-fifth of the required lap splice length or 130 mm.

9.11 Mechanical anchorage
Mechanical anchorage including headed bars or headed studs may be used, provided their effectiveness has been demonstrated by tests that closely simulate the condition in the field and that they can develop at least 1.67 times the required design strength.

10 Design of concrete components prestressed with FRP

10.1 Symbols
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 calculate A is 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 = modulus of elasticity of FRP reinforcement
E_s = modulus of elasticity of steel reinforcement
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_{dc} = decompression moment, equal to the moment when the compressive stress on the tensile face of a prestressed member is zero
M_f = factored moment
M_r = factored moment resistance
N = number of tendon groups tensioned
n = modular ratio
$P_{(x)}$ = 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
t = time in days
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} = factored 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 4.4 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
Δ_{AS} = magnitude of anchorage slip
ΔP_T = variation of prestressing force due to temperature
ΔP_Y = variation of prestressing force due to change in temperature
Δ_T = temperature change
$\Delta\sigma_{pAS}$ = prestress loss due to anchorage slip
$\Delta\sigma_{pES}$ = prestress loss due to elastic shortening
$\Delta\sigma_{pT}$ = prestress loss due to temperature change
ε_{cu} = ultimate compressive strain in concrete
λ = factor to account for low density concrete; or friction parameter per unit length of tendon
μ = coefficient of friction
ϕ_c = resistance factor for concrete
ϕ_F = resistance factor for FRP rebars
ϕ_S = resistance factor for steel rebars
Ω_u = bond reduction coefficient

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 shall be in accordance with Clause 7.1.4. GFRP shall not be used as prestressed reinforcement in concrete.

(b) FRP prestressed concrete members shall not be designed to crack under service loads.

(c) A perfect bond shall be considered between FRP and concrete.

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

(e) The deflection of FRP prestressed concrete members shall be determined either in accordance with Clause 9.8.4 of CAN/CSA-A23.3 or by integration of curvature along the span of the beam.

(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) The strain in reinforcement and concrete shall be assumed to be directly proportional to the distance from the neutral axis, except for unbonded tendons, deep flexural members, and regions of discontinuities.

(b) The maximum concrete strain in compression fibre shall be assumed to be 0.0035.

(c) Balanced failure strain conditions for FRP prestressed members shall 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 shall be neglected in the calculation of the factored flexural resistance of prestressed concrete members.

(e) For all FRP prestressed concrete members, the FRP may be allowed to rupture, provided that the structure as a whole contains supplementary reinforcement designed to carry at least 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).

Concrete cover may 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): $0.25\lambda\sqrt{f'_{ci}}$; and

(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: $0.60f'_c$; and

(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 8. 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 8.

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 in accordance with

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

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 calculated using the following formula:

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

where

L = length of tendon between anchorages

10.6.2.3

Prestress loss due to elastic shortening shall be calculated using the following formulas:
(a) for pretensioned strands:

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

(b) for post-tensioned strands:

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

10.6.2.4

The effect of friction loss in post-tensioning tendons shall be calculated using the following formula:

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

The values of μ and λ shall be determined by testing, except that where the sheaths are used with CFRP, the values μ = 0.3 and λ = 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.

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 following formula:

$$\Delta\sigma_{pT} = \Delta T\left(\alpha_F - \alpha_c\right)E_F \qquad \textbf{(10-6)}$$

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 limit state shall be calculated through Equations (10-7) and (10-8) simultaneously for f_{Fpr}.

$$f_{Fpr} = f_{Fpe} + \Omega_u E_F \varepsilon_{cu}\left(\frac{d_{Fp}}{c} - 1\right)\left(\frac{L_1}{L_2}\right) \qquad \textbf{(10-7)}$$

$$A_{Fp}\phi_{Fp}f_{Fpr} + A_F\phi_F f_F - A_s'\phi_s f_y' = \alpha_1\phi_c f_c'\left(b - b_w\right)h_f + \alpha_1\phi_c f_c' b_w \beta_1 c \qquad \textbf{(10-8)}$$

where

$$\Omega_u = \frac{3.0}{L/d_{Fp}} \text{ for single point loading} \qquad \textbf{(10-9)}$$

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

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 at a distance of 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:

$$M_r \geq 1.5M_{cr} \qquad \textbf{(10-11)}$$

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:

$$M_r \geq 1.6M_f \qquad \textbf{(10-12)}$$

(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 9.

10.10 Shear reinforcement

Members subjected to shear shall be proportioned so that

$$V_f \le V_r \tag{10-13}$$

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

$$V_r = V_c + V_{sF} + 0.5V_p + \frac{M_{dc}}{\frac{M_f}{V_f}} \tag{10-14}$$

The ratio M_f/V_f in Equation (10-14) shall not be less than the height of the member.

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

$$V_r = V_c + V_{ss} + 0.90V_p \tag{10-15}$$

The values of V_c, V_{sF}, and V_{ss}, shall be calculated as specified in Clause 8.4.4.

In Equations (10-14) and (10-15), V_p shall be taken as positive if it acts opposite to the direction of the applied shear force.

10.11 Web crushing

To avoid web crushing, due to shear, the maximum factored shear shall not exceed the limit specified in Clause 8.4.4.4.

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

$$\ell_d = L_T + L_{fb} \tag{10-16}$$

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

$$L_t = \frac{f_{Fpi} d_b}{\alpha_t f_{ci}'^{\,0.67}} \tag{10-17}$$

The transfer length shall not be less than the relevant value shown in Table 10 .

(c) The flexural bond length shall be taken as

$$L_{fb} = \frac{\left(f_{Fpu} - f_{Fpe}\right) d_b}{\alpha_f f_c'^{\,0.67}} \tag{10-18}$$

(d) For AFRP, Table 10 may be used as an alternative to performing the calculations specified in Items (a) and (c), in order to obtain values of development length and transfer length.

(e) For CFRP the relevant requirements of Items (a), (b), and (c) and Table 10 shall apply.

11 Strengthening of concrete masonry and steel components with FRP

11.1 Symbols

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
d_v = effective shear depth for internal steel equal to 0.9 d or 0.72 h, whichever is greater;
E_c = modulus of elasticity of concrete
E_F = modulus of elasticity of FRP composite
f'_c = specified compressive strength of concrete
f'_{cc} = specified confined compressive strength of concrete in columns
f'_{cm} = specified confined compressive strength of masonry
f_F = stress in FRP composite, bar, laminate, or jacket
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; overall height of a beam; overall thickness of a slab; height of corbel
k_1 = concrete strength factor for the bond-reduction coefficient calculation
k_2 = FRP bond configuration factor for the bond-reduction coefficient calculation
k_c = confinement coefficient
k_ℓ = confinement parameter
L = width of shear wall
L_e = effective anchorage length of externally bonded FRP
ℓ_a = anchorage length for externally-bonded FRP laminates beyond the point where no strengthening is required
ℓ_d = anchorage length for near surface mounted reinforcement beyond the point where no strengthening is required
M_f = bending moment due to factored loads
m = 1 or 2 depending on the number of wall faces reinforced
$NSMR$ = near-surface mounted reinforcement
n = number of legs of transverse column ties in the loading direction
n_F = number of plies of FRP reinforcement
P_d = 0.9 of the dead load on the critical shear cross section in a masonry wall
p_F = volumetric ratio of transverse FRP reinforcement of a column
s = spacing of stirrup of a beam, spacing of transverse reinforcement or spiral pitch in a column; or spacing of transverse reinforcement of a wall

s_F = spacing of FRP shear reinforcement of a beam or unit width of a continuous FRP shear reinforcement
t_F = nominal thickness of a single ply of FRP laminate
V_c = shear resistance provided by concrete
V_F = shear resistance provided by FRP reinforcement
V_f = shear force due to factored loads
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
w_F = width of FRP strips used for shear strengthening
α_F = orientation angle of the fibres with respect to the longitudinal axis
β = factor accounting for shear resistance of cracked concrete
γ_g = factor to account for partially grouted or ungrouted walls
Δ_F = increase in axial force
ε_{ci} = initial strain in concrete at the level of the FRP
ε_{cu} = ultimate compression strain of concrete
ε_{Fu} = ultimate strain in FRP reinforcement
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
ε'_{cc} = strain corresponding to peak load in confined concrete
ε'_{co} = concrete strain corresponding to its strength f'_c
θ = acute angle of fibre direction to member axis
κ_v = bond reduction coefficient
λ = factor to account for low-density concrete and concrete masonry units
ϕ_c = resistance factor of concrete
ϕ_F = resistance factor of FRP composites
ϕ_m = resistance factor of masonry
ϕ_s = resistance factor of reinforcing steel

11.2 General design requirements

11.2.1 General

Before applying any strengthening technique, the following points shall be considered:

(a) An assessment of the existing structure that is to be strengthened shall be undertaken in accordance with Clause 11.6.
(b) Surface-bonded FRP reinforced materials shall conform to the requirements of Clause 7.2.
(c) All surface-bonded FRP reinforced components shall be designed as structural elements in accordance with Clauses 5 and 6.
(d) 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.
(e) 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
  (i) determine the condition of the existing materials;
  (ii) establish the structure's load-carrying capacity; and
  (iii) evaluate the feasibility of using externally bonded FRP systems.
(f) When FRP reinforcement is used for enhancement of seismic resistance of members, in addition to the requirements of Clause 11, the relevant provisions of Clause 12 shall also apply.

11.2.2

When applying any strengthening technique, due consideration shall be given to the existing internal reinforcement arrangement and its effect on the performance of the strengthening system.

11.2.3 Required information

11.2.3.1

Prior to undertaking any strengthening, a detailed description of the system shall be provided, including
(a) a description and identification of the product or system involved; and
(b) restrictions or limitations of the selected system.

11.2.3.2

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.

11.2.4 Structural design

11.2.4.1

When a concrete, masonry, or steel component is to be strengthened with surface-bonded FRP, a check shall first be made to ensure that it is capable of supporting the specified (unfactored) loads without any strengthening. If this condition is not satisfied, the strengthening system shall include, in addition to the surface-bonded FRP, other measures that would enable it to support these loads without any FRP strengthening.

The engineering analysis shall consider both ultimate and serviceability limit states and shall take into account the following three states of the structure:
(a) the existing structure prior to strengthening;
(b) the structure after strengthening with the FRP fully effective; and
(c) the structure after strengthening with the FRP no longer effective.

11.2.4.2

The design criteria outlined in Clauses 11.3 to 11.9 do not eliminate the need for structural testing. Situations not covered in Clauses 11.3 to 11.9 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 11.9.

11.3 Design requirements for concrete beam strengthening

11.3.1 Flexural strength

11.3.1.1

The provisions of Clause 11.3.1 shall apply to concrete beams strengthened with surface bonded FRP laminates or near-surface mounted FRP reinforcement (NSMR). If the clear concrete cover is less than 20 mm, NSMR shall not be used.

11.3.1.2

The factored moment resistance shall be based on strain compatibility and equilibrium using material resistance factors and material properties specified in Clause 7.2 and the following additional assumptions:
(a) The strain in reinforcement and concrete shall be assumed to be directly proportional to the distance from the neutral axis, except for unbonded tendons, deep flexural members, and regions of discontinuities.
(b) Perfect bond shall exist between concrete, steel, and FRP composites.

(c) The maximum strain at the extreme compression fibre shall be assumed as 0.0035.

11.3.1.3

The maximum tensile strain in the FRP laminate shall be taken not greater than

$$\varepsilon_{F\max} = 0.41\sqrt{\frac{f_c'}{n_F E_F t_F}} \qquad \textbf{(11-1)}$$

ε_{Fmax} shall not exceed 0.007.

11.3.1.4

The maximum tensile strain in the FRP NMSR reinforcement shall not exceed 0.007.

11.3.1.5

At service loads, stresses shall be calculated based on linear 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.

11.3.1.6

In addition to the failure modes specified in Clause 11.3.1.5, the following modes of debonding failure shall be considered, using currently available information appropriate to the combination of FRP reinforcing system and adhesive:

(a) shear/tension failure of concrete substrate in the vicinity of the FRP cutoff point (anchorage failure or concrete cover separation); and

(b) debonding of adhesive bond line due to vertical section translations caused by cracking (delamination).

11.3.1.7

The initial strains and stresses in a member 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 following equation:

$$f_F = E_F(\varepsilon_F - \varepsilon_{ci}) \qquad \textbf{(11-2)}$$

11.3.1.8

Debonding of the FRP shall be considered in the design. Transverse anchorage using FRP laminates or other proven anchorage methods may be used to achieve the design strength in accordance with Clause 11.3.1.1.

11.3.1.9

For surface-bonded FRP strengthening systems, the anchorage length beyond the point where no strengthening is required shall be not less than ℓ_a, calculated as

$$\ell_a = \sqrt{\frac{n_F E_F t_F}{\sqrt{f_c'}}} \qquad \textbf{(11-3)}$$

ℓ_a shall be not less than 300 mm or the FRP shall be suitably anchored. The effectiveness of the anchoring system shall be demonstrated by tests that closely simulate field conditions and in accordance with Clauses 5.1.2 and 5.1.3.

11.3.1.10

The anchored length ℓ_a given by Equation (11-3) may be reduced by multiplying it by the ratio of the maximum ultimate tensile force that the FRP is required to resist, $F_{required}$, to the maximum tensile force that it can develop, $F_{provided}$, but ℓ_a shall be not less than 300 mm.

11.3.1.11

When calculating the forces $F_{required}$ and $F_{provided}$ in Clause 11.3.1.10, the maximum strain in the FRP shall not exceed the limits specified in Clause 11.3.1.3

11.3.1.12

In one-way slabs, the flexural strength shall be determined as in a beam of unit width, but the spacing of external FRP laminate strips or bars shall not be greater than three times the slab thickness or 400 mm.

11.3.2 Shear strength

11.3.2.1

The provisions of Clause 11.3.2 shall apply to concrete beams strengthened with surface bonded FRP or NSMR FRP bars.

11.3.2.2

If the clear concrete cover is less than 20 mm, NSMR shall not be used.

11.3.2.3

Beams with total depth less than 300 mm shall not be strengthened for shear except as specified in Clause 11.3.2.4.

11.3.2.4

Beams with depth smaller than 300 mm may be strengthened for shear, provided the beam is fully wrapped on all four faces with FRP laminate, or a proven anchorage system is used to develop the design strength of the externally bonded FRP shear reinforcement.

11.3.2.5

The factored shear resistance of the retrofitted beam shall be determined as

$$V_r = V_c + V_s + V_F \leq 0.25\phi_c f_c' b_w d_v \quad \textbf{(11-4)}$$

where V_c and V_s are the contributions of the concrete and steel to the shear resistance of the retrofitted beam, determined in accordance with the provisions of CAN/CSA-A23.3.

11.3.2.6

The contribution of the FRP to the shear resistance of the retrofitted beam, V_F, shall be calculated using

$$V_F = \frac{\phi_F A_F E_F \varepsilon_F d_v (\cot\theta + \cot\alpha_F)\sin\alpha_F}{s_F} \quad \textbf{(11-5)}$$

where

a_F = the orientation angle of the fibres with respect to the longitudinal axis of the member

11.3.2.7

For beams in which the factored shear force is greater than $0.125\lambda\phi_c f'_c b_w d_v$, the spacing, s_F, shall be the smaller of

$w_F + 0.25d_v$; and $w_F + 300$ mm **(11-6)**

11.3.2.8
In beams with transverse steel, the FRP strips shall be placed between steel stirrups rather than over the steel stirrups.

11.3.2.9
The value of ε_F in Clause 11.3.2.6 shall be calculated as follows:

$\varepsilon_F = 0.006 < 0.75\ \varepsilon_{Fu}$ (for fully wrapped sections) **(11-7)**

$\varepsilon_F = 0.005 < 0.75\ \varepsilon_{Fu}$ (for sections with U-shaped stirrups with proven anchoring system) **(11-8)**

$\varepsilon_F = \kappa_v\ \varepsilon_{Fu} < 0.004$ (for sections with U-shaped stirrups without anchoring or side bonded strips) **(11-9)**

However, higher strain values can be used if they are justified by proper tests that closely simulate the actual field conditions.

11.3.2.10
For U-shaped and side bonded strengthening FRP reinforcement, the bond-reduction coefficient, κ_v, shall be calculated as

$$\kappa_v = \frac{k_1 k_2 L_e}{11900\varepsilon_{FU}} \le 0.75 \quad \textbf{(11-10)}$$

where

$$k_1 = \left(\frac{f_c'}{27}\right)^{\frac{2}{3}} \quad \textbf{(11-11)}$$

$$k_2 = \left(\frac{d_F - L_e}{d_F}\right) \quad \textbf{(11-12)}$$

$$L_e = \frac{23300}{(n_F t_F E_F)^{0.58}} \quad \textbf{(11-13)}$$

11.4 Design requirements for concrete column strengthening

11.4.1 Flexural strength enhancement

11.4.1.1
For the enhancement of flexural strength of columns, FRP composites with fibres oriented along the column shall be used, but FRP reinforcement shall be assumed to resist tension only. Section analysis shall be based on strain compatibility and on the assumption of full bond between concrete, reinforcement, and FRP composites. The unfactored tensile force per unit width provided by each ply of laminate with effective thickness, t_F, shall be

$$\Delta F = t_F f_F \quad \textbf{(11-14)}$$

where

$$f_F = \phi_F E_F \varepsilon_F \le f_{Fu} \quad \textbf{(11-15)}$$

ε_F shall not exceed ε_{Fmax} as specified in Clause 11.3.1.3.

11.4.1.2
Debonding or anchorage failure of the FRP flexural reinforcement shall be considered in columns.

11.4.1.3
Proven anchorage methods shall be used to ensure development of the design strength of the FRP at the section considered.

Note: *A proven anchorage system is one that has been demonstrated by tests closely simulating the field conditions to achieve the required design strength.*

11.4.1.4
The column flexural strength shall be calculated by assuming the maximum concrete compressive strain to be 0.0035 and satisfying the requirements of equilibrium and strain compatibility except as stated in Clause 11.4.1.5.

11.4.1.5
When calculating the column flexural strength if the concrete maximum compressive strain is less than 0.0035, the concrete compressive stress and its distribution shall be determined using a suitable stress-strain relationship.

11.4.2 Axial load capacity enhancement

11.4.2.1
Columns may be externally wrapped with FRP composites to enhance the axial load capacity of the columns. Circular sections, and rectangular sections where the ratio of the longer to shorter section dimension does not exceed 1.5, may have their axial compression capacity enhanced by the confining effect of FRP composite fully wrapped around the column with the main fibres running perpendicular to the longitudinal axis of the member.

11.4.2.2
For rectangular sections confined with transverse FRP laminates, section corners shall be rounded to a radius not less than 20 mm before the FRP application.

11.4.2.3
Axial compression capacity enhancement of rectangular sections with an aspect ratio $h/b > 1.5$ by transverse FRP laminates shall be subject to special analysis confirmed by test results.

11.4.2.4
The axial load capacity of columns transversely retrofitted with FRP wraps may be calculated as specified in CAN/CSA-A23.3 but the concrete strength shall be determined in accordance with Clause 11.4.2.5.

11.4.2.5
The axial capacity of a confined column shall be based on the confined compressive strength of concrete, f'_{cc}. In columns transversely wrapped with FRP laminates, f'_{cc} shall be calculated as follows:

$$f'_{cc} = 0.85 f'_c + k_\ell k_c f_\ell \qquad \textbf{(11-16)}$$

where

$$k_\ell = 6.7 (k_c f_\ell)^{-0.17} \qquad \textbf{(11-17)}$$

k_c = 1.0 for circular and oval jackets
= 0.4 for square and rectangular jackets

$$f_\ell = \frac{2n_F t_F f_F}{D} \quad \textbf{(11-18)}$$

where

f_F = the smaller of $0.006E_F$ or $\phi_F f_{Fu}$

11.4.3 Shear strength enhancement

11.4.3.1

Shear strength of circular and rectangular columns can be enhanced by closed hoop FRP composites with fibres oriented essentially perpendicular to the member axis.

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

For columns with open hoop wrap composites, the shear strengthening requirements of beams as stipulated in Clauses 11.3.2.3 to 11.3.2.9 shall be satisfied.

11.4.3.2

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

$$V_r = V_c + V_s + V_F \leq 0.22\phi_c f_c' A_{cv} \quad \textbf{(11-19)}$$

where V_c and V_s shall be calculated according to the provisions of CAN/CSA-A23.3.

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

$$V_F = 2\phi_F n_F t_F f_F D \quad \textbf{(11-20)}$$

where

$$f_F = 0.006E_F \leq f_{Fu} \quad \textbf{(11-21)}$$

11.5 Design requirements of concrete wall strengthening

11.5.1 General

The provisions of this clause shall not be used for in-plane flexural strengthening of squat shear walls.

Note: *For squat shear walls loaded in–plane, detailed analysis may be required.*

11.5.2 Flexural strength

11.5.2.1

FRP laminates bonded to surfaces of concrete walls with an angle $\theta \leq 15°$ between the vertical axis of the wall and the direction of the main fibres in the laminate can be used to enhance the flexural strength of the walls.

11.5.2.2

Section analysis shall be based on the assumption of strain compatibility between concrete, reinforcement, and FRP laminate material and only the FRP that is in tension shall be considered effective.

11.5.2.3

Unless proven otherwise, the flexural strength shall be determined by assuming a maximum concrete compressive strain of $\varepsilon_{cu} = 0.0035$.

11.5.2.4

The maximum tensile strain in the FRP shall not exceed the limits specified in Clause 11.3.1.3.

11.5.2.5

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

$$\Delta F = \phi_F n_F t_F f_F \cos^2\theta \qquad \textbf{(11-22)}$$

where

$$f_F = \phi_E E_F \varepsilon_F \le f_{Fu} \qquad \textbf{(11-23)}$$

ε_F shall not exceed the ε_F max as specified in Clause 11.3 and 11.5.2.6.

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 θ up to 45° shall be considered.

11.5.2.6

For debonding or anchorage failure of the FRP, the requirements of Clauses 11.3.1.8 to 11.3.1.10 shall be satisfied. Proven anchorage methods shall be used to ensure development of the strength of the FRP at the section considered.

11.5.3 Shear strength enhancement

11.5.3.1

The provisions of this Clause shall be applied only to walls strengthened by FRP laminate bonded to the entire width of the wall.

11.5.3.2

The shear resistance of reinforced concrete shear walls strengthened with FRP laminates shall be determined using

$$V_r = V_c + V_s + V_F \le 0.22\phi_c f_c' b_w d \qquad \textbf{(11-24)}$$

11.5.3.3

The concrete contribution, V_c, in Clause 11.5.3.2 shall be determined as follows:

$$V_c = 0.2\lambda\phi_c\sqrt{f_c'}A_e \qquad \textbf{(11-25)}$$

11.5.3.4

The steel reinforcement contribution, V_s, in Clause 11.5.3.2 shall be determined as follows:

$$V_s = \frac{n\phi_s A_h f_{yh} D'}{s} \qquad \textbf{(11-26)}$$

11.5.3.5

The contribution of the FRP composites, V_F, in Clause 11.5.3.2 shall be determined as follows:

$$V_F = m\phi_F n_F t_F f_F D' \qquad \textbf{(11-27)}$$

where

m = 1 for walls strengthened on one face

= 2 for walls strengthened on both faces

$f_F = 0.004E_F \leq f_{Fu}$

11.5.3.6
Sliding shear failure at construction joints shall be checked and the wall strength shall be accordingly determined.

11.6 Design requirements for masonry beam strengthening

11.6.1 Flexural strength

11.6.1.1
The factored moment resistance shall be based on strain compatibility and equilibrium using material resistance factors and material properties specified in Clause 7 and in CSA S304 with the following additional assumptions:
(a) the strain in reinforcement and concrete shall be assumed to be directly proportional to the distance from the neutral axis, except for unbonded tendons, deep flexural members, and regions of discontinuities;
(b) perfect bond shall be assumed between masonry and FRP composites;
(c) the maximum compressive masonry strain shall be 0.003; and
(d) the maximum tensile strain in the FRP laminate shall not exceed the limits specified in Clause 11.3.1.3, but with concrete compressive strength replaced by masonry compressive strength in Equation (11-1).

11.6.1.2
Under service loads, stresses shall be calculated based on linear elastic analysis. Under ultimate loads, the masonry stress and its distribution shall be obtained using the equivalent rectangular stress block, and the following flexural failure modes shall be investigated for a section strengthened with FRP laminates:
(a) crushing of the masonry in compression before rupture of the FRP or yielding of the steel; or
(b) yielding of the steel and/or rupture of the FRP in tension followed by masonry crushing.

11.6.1.3
In addition to the failure modes specified in Clause 11.6.1.2, the following modes of debonding failure shall be considered, using currently available information appropriate to the combination of laminate and adhesive:
(a) shear/tension failure of masonry substrate near the FRP cutoff point (anchorage failure); and
(b) debonding of adhesive bond line due to vertical section translations caused by cracking.

11.6.1.4
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

$$f_F = E_F\left(\varepsilon_F - \varepsilon_{Fi}\right) \qquad \textbf{(11-28)}$$

11.6.1.5
Debonding of the FRP shall be considered in the design. Transverse anchorage using FRP laminates or other proven anchorage methods shall be used to prevent the failure modes described in Clause 11.6.1.3.

11.6.2 Shear strength

11.6.2.1

The provisions of Clause 11.3.2 shall apply to masonry beams strengthened with surface bonded FRP systems.

11.6.2.2

The factored shear resistance of masonry shall be determined as follows:

$$V_r = V_m + V_{ms} + V_F \leq V_m + 0.36\phi_m \lambda \sqrt{f'_m} b_w d \quad \textbf{(11-29)}$$

where

V_m and V_{ms} = calculated as specified in CSA S304.1

$$V_F = \frac{\phi_F A_F E_F \varepsilon_F d_f}{s_F} \quad \textbf{(11-30)}$$

In the absence of more precise information, the value of ε_F may be assumed to be

(a) for U-shaped wrap continuous around the bottom of the web, $\varepsilon_F = 0.004$; and

(b) for side bonding to the web (and only in cases where sufficient development length cannot be provided), $\varepsilon_F = 0.002$.

11.6.2.3

The bond length of FRP composites shall be sufficient to avoid anchorage failure of the FRP, 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.

11.7 Design requirements for fully-grouted masonry column strengthening

11.7.1 Flexural strength enhancement

11.7.1.1

For the enhancement of flexural strength of columns, FRP composites with longitudinally oriented fibres may be used. If fibres having another orientation are used, the provisions of Clause 11.8.1 shall apply.

11.7.1.2

Section analysis shall be based on strain compatibility among masonry, steel reinforcement, and FRP composites and only the FRP that is in tension shall be considered effective.

11.7.1.3

The enhancement of the factored tensile force per unit width provided by FRP composite shall be

$$\Delta F = \phi_F n_F t_F f_F \quad \textbf{(11-31)}$$

where

$$f_F = E_F \varepsilon_F \leq f_{Fu} \quad \textbf{(11-32)}$$

11.7.1.4

The strain ε_F in Clause 11.7.1.3 shall not exceed the limits specified in Clause 11.3.1.3, provided the concrete strength is replaced by the masonry strength in Equation (11-1).

11.7.1.5
Unless the compression zone is confined by transversely oriented fibres in accordance with Clause 11.7.2.1, an extreme compression strain of $\varepsilon_{cu} = 0.003$ shall be assumed in determining the flexural strength of masonry.

11.7.1.6
Debonding or anchorage failure of the FRP flexural reinforcement shall be considered in the design.

11.7.1.7
Proven anchorage methods shall be used to ensure development of the FRP design strength of the FRP at the section considered.

Note: *A proven anchorage system is one that has been demonstrated by tests closely simulating the field conditions to achieve the required design strength.*

11.7.2 Axial load capacity enhancement

11.7.2.1
FRP composites may be bonded to surfaces of masonry columns to enhance their axial load capacity. 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.

11.7.2.2
The axial load capacity of masonry columns transversely retrofitted with FRP wraps shall be calculated as specified in CSA S304.1, but the masonry strength shall be in accordance with Clause 11.7.2.4 of this Standard.

11.7.2.3
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. The axial compressive strength enhancement by composite material in rectangular sections with an aspect ratio $h/b > 1.5$ shall be subject to special analysis confirmed by test results in accordance with Clauses 5.1.3 and 7.2.8.

11.7.2.4
The axial capacity of a confined masonry column shall be based on the confined compressive strength of masonry, f'_{cm}. In FRP wrapped columns, f'_{cm} shall be calculated as follows:

$$f'_{cm} = 0.85 f'_m + k_\ell k_c f_\ell \quad \textbf{(11-33)}$$

where

$$k_\ell = 6.7 \left(k_c f_\ell\right)^{-0.17} \quad \textbf{(11-34)}$$

k_c = 1.0 for circular and oval jackets

= 0.4 for square and rectangular jackets

$$f_\ell = \frac{2 n_F t_F f_F}{D} \quad \textbf{(11-35)}$$

where

f_F = the smaller of $0.006E_F$ or $\phi_F f_{Fu}$

11.7.3 Ductility enhancement

FRP composites oriented essentially perpendicular to the axis of masonry columns may be used to enhance the flexural ductility capacity of circular and rectangular sections where the ratio of the section longer to shorter 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.

11.7.4 Shear strength enhancement

11.7.4.1

Shear strength of circular and rectangular masonry columns can be enhanced by FRP composites with fibre oriented essentially perpendicular, to the members' axis.

For rectangular sections with shear enhancement provided by transverse FRP composite material, section corners shall be rounded to a radius of not less than 25 mm before placing composite material.

11.7.4.2

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

$$V_r = V_m + V_{ms} + V_F \leq 0.4\phi_m \lambda \sqrt{f'_m}\, b_w d \quad \textbf{(11-36)}$$

V_m and V_{ms} shall be determined in accordance with CSA S304.1.

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

$$V_F = 2\phi_F n_F t_F f_F D \quad \textbf{(11-37)}$$

where

$$f_F = 0.006E_F \leq f_{Fu} \quad \textbf{(11-38)}$$

11.8 Design requirements of masonry wall strengthening

11.8.1 Out-of-plane flexural strength

11.8.1.1

FRP composites bonded to surfaces of masonry walls with fibres orientation $\theta \leq 15°$ to the wall height may be used to enhance the flexural strength of the walls. Only the tension FRP reinforcement shall be considered effective. Section analysis shall be based on strain compatibility between concrete or masonry reinforcement and composite material. Unless the flexural strength is determined by tests closely simulating field conditions, an extreme masonry compression strain of $\varepsilon = 0.003$, and maximum FRP tensile strain not exceeding the limits specified in Clause 11.3.1.2, provided the concrete strength is replaced by the masonry strength in Equation (11-1).

11.8.1.2

The tensile force per unit width provided by FRP composite reinforcement with its fibres, oriented at angle θ to the direction of member axis, shall be

$$\Delta F = \phi_F n_F t_F f_F \cos^2 \theta \quad \textbf{(11-39)}$$

where

$f_F = E_F \varepsilon_F \leq f_{Fu}$

where

ε_F = the strain in the masonry to which the fibre is bonded but not greater than the limits specified in Clause 11.7.1.4

11.8.1.3
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 wall axis, the contribution of fibres with up to 45° shall be considered.

11.8.1.4
Debonding or anchorage failure of the FRP flexural reinforcement shall be considered in the design.

11.8.1.5
Proven anchorage methods shall be used to ensure development of the strength of the FRP at the section considered.

Note: *A proven anchorage system is one that has been demonstrated by tests closely simulating the field conditions to achieve the required design strength.*

11.8.2 In-plane shear strength enhancement

11.8.2.1
The shear-resistant capacity of FRP reinforced masonry shear walls shall be determined as follows:

$$V_r = V_m + V_{ms} + V_F \leq 0.4\phi_m \gamma_g \sqrt{f'_m} b_w d_v \quad \textbf{(11-40)}$$

where

$$V_F = \frac{\phi_F A_F E_F \varepsilon_F d_f}{s_F} \quad \textbf{(11-41)}$$

V_m and V_{ms} shall be in accordance with CSA S304.1.

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 wall web, $\varepsilon_F = 0.004$; and

(b) for side bonding to the wall web (and only in cases where sufficient development length cannot be provided), $\varepsilon_F = 0.002$.

11.8.2.2
The provisions in Clause 11.8.2.1 apply only to walls strengthened by fibre covering the entire length of the wall.

11.8.2.3
The sliding shear failure capacity of the strengthened wall shall not exceed the sliding shear capacity of the unstrengthened wall unless specific measures are taken to increase its sliding shear capacity.

11.9 Design requirements for steel and composite steel-concrete beam strengthening

11.9.1
The factored moment resistance of a steel beam or a composite steel-concrete beam strengthened with FRP composite bonded to its tensile flange shall be based on the assumption of perfect bond and strain compatibility and equilibrium using material resistance factors as specified in Clause 6.5.3.

11.9.2
The maximum tensile FRP strain shall not be taken greater than 0.007, assuming no anchorage failure.

11.9.3
At service loads, stresses shall be calculated based on linear elastic analysis. At ultimate loads, all possible flexural failure modes shall be investigated for a steel or a composite steel concrete section strengthened with FRP laminates. These failure modes include yielding of steel in compression and/or tension, local stability failure, concrete crushing, and concrete-steel interface failure.

11.9.4
In addition to the failure modes specified in Clause 11.9.3, in the case of CFRP strengthening material, galvanic corrosion and the resulting debonding failure shall be considered, using currently available information appropriate to the CFRP and the adhesives and steel involved.

12 Provisions for seismic design

12.1 Symbols
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_{st} = total area of longitudinal steel reinforcement, mm^2

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

d = distance from extreme compression fibre to centroid of tension reinforcement

E_c = modulus of elasticity of concrete

E_F = elastic modulus of FRP composite

F_a = acceleration-based site coefficient, as defined in *National Building Code of Canada* (NBCC)

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

h_c = cross-sectional dimension of column core

I_E = earthquake importance factor of the structure as defined in *National Building Code of Canada* (NBCC)

I_g = moment of inertia of gross concrete section about the centroidal axis, neglecting the reinforcement

k_c = confinement efficiency coefficient

L_v = shear retrofit length

ℓ_o = minimum length measured from the face of the joint along the axis of the column, over which FRP reinforcement must be provided for seismic confinement

P = specified axial load on column section

P_f = factored axial load

P_o = nominal unconfined axial load capacity of column, taken as $\alpha_1 f'_c(A_g–A_{st})+f_yA_{st}$, for columns with longitudinal steel reinforcement and $\alpha_1 f'_c(A_g – A_F)$ for columns with FRP longitudinal reinforcement

P_{ro} = factored axial load resistance at zero eccentricity

R_d = ductility related force modification factor as defined in *National Building Code of Canada* (NBCC)

R_o = over-strength related force modification factor as defined in *National Building Code of Canada* (NBCC)

$S_a(0.2)$ = 5% damped spectral response acceleration, expressed as a ratio to gravitational acceleration, for period $T = 0.2$ s [(defined in the *National Building Code of Canada* (NBCC)]
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 = factored shear resistance
V_s = factored shear resistance provided by the transverse steel reinforcement
Wi = lumped seismic gravity load assigned to level i
Y_p = parameter to account for the effect of axial load on seismic confinement requirement
β_c = confinement efficiency parameter for circular columns
δ = design lateral drift ratio (i.e., horizontal drift/building height)
ε_{cu} = ultimate compressive strain of concrete
λ = factor to account for concrete density
ϕ = curvature of column section, rad/mm
ϕ_c = resistance factor of concrete
ϕ_F = resistance factor or FRP composites
ϕ_j = capacity reduction factor for FRP jacket reflecting the quality of workmanship, not to be taken higher than 0.8
ϕ_s = resistance factor for reinforcing bars

12.2 General

Earthquake resistant buildings reinforced with FRPs shall be designed by recognizing the mechanical characteristics of FRP, in particular; lack of ductility, lower modulus of elasticity, higher ultimate strength, and substantially different bond characteristics, that may result in different strength, stiffness, damping, and seismic force resistance characteristics of structures.

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 either with longitudinal steel and transverse FRP reinforcement; or longitudinal and transverse FRP reinforcement; and
(b) the rehabilitation and repair of existing structures with internal steel reinforcement, in which case the relevant provisions of Clause 11 shall also apply.

12.4 Seismic loads

12.4.1 Seismic loads for repair and retrofit

The seismic loads acting on concrete structures repaired or retrofitted with FRP materials shall be determined in accordance with the relevant provisions of the *National Building Code of Canada* with due considerations given to the strengthening and stiffening effects of FRP and their impact on fundamental period and earthquake induced inertia forces.

12.4.2 Seismic loads for new construction

12.4.2.1

The seismic loads for new concrete structures having seismic force resisting systems (SFRS) that include steel longitudinal and FRP transverse reinforcement, or FRP longitudinal and transverse reinforcement shall be determined in accordance with the relevant provisions of the *National Building Code of Canada*, with the modifications specified in Clauses 12.4.2.2 to 12.4.2.5 of this Standard.

12.4.2.2
The fundamental period, T, of the structure shall be determined in accordance with the relevant provisions of the *National Building Code of Canada* for concrete buildings.

12.4.2.3
When the fundamental period of the structure is calculated by established methods of mechanics in accordance with the relevant provisions of the *National Building Code of Canada*, cracked section properties of FRP reinforced concrete structural elements may be used. For a cracked section, moment of inertia I_{cr} shall be used.

12.4.2.4
Ductility related force modification factor R_d for all FRP reinforced concrete buildings shall be taken as 1.0.

12.4.2.5
Overstrength related force modification factor R_o for all FRP reinforced concrete buildings shall be taken as 1.0.

12.5 Design requirements for column retrofit and rehabilitation

12.5.1 General
FRP composites may be used for seismic retrofit of columns as follows:
(a) surface-bonded FRP composites with fibres oriented in the direction of longitudinal column axis for flexural strength enhancement;
(b) FRP composites wrapped around circular, oval, and rectangular columns with fibres aligned perpendicular to the longitudinal column axis, overlapping a minimum of 100 mm, for concrete confinement. Rectangular column corners shall be rounded to a radius not less than 20 mm before placing the composite material. The ratio of longer, h, to shorter, b, sectional dimensions of rectangular columns shall not exceed 1.5; and
(c) surface bonded or wrapped FRP composites with fibres running essentially perpendicular to the longitudinal column axis for shear strength enhancement.

12.5.2 Retrofit for flexural strength enhancement

12.5.2.1
For the enhancement of flexural strength of columns, FRP composites with fibres oriented along the longitudinal column axis shall be used as specified in Clause 11.4.1.

12.5.2.2
Columns with flexural strength enhancement shall be checked for shear capacity to ensure the prevention of premature shear failure. This may be done by ensuring that the requirements of CAN/CSA-A23.3 are satisfied for columns of ductile ($R_d = 4.0$) and moderately ductile ($R_d = 2.5$) moment-resisting frames, respectively.

12.5.3 Retrofit for enhancement of concrete confinement

12.5.3.1
The thickness of the FRP jacket shall be determined by either Equation (12-1) or Equation (12-2) for concrete confinement unless a larger amount is required by Clause 12.5.4 or 12.5.5.

12.5.3.2
The thickness of the FRP jacket for satisfying a given drift ratio, δ, shall be determined using

$$t_j = 2D\frac{f_c'}{\phi_F f_{Fj}}\frac{P}{P_o}\frac{\delta}{\sqrt{k_c}} \qquad \textbf{(12-1)}$$

where

$\frac{P}{P_o} \geq 0.15$

δ = design lateral drift ratio, which shall not be less than 0.04 for columns in ductile moment-resisting frames (R_d = 4.0) and 0.025 for columns in moderately ductile moment-resisting frames (R_d = 2.5)

k_c = 1.0 for circular and oval jackets

= 0.4 for square and rectangular jackets

The stress in FRP jacket f_{Fj} shall be determined as follows:

(a) for columns with circular and oval jackets, $f_{Fj} = 0.005E_F$ when $\frac{P}{P_o} \leq 0.15$ and $f_{Fj} = 0.01E_F$ when $\frac{P}{P_o} \geq 0.30$ with linear interpolation for in-between values of P/P_0;

(b) for square and rectangular jackets, $f_{Fj} = 0.003E_F$ when $\frac{P}{P_o} \leq 0.15$ and $f_{Fj} = 0.006E_F$ when $\frac{P}{P_o} \geq 0.30$ with linear interpolation for in-between values of P/P_0; and

(c) f_{Fj} shall not be more than $\phi_F f_{Fu}$.

12.5.3.3

The thickness of the FRP jacket for satisfying a certain ductility level shall be determined using

$$t_j = \beta Y_p D\frac{f_c'}{\phi_F f_{Fu}} \qquad \textbf{(12-2)}$$

where

β = constant to account for different cross-section shape and ductility level

= 0.05 for circular columns in ductile moment resisting frames

= 0.025 for circular columns in moderately ductile moment resisting frames

= 0.12 for rectangular columns in ductile moment resisting frames

t_j = 0.06 for rectangular columns in moderately-ductile moment resisting frames

= $n_F t_F$

The factor Y_P reflects the influence of the axial load acting on the column and shall be determined by Equation (12-3).

$$Y_P = 1 + 13\left(\frac{P}{P_o}\right)^5 \qquad \textbf{(12-3)}$$

12.5.3.4

FRP reinforcement in the amount determined in accordance with Equations (11-1) or (11-2) shall be provided continuously over a 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

(a) 1.2 times the width of the column section, D, from the face of the joint or from the section where flexural yielding may occur;

(b) one-sixth of the clear span of the member; or

(c) 600 mm.

12.5.3.5

FRP jacket with at least one-half the thickness computed by Equation (12-1) or (12-2) shall extend beyond length ℓ_o for a distance not less than the column section width D.

12.5.3.6
A gap of 25 mm shall be left 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 with splice lengths being less than that specified in CAN/CSA-A23.3, but not less than 20 times the longitudinal bar diameter.

12.5.4.2
The requirement of Clause 12.5.4.1 may be met by providing the FRP jacket as required by Equation (12-1), with f_{Fj} limited to $0.0015E_F$ or 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 by Clause 12.5.4.2. The length L refers to the clear height of the column.

12.5.4.5
Circular columns with splice lengths in potential plastic hinges of less than 20 times the longitudinal bar diameter shall not be retrofitted by FRP jacketing. Other retrofit strategies shall be sought for such columns.

12.5.4.6
Lap splice regions in square and rectangular columns shall not be retrofitted by FRP jacketing. Other retrofit strategies shall be sought for such columns.

12.5.5 Retrofit for shear strength enhancement

12.5.5.1
For shear strength enhancement of columns, FRP composites shall be used in accordance with Clause 11.4.3.

12.5.5.2
The factored shear resistance of retrofitted columns shall conform to the requirements of of CAN/CSA-A23.3 for columns of ductile ($R_d = 4.0$) and moderately ductile ($R_d = 2.5$) moment-resisting frames.

12.6 Design for shear wall retrofits

12.6.1 General

12.6.1.1
Externally bonded FRP composites may be used as additional reinforcement in the seismic strengthening and repair of reinforced concrete, reinforced masonry, and unreinforced masonry shear walls.

12.6.1.2
FRP sheets for wall retrofits 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.

12.6.1.3
Shear walls retrofitted with externally bonded FRP composites shall be checked against sliding shear at the construction joint and at member ends.

12.6.2 Retrofitting reinforced concrete shear walls

12.6.2.1
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.

12.6.2.2
Seismic retrofit for flexural and shear strength enhancements of concrete walls with surface bonded FRP composites shall conform to Clause 11.5.

12.6.2.3
The vertical FRP sheets used for flexural enhancement shall be anchored to the adjoining elements at the base and at wall ends when moment transfer is expected, by an anchoring system designed to sustain cyclic loading.

12.6.2.4
Reinforced concrete shear walls with insufficient transverse reinforcement in boundary regions at wall ends shall be retrofitted by FRP composites with fibres oriented perpendicular to the longitudinal wall axis, covering the wall ends over wall corners rounded to a minimum diameter of 20 mm.

12.6.3 Retrofitting masonry shear walls

12.6.3.1
Ductile reinforced masonry shear walls retrofitted and/or repaired with FRP shall be designed to continue responding 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.

12.6.3.2
Seismic retrofit for flexural and shear strength enhancements of masonry shear walls with surface bonded FRP composites shall conform Clause 11.8.

12.6.3.3
Unreinforced masonry walls retrofitted with surface-bonded FRP composites shall be designed to respond seismic forces in the elastic range of deformations.

12.7 Seismic design of FRP reinforced concrete in new construction

12.7.1 General

12.7.1.1

Seismic force resisting systems (SFRS) involving the use of FRP reinforcement shall consist of members with

(a) longitudinal steel and transverse FRP reinforcement conforming to Clause 12.7 in this Standard and to the relevant requirements of CAN/CSA-A23.3 for seismic design; and

(b) longitudinal and transverse FRP reinforcement conforming to Clause 12.7.

12.7.1.2

For SFRS involving longitudinal and transverse FRP reinforcement, Clauses 1 to 11 and 13 to 14 of this Standard shall apply to design and detailing of structural members unless modified by Clause 12.

12.7.1.3

Specified compressive strengths used in the SFRS shall not exceed 80 MPa.

12.7.1.4

The specified compressive strength of structural low-density concrete used in the SFRS shall not exceed 30 MPa unless experimental evidence demonstrates that structural members made with such concrete provide strength and toughness equal to or exceeding the strength and toughness of comparable members made with normal-density concrete of the same strength.

12.7.2 Moment resisting frame members with longitudinal steel and transverse FRP reinforcement subjected to predominant flexure

12.7.2.1

Beams of ductile moment-resisting frames ($R_d = 4.0$) shall conform to the geometric and the longitudinal reinforcement requirements of CAN/CSA-A23.3 for seismic design.

Beams of moderately ductile moment-resisting frames ($R_d = 2.5$) shall conform to the longitudinal reinforcement requirements of CAN/CSA-A23.3 for seismic design.

12.7.2.2

Beams of moment-resisting frames shall be reinforced with transverse FRP hoops or FRP grids in accordance with Clause 7.1.5.3 and placed in the following regions of the beams:

(a) over a length equal to $2d$, measured from the face of the joint; and

(b) over regions where plastic hinges can occur and for a distance d on either side of these hinge regions.

12.7.2.3

The first hoop shall be located not more than 50 mm from the face of a supporting member. The maximum spacing of the hoops shall not exceed

(a) $d/4$;

(b) eight times the diameter of the smallest longitudinal bars;

(c) 24 times the cross-sectional dimension of the hoop FRP; or

(d) 300 mm.

12.7.2.4

The factored shear resistance of beams in ductile moment-resisting frames ($R_d = 4.0$) shall satisfy the seismic design requirements of CAN/CSA-A23.3. The shear design of the same beams shall conform to Clause 8.4.4 of this Standard.

12.7.2.5

The factored shear resistance of beams in moderately ductile moment-resisting frames (R_d = 2.5) shall satisfy the requirements of CAN/CSA-A23.3. The shear design of the same beams shall conform to Clause 8.4.4 of this standard.

12.7.3 Moment resisting frame members with longitudinal steel and transverse FRP reinforcement subjected to significant axial load

12.7.3.1

Minimum flexural resistance of columns in ductile moment-resisting frames (R_d = 4.0) shall satisfy the requirements of CAN/CSA-A23.3, as well as the relevant seismic provisions of CAN/CSA-A23.3 with respect to longitudinal column reinforcement.

12.7.3.2

Minimum flexural resistance of columns in ductile moment-resisting frames (R_d = 2.5) shall satisfy the reinforcement seismic requirements of CAN/CSA-A23.3.

12.7.3.3

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. The required area of the transverse FRP reinforcement shall be calculated as follows:

$$A_{sh} = 14 s h_c \frac{f_c'}{f_{Fh}} \left(\frac{A_g}{A_c} - 1 \right) \frac{P}{P_o} \frac{\delta}{\sqrt{k_c}} \qquad \textbf{(12-4)}$$

where

$$\frac{P}{P_o} \geq 0.2$$

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

δ = design lateral drift ratio, which shall not be less than 0.04 for columns in ductile moment resisting frames with R_d = 4.0 and 0.025 for columns in moderately ductile moment resisting frames with R_d = 2.5

f_{Fh} = $0.006E_F$ or $\phi_F f_{Fu}$, whichever is less

k_c = 1.0 for circular spirals and circular hoops

$$= 0.15\sqrt{\frac{h_c}{s}\frac{h_c}{s\ell}} \text{ for rectilinear transverse reinforcement} \qquad \textbf{(12-5)}$$

12.7.3.4

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; or

(c) 6 times the diameter of the smallest longitudinal bar.

12.7.3.5
Transverse reinforcement in the amount specified in Clauses 12.7.3.3 and 12.7.3.4 shall be provided over the length, ℓ_o, from the face of each joint and on both sides of any section where flexural yielding might 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 might occur;
(b) one-sixth of the clear span of the member; or
(c) 450 mm.

12.7.3.6
Where transverse reinforcement, as specified in Clauses 12.7.3.3 to 12.7.3.5, 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.

12.7.3.7
Columns that can develop plastic hinges because of their connection to rigid members, such as discontinued walls or foundations or due to their position at the base of the structure, shall be provided with transverse reinforcement as specified in Clauses 12.7.3.3 and 12.7.3.4 over their clear height. This transverse reinforcement shall continue into the discontinued member for at least the development length of the largest longitudinal reinforcement in the column in accordance with the requirements of CAN/CSA-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 into the footing or mat as required by CAN/CSA-A23.3.

12.7.3.8
Shear strength requirements of columns in ductile moment-resisting frames ($R_d = 4.0$) shall satisfy the requirements of CAN/CSA-A23.3 and shear design shall conform to Clause 8.4.4 of this Standard.

12.7.3.9
Shear strength requirements of columns in moderately ductile moment-resisting frames ($R_d = 2.5$) shall satisfy the requirements of CAN/CSA-A23.3 and shear design shall conform to Clause 8.4.4 of this Standard.

12.7.4 Moment resisting frame members with longitudinal and transverse FRP reinforcement subjected to predominant flexure

12.7.4.1
The positive moment resistance of beams of moment-resisting frames with $I_E F_a S_a(0.2) > 0.75$ at the face of a joint shall be not less than one-half of the negative moment resistance, provided at that face of the joint. Neither the negative nor the positive moment resistance at any section along the member length shall be less than one-quarter of the maximum moment resistance provided at the face of either end point.

12.7.4.2
The positive moment resistance of beams of moment-resisting frames with $I_E F_a S_a(0.2) \leq 0.75$ at the face of a joint shall be not less than one-third of the negative moment resistance, provided at that face of the joint. Neither the negative nor the positive moment resistance at any section along the member length shall be less than one-fifth of the maximum moment resistance provided at the face of either end point.

12.7.4.3
Beams of moment-resisting frames shall be reinforced to have transverse FRP hoops or FRP grids in accordance with Clause 7.1.3 and placed in the following regions of the beams:
(a) over a length equal to $2d$, measured from the face of the joint; and
(b) over regions where plastic hinges can occur and for a distance d on either side of these hinge regions.

12.7.4.4
The first hoop shall be located not more than 50 mm from the face of a supporting member. The maximum spacing of the hoops shall not exceed
(a) $d/4$;
(b) eight times the diameter of the smallest longitudinal bars;
(c) 24 times the cross-sectional dimension of the hoop FRP; or
(d) 300 mm.

12.7.4.5
The factored shear resistance of beams resisting earthquake effects shall be not less than the lesser of
(a) the sum of the maximum shear associated with the development of nominal moment strengths of the members at each restrained end of the clear span and shear calculated using earthquake load combinations for gravity loads; or
(b) the maximum shear obtained from factored load combinations.

12.7.4.6
Shear design of beams shall conform to Clause 8.4.4.

12.7.5 Moment resisting frame members with longitudinal and transverse FRP reinforcement subjected to significant axial load

12.7.5.1
The sum of the factored flexural resistances of the column sections framing into a joint, accounting for axial loads, shall exceed the sum of the nominal flexural resistances of the beams framing into the same joint. In T-beam construction where the slab is in tension under moments at the face of the joint, slab reinforcement within the effective slab width shall be assumed to contribute to flexural strength if the slab reinforcement is developed at the critical section for flexure. Flexural resistances shall be summed in such a manner that the column moments oppose the beam moments. This requirement shall be satisfied for beam moments acting in either direction. The design columns forces need not exceed those determined from the factored load combinations.

12.7.5.2
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. The required area of the transverse FRP reinforcement shall be calculated in accordance with Clauses 12.7.3.3 and 12.7.3.4 with design drift ratio $\delta = 0.04$ for frames with $I_E F_a S_a(0.2) > 0.75$ and $\delta = 0.025$ for frames with $I_E F_a S_a(0.2) \leq 0.75$.

12.7.5.3
Transverse reinforcement in the amount specified in Clause 12.7.5.2 shall be provided over the length, ℓ_o, from the face of each joint and on both sides of any section where maximum moment can occur in connection with 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 maximum moment can occur;
(b) one-sixth of the clear span of the member; or
(c) 450 mm.

12.7.5.4
Where transverse reinforcement, as specified in Clauses 12.7.5.2 and 12.7.5.3, 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.

12.7.5.5
Columns that are connected to rigid members such as discontinued walls or foundations or that are positioned at the base of the structure shall be provided with transverse reinforcement as specified in Clauses 12.7.5.2 over their clear height. This transverse reinforcement shall continue into the discontinued member for at least the development length of the largest longitudinal reinforcement in the column. If the column terminates on a footing or mat, this transverse reinforcement shall extend into the footing or mat by at least 300 mm.

12.7.5.6
The factored shear resistance of columns resisting earthquake effects shall be not less than the lesser of
(a) the sum of the maximum shear associated with the development of nominal moment strengths of the members at each restrained end of the clear span; or
(b) the maximum shear obtained from factored load combinations.

12.7.5.7
Shear design of columns shall conform to the requirements of Clause 8.4.4.

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 to 13.2.7, as applicable.

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 CSA A23.4 and 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 shall 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 might require special care and protection prior to installation.

14.2 Material storage and handling

14.2.1 General
The following general requirements shall apply to the storage and handling of materials and components covered by this Standard:
(a) All materials shall be stored in a manner that will prevent contamination or deterioration in strict accordance with the manufacturer's recommendations. Materials shall be protected during storage to prevent damage due to temperature extremes, ultraviolet rays, excessive moisture, or foreign substances. Access shall be provided to the storage facilities to allow for inspection.
(b) Protective gloves and clothing shall be worn when handling materials in order to prevent injury due to chemical contact, exposed fibres, or sharp edges.
(c) All materials shall be stored with readily accessible identifying tags or markings that permit easy identification.

(d) Unless otherwise approved by the engineer, damaged materials and/or components shall not be used.
(e) The manufacturer's recommendations shall be followed for the transportation, handling, lifting, and storage of materials and components.

14.2.2 Manufactured FRP bars, plates, and laminates

The following additional requirements shall apply to the storage and handling of FRP bars, plates, and laminates:
(a) FRP materials stored outdoors shall be covered at all times. Materials shall not be stored directly on the ground.
(b) FRP materials packaged and stored as coils are generally under high tension. Coils shall be properly braced against unravelling as they are unpacked so as to avoid injury to workers and damage to the reinforcement. For safety reasons, the manufacturer's instructions shall be strictly followed.
(c) Any foreign material shall be cleaned from interfacing surfaces. The manufacturer shall be consulted for proper cleaning products and procedures.
(d) 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. Cuts shall be made by sawing, not shearing. Cutting FRP materials will create nuisance dust. Appropriate protection of workers and surrounding environment shall be provided. Workers shall generally wear protective gloves and respiratory protection while cutting FRP materials.

14.2.3 Dry fibre fabrics and prepreg fabrics

The following additional requirements shall apply to the storage and handling of dry fibre fabrics:
(a) Fibre fabrics that have exceeded their shelf life shall not be used.
(b) Fabrics shall be handled carefully to avoid folding or otherwise damaging the fibres. Cut fabrics may be stored in rolls (100 mm diameter or greater) or laid flat.
(c) Fabrics shall be stored in a dry environment protected from dust and debris. Prepreg fabrics might require additional storage considerations. The manufacturer shall be consulted on specific guidelines for storing these materials.
(d) Material safety data sheets (MSDS) from the manufacturer shall be kept with dry fibre fabric materials for reference.

14.2.4 Resins and adhesives

The following additional requirements shall apply to the storage and handling of resins and adhesives
(a) Resins and adhesives that have exceeded their shelf life shall not be used.
(b) Resins and adhesives shall be stored in original, unopened containers. Resins and hardeners shall be stored separately.
(c) Proper ventilation and proper protection of workers and the work environment shall be provided when materials are applied. Proper respiratory protection, eye protection, and protective gloves and clothing shall be used.
(d) Materials shall not be used near sources of ignition, and flammability and flash point restrictions of the material shall be observed.
(e) Many resins and adhesives develop exothermic reactions as they cure. Care should be taken to manage these reactions as the material is applied.
(f) Manufacturers should be consulted regarding the proper clean-up and disposal of resins and adhesives.
(g) MSDS from the manufacturer shall be kept with all resins and adhesives for reference.

14.3 Installation and placement

14.3.1 General

The following requirements shall apply to the installation and placement of FRP materials:

(a) Placement of FRP materials, installation details, and tolerances shall be determined prior to execution of the work.

(b) FRP materials shall only be installed by qualified personnel. Materials and installation steps can vary depending on the FRP material manufacturer. Personnel installing these materials shall have training and/or experience with the specific manufacturer and specific material being installed.

14.3.2 Internal FRP reinforcement (new construction)

The following additional requirements shall apply to the installation of FRP reinforcing and prestressing bars for new construction:

(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 where feasible (most FRP bars cannot be field bent) and only by personnel authorized by the manufacturer and approved by the designer. Hook configuration, radius, and extensions shall be in accordance with the manufacturer's recommendations and shall be as shown on the construction documents.

(c) 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. Bar supports and tie-downs shall be of plastic or other non-corroding material.

(d) 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. 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 FRP bar ties shall be stipulated in the contract documents. Ties may be coated-wire ties, plastic ties, nylon ties, or plastic snap ties.

(f) Splicing of FRP bars shall be made only as permitted by the construction documents.

14.3.3 External FRP reinforcement (strengthening)

14.3.3.1 General requirements of installation

Construction process and quality control of surface bonded and near-surface-bonded FRP reinforcement shall be in accordance with the specifications of the system manufacturer.

14.3.3.2

A typical installation sequence of a near-surface mounted FRP fabric system onto a concrete substrate is shown schematically in Figure 1b. Non-preg fibres may be saturated in epoxy resin before being applied to the concrete surface or be saturated directly on the concrete surface. The concrete surface preparation for surface-bonded FRP shall be in accordance with Clause 14.3.3. The concrete surface preparation for near-surface -mounted FRP shall be in accordance with Clause 14.3.3.

14.3.3.3

The following additional requirements shall apply to the installation of FRP laminate and fabric systems for strengthening applications:

(a) The FRP system shall be applied to an existing substrate that is sound. Spalled, fractured, or delaminated areas of concrete shall be removed and repaired using appropriate means and methods. Substrates with on-going corrosion, alkali silica reactions (ASR), or other similar deterioration mechanisms shall be stabilized prior to applying an FRP system. Causes of corrosion, ASR, etc. shall be determined and addressed as needed. Existing cracks that the FRP system will bridge and that are greater than 0.25 mm in width shall be repaired by epoxy injection.

(b) For surface mounted FRP reinforcement, any surface irregularities (offsets, fins, etc.) greater than one mm shall be ground smooth. Sharp corners or edges that the FRP system will turn shall be rounded to meet the manufacturer's requirements. Re-entrant corners, concave surfaces, and embedded obstructions can interfere with the performance of the FRP system. These conditions shall be considered and appropriately addressed prior to applying the FRP system.

(c) For surface mounted FRP reinforcement, the substrate surface shall be cleaned of any dust, dirt, oil, laitance, existing coatings, or other material that could impede bond of the FRP system to the substrate. The substrate shall be profiled by abrasive means. Surface moisture and water in the pores of the substrate can impede the bond and reduce penetration of resins and adhesives. The substrate shall be dry as recommended by the FRP system manufacturer. Moisture migration into and out of the substrate during installation and cure of the FRP system shall be considered. Preliminary bond pull-off tests may be conducted on the substrate material to evaluate proper surface preparation techniques.

(d) Unless the reinforcement is properly anchored to the concrete substrate, for near surface mounted FRP reinforcement, sawcuts shall be deep enough to fully embed the FRP reinforcement along the full length of the bar. Sawcuts shall be free of standing water, dirt, debris, oil, or other bond inhibiting materials. Immediately prior to installation of the FRP reinforcement, the sawcut groove shall be cleared with clean, compressed air.

(e) Resins and adhesives used for these systems shall not be applied when the ambient temperature is outside of the limits prescribed by the manufacturer (typically temperatures below 5 °C and above 65 °C are of concern). When temperatures are outside of these limits, provisions may be made to provide supplemental conditioning of the work environment. Use of supplemental heating or cooling systems should be approved by the manufacturer.

(f) Resins and adhesives should be mixed and applied in strict accordance with the manufacturer's guidelines. Proper mix ratios, mixing times, placement methods, and coverage rates shall be followed. Resins and adhesives generally have limited working time (pot life). Resins and adhesives shall be used within the working time. The manufacturer shall be consulted regarding working time limitations.

(g) FRP systems shall be applied with proper fibre orientation and free of kinks, folds, or waviness. Deviations in fibre placement shall be evaluated by the engineer.

(h) Adverse temperatures, moisture and humidity, UV exposure, or physical disturbance of the material can damage the material during its cure. The FRP system shall be temporarily protected during curing as required by the manufacturer. When thermal curing is required, uniform heat distribution shall be provided.

(i) Coatings applied over the FRP system shall be compatible with the FRP system and shall be applied in accordance with the manufacturer's recommendations.

14.4 Quality control and inspection

14.4.1 General

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

14.4.2 Material properties control

Relevant properties of FRP materials shall be determined by tests carried out by a qualified independent testing agency or company. Where appropriate, the tests shall be in accordance with CSA S807. The following information shall be available prior to construction:

(a) the results of quality tests performed by acceptable test methods to verify relevant properties; and

(b) if required, 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.

14.4.3 Field conditions

The following requirements shall apply to FRP laminate and fabric systems used for strengthening:

(a) All field quality control testing shall be carried out after the FRP material and/or adhesives are fully cured.

(b) All areas where the FRP material has been installed shall be inspected for voids, bubbles, and delaminations. All defective areas with a leading edge greater than 25 mm or an area greater than 600 mm^2 shall be repaired. Delaminated areas may be repaired by injection of resin into the damaged area or by selectively removing and patching delaminated areas. Repair methods shall be performed in accordance with the manufacturer's recommendations.

(c) When specified, direct tension pull-off tests shall be conducted to verify the tensile bond between the existing substrate and the FRP system. Tensile adhesion strength shall exceed 1.4 MPa and exhibit failure of the concrete substrate. Lower strengths or other failure modes (e.g., failure at the FRP/substrate interface or interlaminar failure) shall be reported to the engineer for assessment. Frequency of pull-off tests shall be as specified in the construction documents. The test areas shall be reinstated to the satisfaction of the owner.

(d) When specified, samples of the FRP system may be constructed on site for off site laboratory evaluation. These samples may include resin or adhesive samples to evaluate cure of these materials or sample panels of the FRP system for evaluation of mechanical properties. Samples shall be constructed and cured on site under similar conditions to the materials installed.

Table 1
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 (Annex C)	√	√
Transverse compressive modulus of elasticity	√	√*
Shear strength and modulus (Annex L)	√	
Creep rupture strength (Annex H)	√	√‡
Bond strength (Annex G), and anchorage and junction strength (Annex D)	√†	√
Bond-dependent coefficient, kb (Annex S)		√
Axial and transverse coefficients of thermal expansion (Annex K)	√§	√
Volume change due to moisture	√	
Relaxation (Annex I)		√
Fire performance characteristics		√
(a) thermal properties at elevated temperatures		√
(i) thermal expansion (dilatometric apparatus)	√	
(ii) mass loss with temperature (thermogravimetric analysis)	√	
(b) mechanical properties at elevated temperatures		√
(i) glass transition temperature, TF (dynamic thermal analysis)		√
(ii) stress/strain relationships at elevated temperatures	√	√
(iii) bond characteristics at elevated temperature	√	

**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 2
Resistance factors for prestressed reinforcement
(See Clause 7.1.6.3.)

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

Table 3
Test methods for FRP composites
(See Clause 7.2.5.)

Properties	Test method	Number of specimens*
Tensile strength	ASTM D3039/D3039M	20†
Elongation	ASTM D3039/D3039M	20†
Tensile modulus	ASTM D3039/D3039M	20†
Coefficient of thermal expansion (CTE)	ASTM D696 or E1142	5†
Creep	ASTM D2990‡	5†
Void content	ASTM D2584§ or D3171§	5
Glass transition (T_g) temperature	ASTM D4065	5**
Impact	ASTM D5420††	5
Composite interlaminar shear strength	ASTM D2344/D2344M	20
Curing properties	ASTM D5028	
Fibre-resin ratio	ASTM D2584	
Density	ASTM D792	
Compression test	ASTM D3410/D3410M	
Shear test	ASTM D5379/D5379M	
Fatigue test	ASTM D3479/D3479M	

**Specimen sets shall exhibit a coefficient of variation (COV) of 6% or less. Outliers are subject to further investigation according to ASTM E178. 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%.*
***The maximum service temperature for an FRP, adhesive, or primer should not be more than T_g – 15 °C for the lowest T_g of all the resins in a given system, with T_g measured on the first heating cycle.*
††*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.*

Table 4
Environmental durability test matrix
(See Clause 7.2.5.)

Environmental durability test	Relevant specifications	Test conditions	Test duration, h	% retention	
				1000 h	3000 h
Water resistance	ASTM D2247 ASTM E104	100%, 38 ± 1 °C	1000, 3000, and 10 000	90	85
Saltwater resistance	ASTM D1141 ASTM C581	Immersion at 23 ± 1 °C	1000, 3000, and 10 000		
Alkali resistance	ASTM C581	Immersion in $CaCO_3$ at pH = 9.5 and 23 ± 1.5 °C	1000 and 3000		
Dry heat resistance	ASTM D3045	60 ± 3 °C	1000 and 3000		

Table 5
List of ASTM Standards
(See Clause 7.3.3.2.)

Properties	ASTM Standard
Mechanical:	
Tensile strength and modulus	D638 or D3916
Compressive strength and modulus	D695
Flexural strength and modulus	D790
Izod impact strength	D256
Bearing strength	D953
Creep	D2990
Chemical:	
Chemical resistance	D543
Physical:	
Density	D792
Hardness	D785
Water absorption	D570
Brittleness temperature	D746
Void content	D2734
Deflection temperature under load	D648
Thermal expansion	D696
Fire:	
Rate of burning	D635
Smoke density	D2834
Oxygen index	D2863
Surface burning	E84
Electrical:	
Dielectric strength	D149
Dielectric constant	D150
Resistivity	D257
Arc resistance	D495

Table 6
Maximum permissible computed deflections
(See Clause 8.3.2.1.)

Type of member	Deflection to be considered	Deflection limitation
Flat roofs not supporting or attached to nonstructural elements likely to be damaged by large deflections	Immediate deflection due to specified live load, *L*	ℓ_n/180*
Floors not supporting or attached to nonstructural elements likely to be damaged by large deflections	Immediate deflection due to specified live load, *L*	ℓ_n/360
Roof or floor construction supporting or attached to nonstructural elements likely to be damaged by large deflections	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)‡	ℓ_n/480†
Roof or floor construction supporting or attached to nonstructural elements not likely to be damaged by large deflections		ℓ_n/240§

**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.*

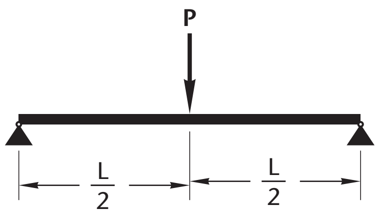
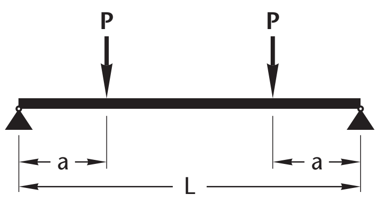
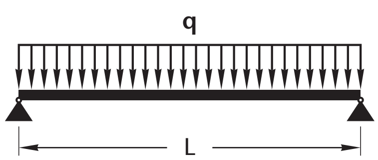
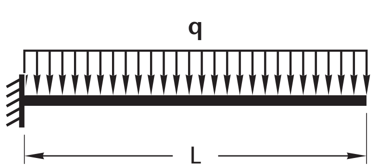
†*Limit may be exceeded if adequate measures are taken to prevent damage to supported or attached elements.*

‡*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 7
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 8
Permissible stresses in tendons as a function of f_{Fpu}

(See Clause 10.5.1.)

Tendon	Stresses at jacking	Stresses at transfer
AFRP	$0.40f_{Fpu}$	$0.35f_{Fpu}$
CFRP	$0.7f_{Fpu}$	$0.65f_{Fpu}$

Table 9
Minimum area of bonded non-prestressed reinforcement

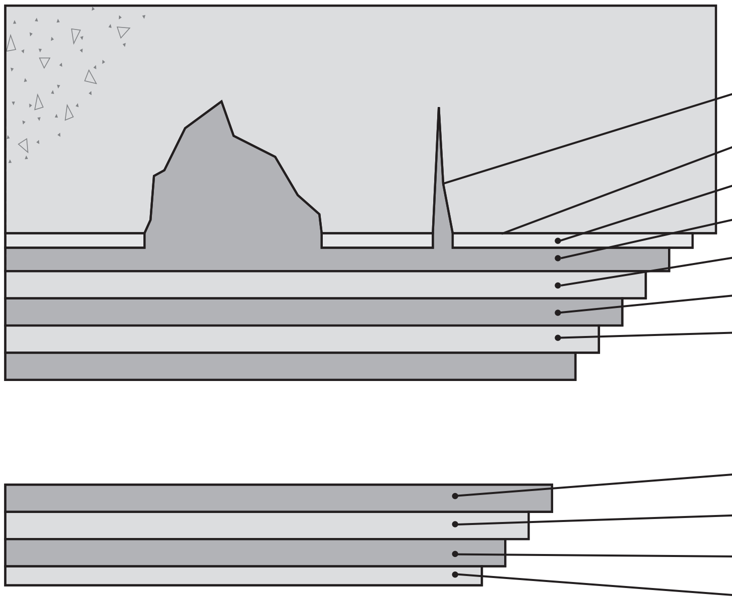
(See Clause 10.9.)

	Concrete tensile stress			
	$\leq 0.5\lambda\left(\sqrt{f_c'}\right)$		$> 0.5\lambda\sqrt{f_c'}$	
	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 10
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	$50d_b$	$26d_b$
CFRP rebar	N/A	$180d_b$	$60d_b$
AFRP	$8 \geq d_b < 12$	$120d_b$	$50d_b$
AFRP	$12 \geq d_b < 16$	$100d_b$	$40d_b$
AFRP	$16 \geq d_b$	$80d_b$	$35d_b$



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 saurating 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 1a
A typical installation sequence of a surface mounted FRP fabric onto a concrete substrate
(See Clause 7.2.2.1)

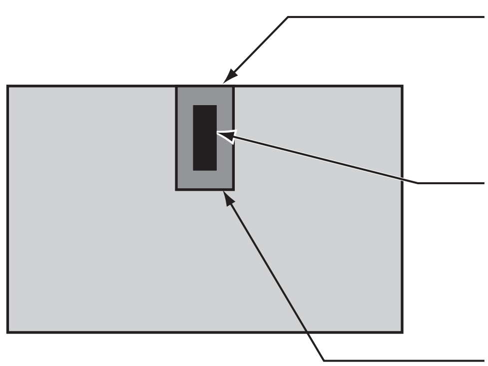
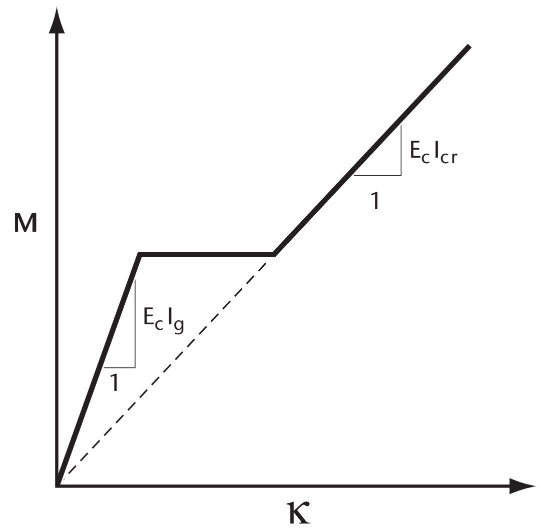
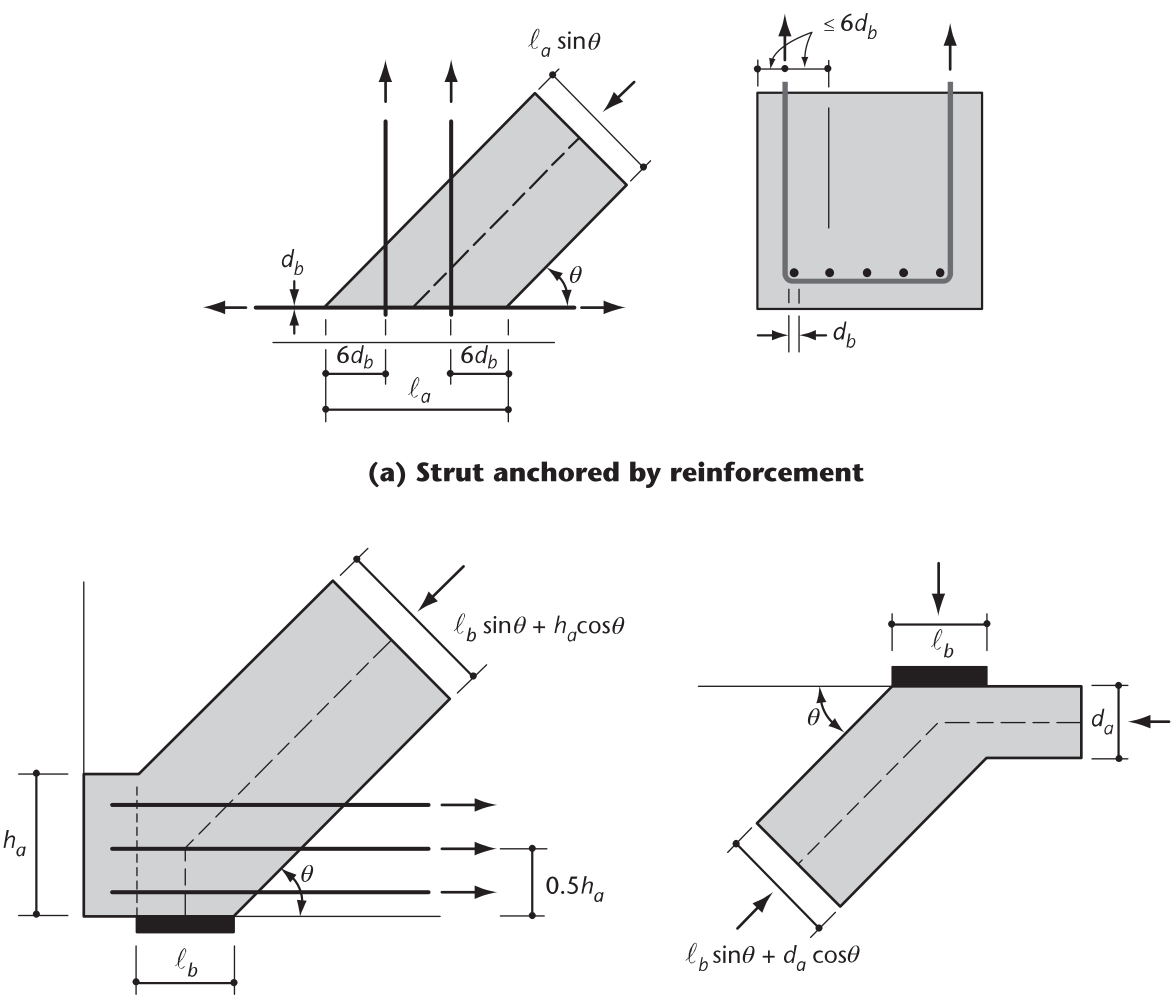


Figure 1b
Near-surface mounted (NSM) external FRP reinforcement
(See Clause 14.3.3.2.)



Legend:
M = moment
κ = curvature

Figure 2
Moment-curvature relation of FRP reinforced concrete
(See Clause 8.3.2.5.)



(a) Strut anchored by reinforcement

(b) Strut anchored by bearing plate and reinforcement

(c) Strut anchored by bearing plate and strut

Figure 3
Influence of anchorage conditions on effective cross-sectional area of strut
(See Clauses 8.4.7.5 and 8.5.2.2.)

Annex A (normative) **Determination of cross-sectional area of FRP reinforcement**

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

A.1 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.

A.2 Symbols

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

A.3 Apparatus

A.3.1 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 A.1).

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.*

A.3.2 Weighing scale

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

A.4 Specimens

A.4.1 Cutting specimens

All specimens shall be cut squarely and cleanly.

A.4.2 Specimen length

The length of specimens shall 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.

A.4.3 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 A.1.

A.5 Test environment

The temperature of the laboratory shall be maintained at 23 ± 3°C and the relative humidity at 50 ± 10%.

A.6 Procedures

A.6.1 Conditioning

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

A.6.2 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.

A.6.3 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 mL.

A.6.4 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.

A.6.5 Adding water

Water shall be added to fill the container up to 10 mm 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; there shall be no bubbles trapped inside.

A.6.6 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 A.6.4 from this new weight.

A.7 Calculations

A.7.1 Cross-sectional area

The average cross-sectional area, A, of the specimens shall be calculated as follows:

$$A = \frac{V_0 - V_1}{L} \times 1000 \quad \textbf{(A7-1)}$$

A.7.2 Rounding

The combined total length shall be rounded to the nearest 1 mm and the cross-sectional area to the nearest 1 mm^2.

A.8 Report

A.8.1
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.

A.8.2
The temperature and relative humidity at the beginning of the test shall be reported.

A.8.3
The average cross-sectional area determined shall be reported.

Table A.1
Number or combined length of specimens
(See Clause A.4.3.)

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

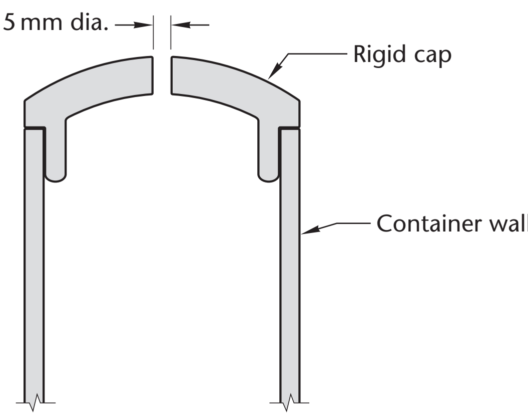


Figure A.1
Specimen container cap
(See Clause A.3.1.)

Annex B (normative)
Anchor for testing FRP specimens under monotonic, sustained, and cyclic tension

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

B.1 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.

B.2 Symbols

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

B.3 Specification of anchor

B.3.1 Geometry

The geometrical dimensions of the anchor shall be as shown in Figure B.1. 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 $f_uA/350$, but not less than 250 mm.

B.3.2 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 B.2.

B.3.3 Anchor filler material

The cylinder shall be filled with either pure resin or a 1:1 mixture of resin and clean sand (by weight) or non-shrink cement grout. The filler shall be compatible with the resin of the test specimen.

B.3.4 Specimen preparation

B.3.4.1 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. A 2 mm projection of the cross bars should be left to enhance gripping.

B.3.4.2 Specimen length
The total length of the specimen shall be $40d + 2L_g$ or greater.

B.3.4.3 Surface preparation
Mechanical or chemical surface treatment may be used for promoting adhesion of the specimen with the casting resin, 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.

B.3.5 Anchor casting procedure

B.3.5.1 Casting position
Whenever possible, the anchor shall be cast in a vertical position, as shown in Figure B.1. 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 h shall elapse before the first anchor is flipped in order to cast the other anchor. A suitable jig, as shown in Figure B.3, may be used to keep both cylinders and the specimen axially aligned.

If necessary (e.g., 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 B.1. 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.*

B.3.5.2 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 B.1 to prevent any possible leakage of resin.

B.3.5.3 Mixing and handling resin
The resin shall be mixed and handled following the manufacturer's instructions, paying particular attention to safety.

B.3.5.4 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.

B.3.5.5 Curing
At least 48 h shall be allowed before testing for the resin to set inside the cylinder.

B.3.5.6 Handling
The anchored specimen shall be handled by holding both grips to avoid bending or twisting of it.

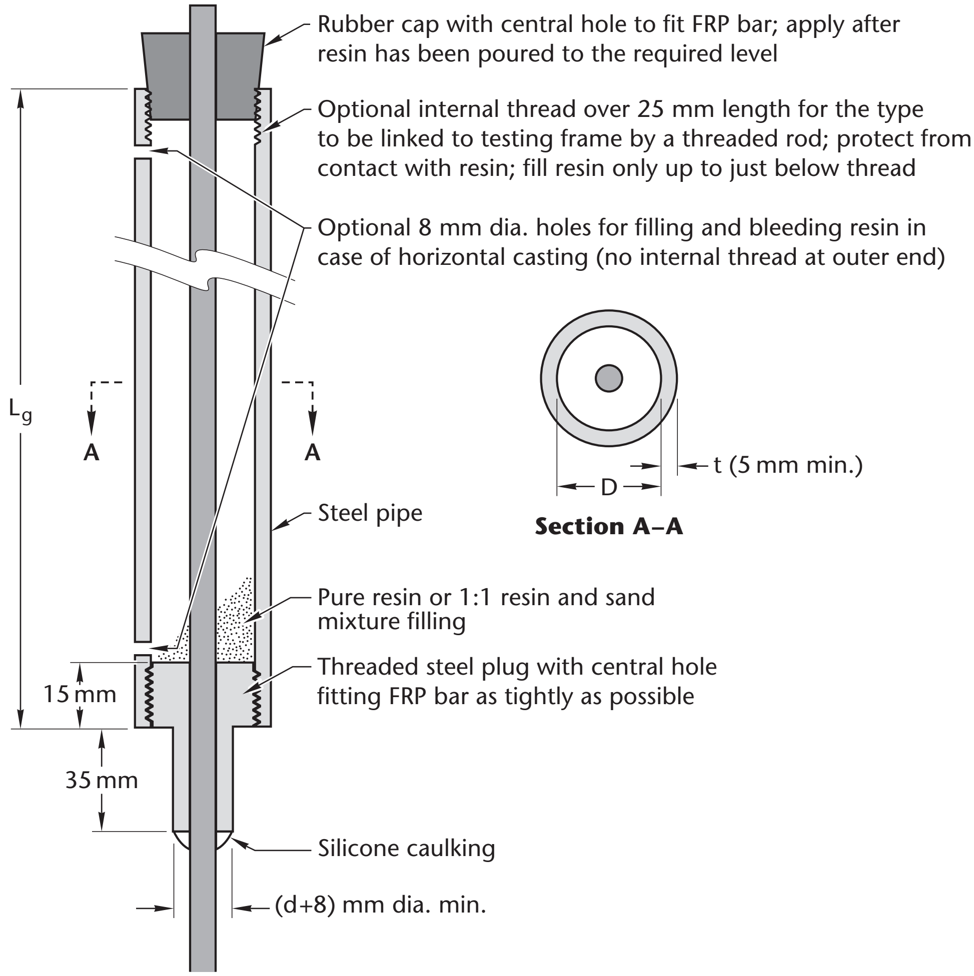


Figure B.1
Anchor details
(See Clauses B.3.1, B.3.5.1, and B.3.5.2.)

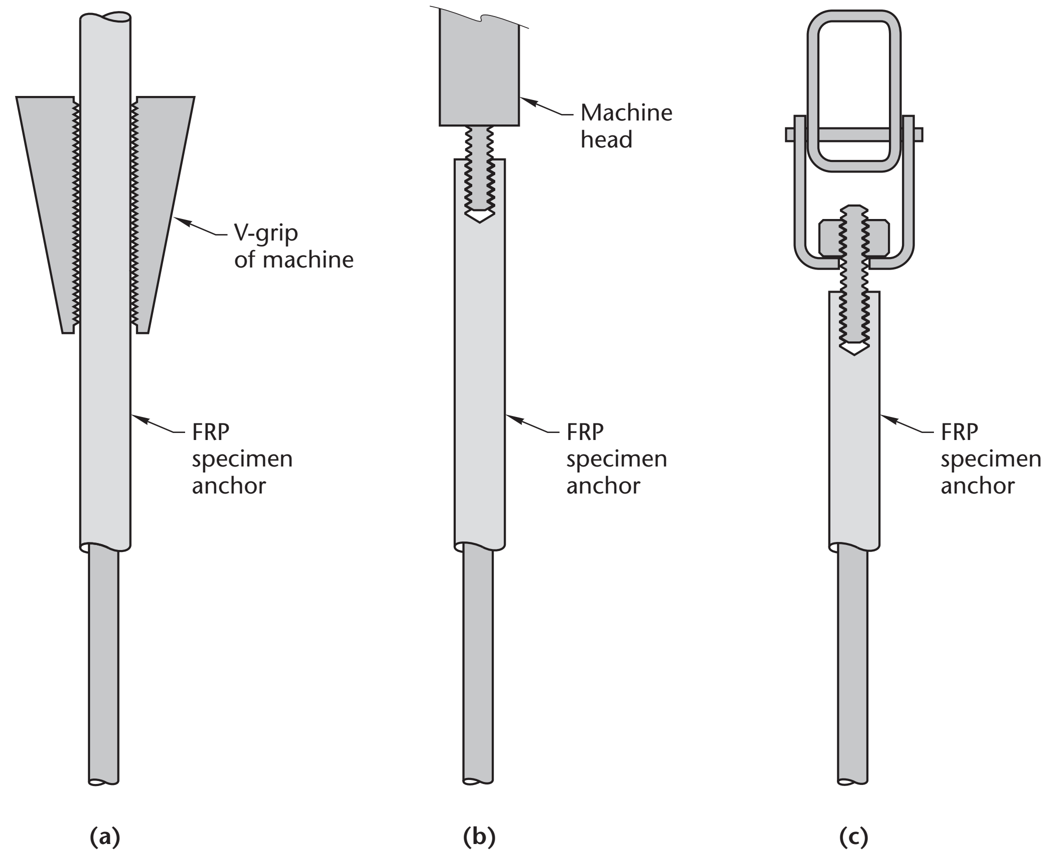


Figure B.2
Attachment of anchor to various testing machines and frames
(See Clause B.3.2.)

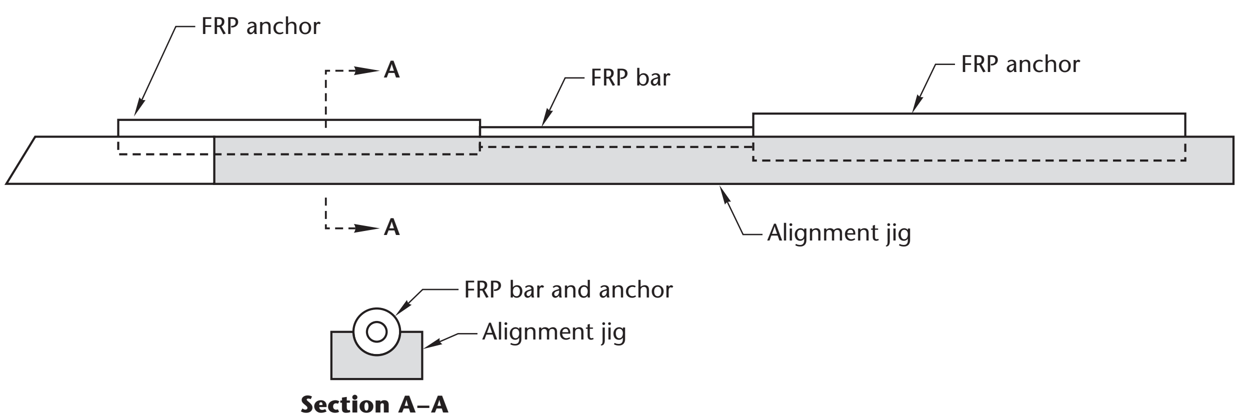


Figure B.3
Jig to align specimen and anchors
(See Clause B.3.5.1.)

Annex C (normative)
Test method for tensile properties of FRP reinforcements

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

C.1 Scope

This Annex specifies a test method for determining the tensile strength, modulus of elasticity, and ultimate elongation of FRP reinforcements.

C.2 Symbols

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

C.3 Apparatus

C.3.1 Testing machine

The machine shall generally conform to ASTM E4. 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 might not have enough clearance to accommodate the relatively long anchors required by specimens of high load capacity. Special testing frames might be required in such cases.*

C.3.2 Specimen-anchoring devices

The anchor specified in Annex B 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.*

C.3.3 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.

C.3.4 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.

C.3.5 Ultimate-elongation-measuring device

An LVDT may be set up to measure the displacement between the machine cross-heads or between the specimen anchors.

C.3.6 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
(a) 100 N for load;
(b) one microstrain for strain; and
(c) 0.01 mm for displacement.

C.4 Specimens

C.4.1 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.

C.4.2 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.

C.4.3 Number of specimens

At least five specimens shall be tested, unless otherwise specified in CSA S807.

C.4.4 Cross-sectional area

The cross-sectional area shall be determined in accordance with Annex A.

C.5 Test environment

Tests shall be carried out with the room temperature maintained at 20 ± 10°C and relative humidity at 50 ± 25%.

C.6 Procedure

C.6.1 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.

C.6.2 Mounting of specimens
If the anchor described in Clause B.3 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 C.1. For other anchors, the mounting shall ensure concentric and torsion-free loading.

C.6.3 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.

C.6.4 Recording
The data acquisition system shall be started 10 s before the commencement of loading.

C.6.5 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 using the extensometer of IVDT data.

C.6.6 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.

C.6.7 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.

C.6.8 Rejection
If any test specimen fails partly or fully inside the grip, the test shall be discarded and another sample tested in its place.

C.7 Calculations

C.7.1 Tensile strength
The highest load recorded shall be divided by the cross-sectional area in order to calculate the tensile strength.

C.7.2 Modulus of elasticity
The following equation shall be used to calculate the value of the modulus of elasticity:

$$E = \frac{1000(P_1 - P_2)}{(\varepsilon_1 - \varepsilon_2)A} \quad \textbf{(C-1)}$$

C.7.3 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. The ultimate elongation can be calculated by dividing the ultimate tensile strength by the tensile modulus of elasticity of the tested FRP bar.

C.7.4 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.

C.8 Report

C.8.1

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.

C.8.2

A brief description of the gripping device used shall be given.

C.8.3

The cross-sectional area of each type and size of specimen shall be reported.

C.8.4

For each specimen, the values of each the following shall be reported:

(a) tensile strength;
(b) modulus of elasticity;
(c) ultimate elongation; and
(d) the average values and standard deviation of the quantities in Items (a) to (c) for the set of specimens tested.

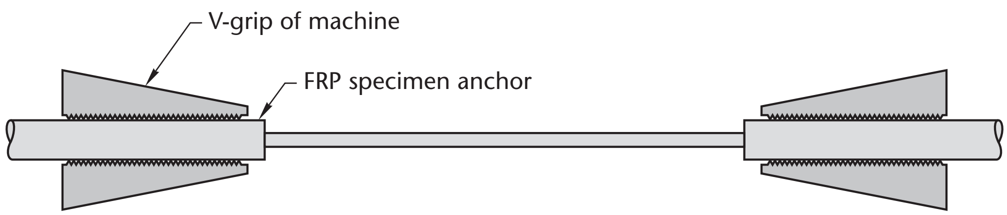


Figure C.1
Mounting specimen in testing machine with V-grips
(See Clause C.6.2.)

Annex D (normative)
Test method for FRP bent bars and stirrups

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

D.1 Scope

This Annex specifies the test requirements for determining the strength capacity of FRP bent bars used as anchorage for stirrups in concrete structures.

D.2 Symbols

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
F_{ult} = ultimate load capacity according to bend tests
χ = strength reduction factor due to bend effect

D.3 Significance and use

D.3.1

Annex D 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.

D.3.2

The bending of FRP stirrups 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.

D.3.3

Annex D measures the ultimate load capacity of a single FRP stirrup subjected to tensile force in the direction of the straight portion.

D.4 Definitions

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 D.1.

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 D.1.

Tensile strength — ultimate tensile strength of FRP bars in the direction parallel to the fibres.

D.5 Specimen preparation

D.5.1
The configuration of a typical specimen is shown in Figure D.1. 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 be less than 200 mm. The concrete block shall be reinforced using steel stirrups, as shown in Figure D.1, to prevent splitting of the concrete block prior to rupture of the stirrup at the bend. The dimensions of the stirrups may vary; however, the height of the FRP stirrup being tested should not exceed 750 mm. The concrete should be a standard mixture, with coarse aggregates having a maximum dimension of 20 to 25 mm. It should be batched and mixed in accordance with the applicable portions of ASTM C192/C192M. The concrete should have slump of 100 ± 20 mm in accordance with ASTM C143 and the compressive strength at 28 days should be 30 ± 3 MPa in accordance with ASTM C39/C39M.

D.5.2
The number of test specimens for each test condition shall not be less than five or as specified in CSA S807. 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.

D.5.3
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.

D.6 Test method and requirements

D.6.1
The test set-up, shown in Figure D.2, 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.

D.6.2
The hydraulic jack and the load cell shall be calibrated prior to performing the bend tests.

D.6.3
Extensometers shall be used on the stirrup's legs to ensure uniform distribution of the applied load.

D.6.4
The tensile strength of straight FRP bars with the same diameter as the FRP stirrups and manufactured by the same process as the stirrups shall be evaluated in accordance with Annex C.

D.6.5
The temperature shall normally be within the range of 20 ± 2 °C.

D.6.6
The test specimens shall not be subjected to any shock, vibration, or torsion.

D.7 Calculation

D.7.1

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.

D.7.2

The bend capacity of the FRP stirrup shall be calculated in accordance with Equation (D-1), to three significant digits:

$$f_{bend} = \frac{F_{ult}}{2A_b} \qquad \textbf{(D-1)}$$

D.7.3

The strength reduction factor shall be calculated in accordance with Equation (D-2):

$$\chi = \frac{f_{bend}}{f_{fu}} \qquad \textbf{(D-2)}$$

D.8 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) for all specimens that failed at the bend as intended, the average bend capacity, its standard deviation, and strength reduction factor.

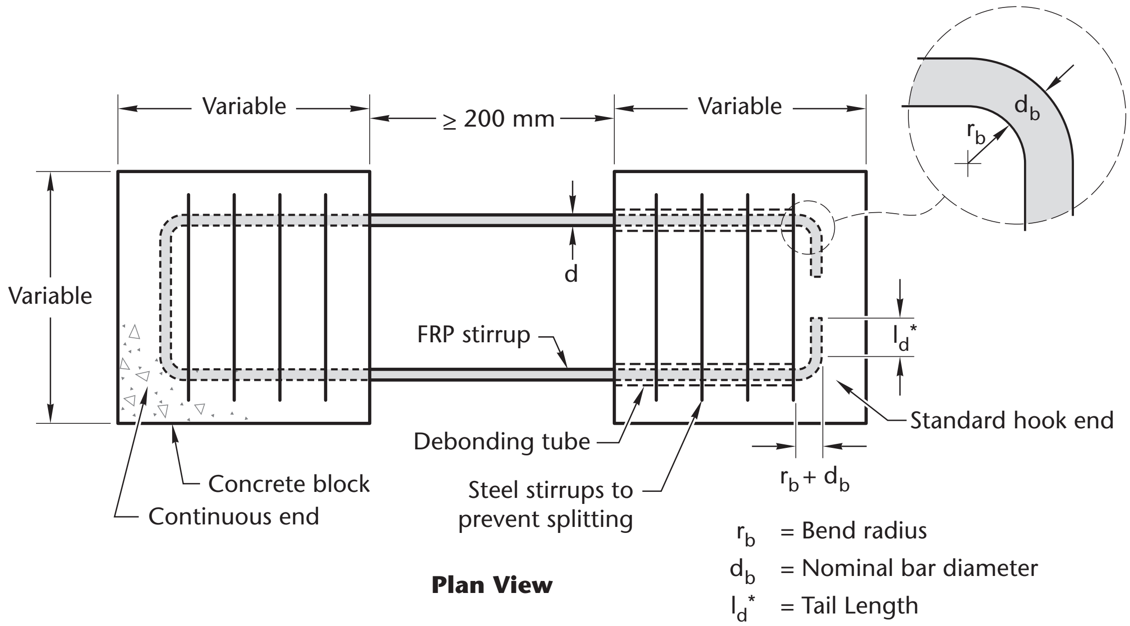


Figure D.1
Configuration of test specimen
(See Clause D.4 and D.5.1.)

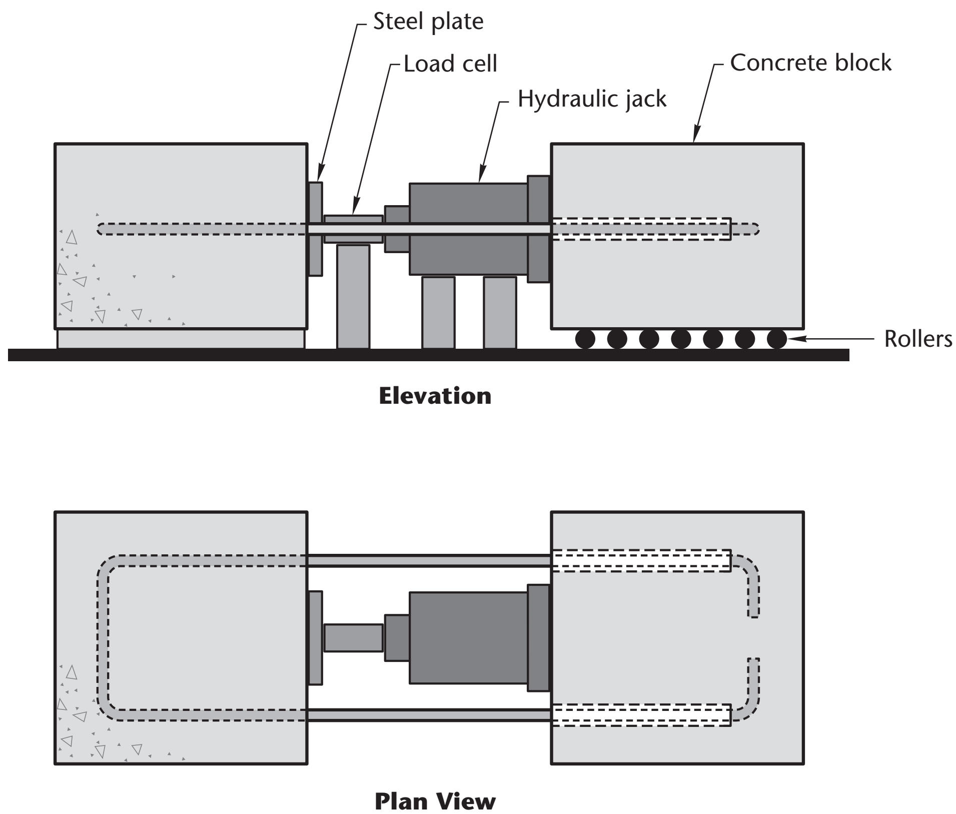


Figure D.2
Test set-up
(See Clause D.6.1.)

Annex E (normative) ***Test method for direct tension pull-off test***

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

E.1 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.

E.2 Summary

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.

E.3 Test apparatus

E.3.1

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.

E.3.2

The portable adhesion tester shall include the following mandatory components, which are illustrated in Figure E.1:
(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 the manufacturer's instructions.

E.4 Test preparation and procedure

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:
(a) Select a flat measurement site in accordance with the sampling schedule.
(b) 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 in accordance with prescribed cleaning methods.
(c) 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.
(d) Attach the adhesion fixture with the designated bonding agent. Leave to cure in accordance with the bonding agent manufacturer's instructions.
(e) 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.
(f) Take up the slack in the adhesion tester by screwing down the adjustment knob.
(g) Set the force indicator to the zero mark.
(h) 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.
(i) Record the pull-off force measurement, and compute and record the tensile bond strength or concrete strength, whichever is applicable, from the following formula:

$$\text{Tensile bond strength} = \frac{\text{pull-off force}}{\text{adhesion fixture contact area}}$$

E.5 Interpretation of results

E.5.1

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).

E.5.2

Bonding agent failure resulting from poor preparation shall not be an acceptable failure mode.

E.5.3

The preferred mode of failure is cohesive failure within the concrete at a stress level in excess of 1.4 MPa.

E.6 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 and it's standard deviation for the sample population; and
(g) the test operator.

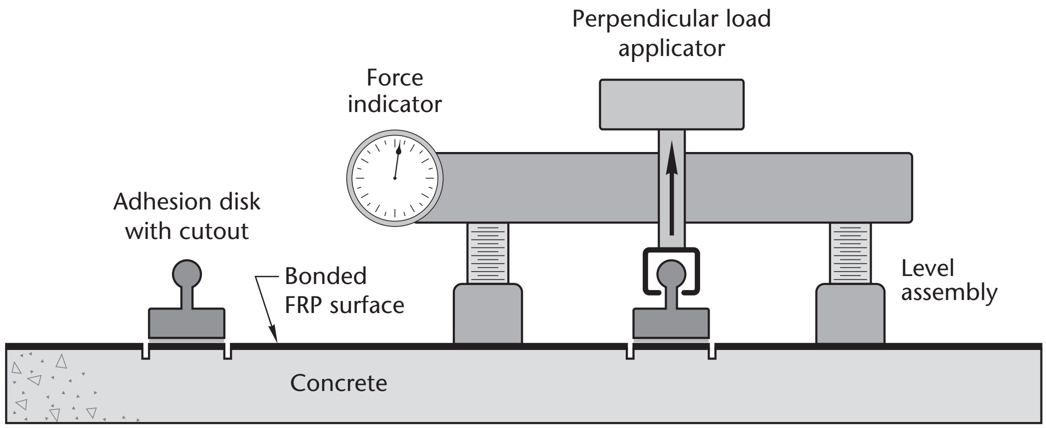


Figure E.1
Direct tension pull-off test
(See Clause E.3.2.)

Annex F (normative)
Test method for tension test of flat specimens

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

F.1 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° and continuous bidirectional fabrics at 0/90°. The method also provides specific instructions for calculating strength and modulus based on an equivalent cross-sectional area.

F.2 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

F.3 Definitions

The following definition applies in this Annex:

Gauge section — one specimen-width away from the tab edge on each end.

F.4 Summary

The tension specimen shown in Figure F.1 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.

F.5 Test apparatus

F.5.1

The testing machine shall be in accordance with ASTM D3039.

F.5.2

Micrometers shall be suitable for reading to 0.025 mm of the specimen thickness and width.

F.5.3
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.

F.6 Specimen preparation

F.6.1 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.

F.6.2 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.

F.6.3 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.

F.6.4 Geometry
The test specimen shall be as shown in Figure F.1, where the specimen has a constant cross-section with tabs bonded to the ends. Table F.1 gives the width and gauge length of specimens used for different fibre orientations. Variation in specimen width shall be not greater than ± 1%. Variation in laboratory prepared-specimen thickness shall be not greater than ± 2%. Variation in field-prepared specimen thickness shall be not greater than ± 10%.

F.6.5 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.

F.7 Conditioning

F.7.1 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.

F.7.2 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.

F.8 Test procedure

F.8.1 Number of specimens

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

F.8.2 Measurement

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

F.8.3 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 millimetres or inches. 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.

F.8.4 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.

F.8.5 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

$$f_u = \frac{p}{bd} \quad \textbf{(F-1)}$$

$$E = \left(\frac{dp}{dl}\right)\left(\frac{l}{bd}\right) \quad \textbf{(F-2)}$$

F.8.6 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:

$$f_u' = \frac{P}{bd'} \quad \textbf{(F-3)}$$

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

F.8.7

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.

F.9 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 F.1
Width and gauge lengths of specimens
(See Clause F.6.4.)

Fibre orientation	Specimen minimum width, mm	Gauge length, mm
0°	12.7	127
90°	25.4	38
0/90°	25.4	127

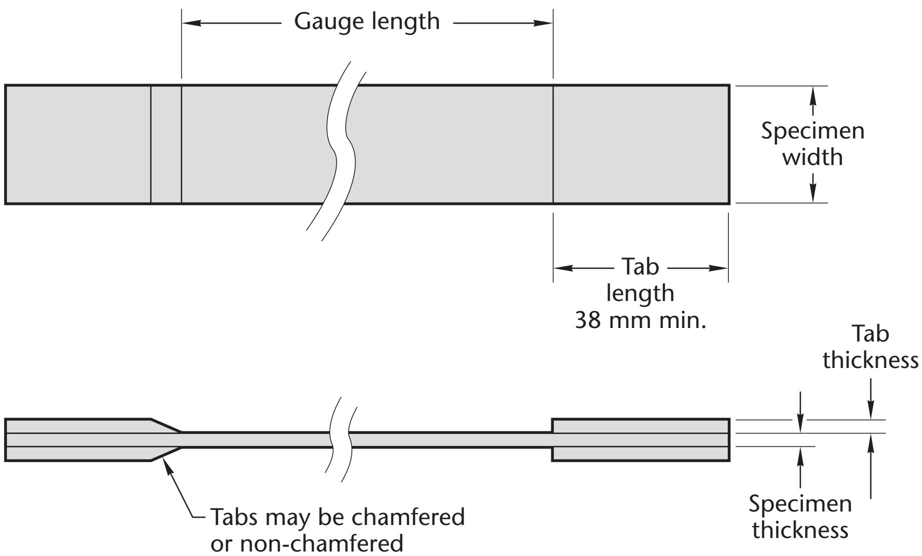


Figure F.1
Direct tension pull-off test
(See Clauses F.4 and F.6.4.)

Annex G (informative) ***Test method for bond strength of FRP rods by pullout testing***

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

G.1 Scope

G.1.1

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.*

G.1.2

This Annex 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.

G.1.3

This Annex 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.

G.2 Symbols

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

G.3 Definition

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.
Note: *The length is determined separately for each FRP rod.*

G.4 Specimen preparation

G.4.1

G.4.1.1

The test specimens shall be of two types: one containing a single 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.

G.4.1.2 Specimens for vertically embedded bar

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 can become a problem.

Note: *See Figure G.1.*

G.4.1.3 Specimens for horizontally embedded bar

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.

Note: *See Figure G.2.*

G.4.1.4 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.

G.4.2

The number of test specimens shall be at least five or as specified for bond strength in CSA S807. The moulds for bond test specimens shall be in accordance with the moulds as shown in Figures G.3 and G.4. 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.

G.4.3
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.

G.4.4
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 100 ± 20 mm, 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.

G.4.5
Moulds shall not be removed from the specimens earlier than 20 h 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 C511 until the time of test. Specimens shall be tested after 28 days.

G.4.6
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 C293. 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.

G.4.7
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 C617 regarding capping materials and procedures shall be used.

G.5 Test equipment and requirements

G.5.1
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.

G.5.2
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.

G.5.3
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.

G.5.4
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.

G.6 Test method

G.6.1
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 G.5.

G.6.2
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.

G.6.3
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 G.5.1.

G.6.4
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.

G.6.5
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.

G.7 Calculations

G.7.1

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.

G.7.2

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:

$$\tau = \frac{P}{ul} \qquad \textbf{(G-1)}$$

G.7.3

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.

G.7.4

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.

G.8 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 the bond stress-slippage displacement (free end and loaded end) curves for each test specimen; and
(k) the average maximum bond stress and its standard deviation for all the test specimens.

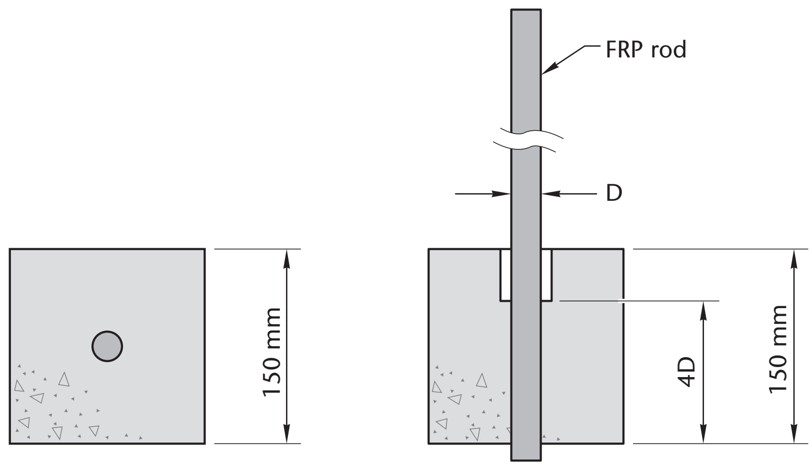


Figure G.1
Vertical bond test specimen
(See Clause G.4.1.2.)

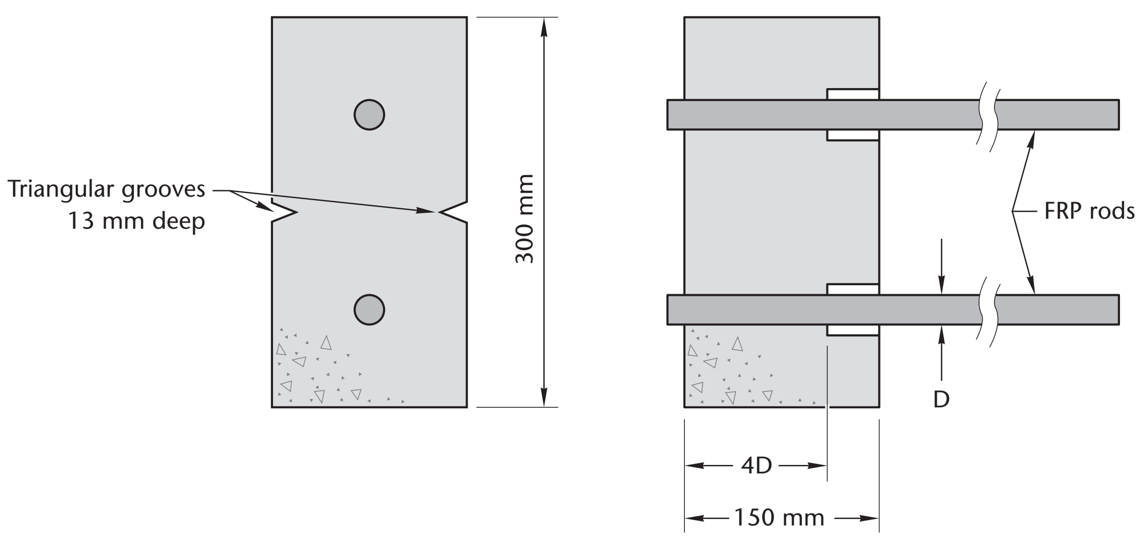
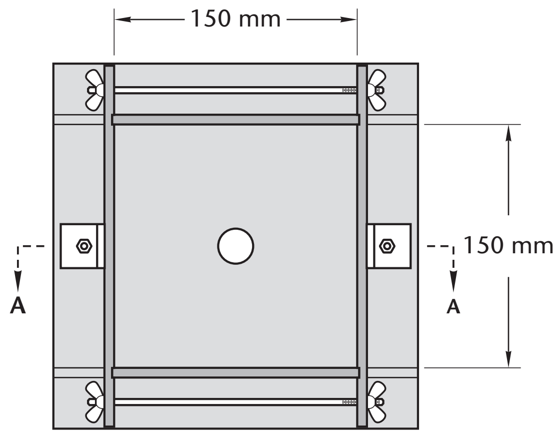
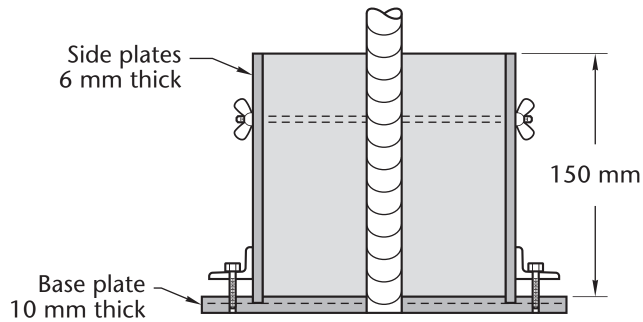


Figure G.2
Horizontal bond test specimen
(See Clause G.4.1.3.)



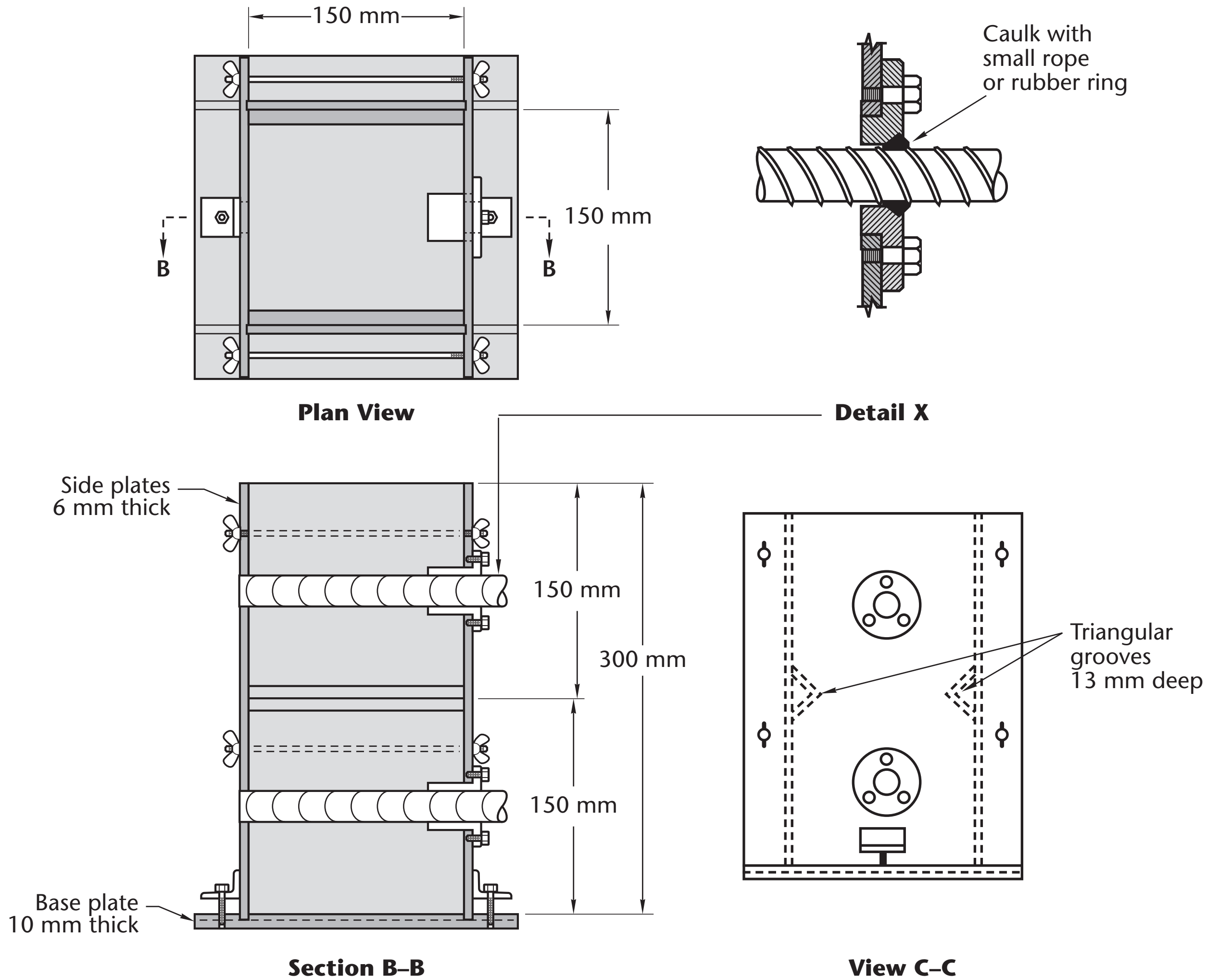
Plan View



Section A–A

Note: *This figure is based on a figure from ASTM C234.*

Figure G.3
Mould for bond test specimens for vertical bars
(See Clause G.4.2.)



Note: *This figure is based on a figure from ASTM C234.*

Figure G.4
Mould for bond test specimens for horizontal bars
(See Clause G.4.2.)

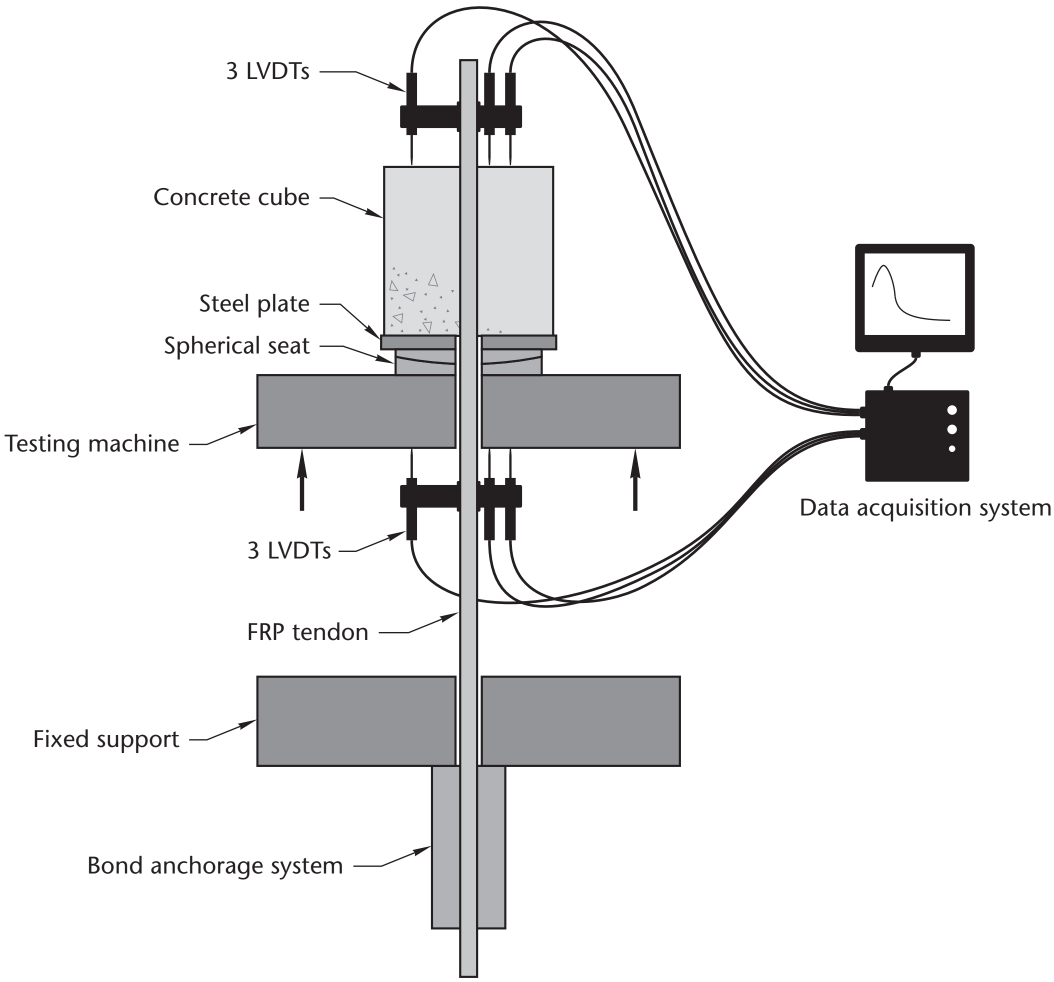


Figure G.5
Bond test set-up
(See Clause G.6.1.)

Annex H (informative)
Test method for creep of FRP rods

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

H.1 Scope

This Annex specifies the test requirements to determine the creep properties of FRP rods used as reinforcing bars or prestressing tendons in concrete.

H.2 Symbols

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
r^2 = coefficient of correlation
T = time, h
Y = load ratio

H.3 Significance and use

H.3.1

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.

H.3.2

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.

H.3.3

This Annex 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.

H.4 Definitions

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.
Note: *In particular, the stress causing failure after 1 000 000 h 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.
Note: *In particular, the stress causing failure after 1 000 000 h 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.

H.5 Specimen preparation

H.5.1

Test specimens shall be prepared and handled in accordance with Annex C.

H.5.2

The number of test specimens for each test condition shall not be less than five, or less than as specified in CSA S807. 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.

H.6 Test equipment and requirements

H.6.1

The testing machine shall be capable of maintaining constant, sustained loading during deformation of the test specimen.

H.6.2

The anchorage shall be in accordance with Annex B.

H.6.3

The extensometer or strain gauge used shall be in accordance with Annex C.

H.6.4

The device for measuring the passage of time shall be accurate to within 1% of the elapsed time.

H.6.5

The test temperature shall be 20 ± 2 °C.

H.7 Test method

H.7.1

The mounting of the test specimen and the gauge length shall be in accordance with Annex C.

H.7.2
Test specimens shall not be subjected to shock, vibration, or torsion.

H.7.3
Creep test measurement shall begin at the moment that the test specimen has attained the prescribed load.

H.7.4
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.

H.7.5
For each value of load ratio, failure shall not occur in five test specimens after 1000 h of loading.

H.7.6
Creep strain should 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.

H.7.7
The times to rupture should span at least three decades of time (such as 1, 10, 100, and 1000 h) to allow construction of a regression line through reasonably spread data. The linear regression should have an acceptable regression coefficient (r2 > 0.98).

H.8 Calculations

H.8.1
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.

H.8.2
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.

H.8.3
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.

H.8.4
A creep failure line chart shall be prepared by calculating an approximation line from the graph data by means of the least-square method in accordance with Equation (H-1):

$$Y = a - b \log T \quad \textbf{(H-1)}$$

H.8.5

The load ratio at 1 000 000 h, 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 in accordance with Equation (H-2), to three significant digits:

$$f_r = \frac{F_r}{A} \quad \textbf{(H-2)}$$

H.9 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 and test temperature;
(f) the type and name of the testing machine;
(g) the type and name of the anchorage;
(h) the tensile strength for each test specimen, average tensile strength, and its standard deviation for all the test specimens;
(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 I (informative)
Test method for long-term relaxation of FRP rods

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

I.1 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.

I.2 Symbols

The following symbols are used in this Annex:

a, b = empirical constants
T = time, h
Y = relaxation rate, %

I.3 Significance and use

I.3.1

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.

I.3.2

This Annex 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.

I.4 Definitions

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.
Note: *In particular, the relaxation value after 1 000 000 h 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.

I.5 Specimen preparation

I.5.1

Test specimens shall be prepared and handled in accordance with Annex C.

I.5.2
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.

I.6 Test equipment and requirements

I.6.1
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.

I.6.2
The anchorage shall be in accordance with Annex B.

I.6.3
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 greater than 1 kN: ± 2.0% of set load.

I.6.4
The accuracy of readings or automatic recordings of loads shall be within 0.1% of the initial load.

I.6.5
The testing machine shall limit strain fluctuations in the test specimen to not 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 to not affect the test results.

I.6.6
If an extensometer or strain gauge is to be fitted to the test specimen, it shall be in accordance with Annex C.

I.6.7
The device for measuring the passage of time shall be accurate to within 1% of the elapsed time.

I.6.8
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.

I.7 Test method

I.7.1
Mounting of the test specimen and the gauge length shall be in accordance with Annex C.

I.7.2
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.

I.7.3
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 can 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.

I.7.4
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.

I.7.5
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.

I.8 Calculations

I.8.1
The relaxation value shall be calculated by dividing the load measured in the relaxation test by the initial load.

I.8.2
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 in accordance with Equation (I-1):

$$Y = a - b \log T \quad \textbf{(I-1)}$$

I.8.3
The relaxation rate after 1 000 000 h 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.

I.9 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 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 J (informative) Test method for tensile fatigue of FRP rods

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

J.1 Scope

J.1.1
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.

J.1.2
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.

J.1.3
Various versions of fatigue testing, such as tension-tension, tension-compression, compression-compression, may be used. The test method given here is generic for evaluating material characteristics. The intended usage of the material shall guide the choice of fatigue test.

J.2 Significance and use

J.2.1
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.

J.2.2
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 in accordance with this Annex, in keeping with the intended purposes.

J.2.3
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.

J.3 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 tressing.

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).

J.4 Specimen preparation

J.4.1
The test specimen shall be prepared and handled in accordance with Annex C.

J.4.2
The number of tests shall be as specified in CSA S807. At least three loading (stressing) levels should be applied for each test. 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.

J.4.3
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.

J.5 Test equipment and requirements

J.5.1
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.

J.5.2
Anchorages shall be in accordance with Annex B. Preferably, the same type of anchorage shall be used for all specimens in a given series of tests.

J.5.3
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.

J.5.4
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.

J.6 Test method

J.6.1
The mounting of test specimens shall be in accordance with Annex C.

J.6.2
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 in accordance with 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 103 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 104 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 104 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%.

J.6.3
The frequency shall be within the range of 1 to 10 Hz, preferably close to 4 Hz.

J.6.4
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.

J.6.5
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.

J.6.6
Tests for each test specimen shall, whenever practicable, be conducted without interruption from the start to the end. When a test is interrupted, the number of cycles up to the time of interruption and the period of the interruption shall be recorded.

J.7 Calculations

J.7.1

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.

J.7.2

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.

J.7.3

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.

J.8 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 K (informative) ***Test method for coefficient of thermal expansion of FRP rods***

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

K.1 Scope

K.1.1
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.

K.1.2
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.

K.2 Symbols
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

a_{sp} = coefficient of thermal expansion, °C

K.3 Significance and use

K.3.1
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.

K.3.2
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.

K.4 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.
Note: *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).

K.5 Specimen preparation

K.5.1

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.

K.5.2

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.

K.5.3

The number of test specimens shall be as specified in CSA S807

K.6 Test equipment and requirements

K.6.1

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.

K.6.2

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.

K.6.3

The thermal mechanical analysis apparatus shall be installed in a location where it is not subjected to vibration during testing.

K.7 Test method

K.7.1
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.

K.7.2
The gauge rod shall be placed in the centre of the test specimen, with no pressure applied.

K.7.3
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.

K.7.4
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.

K.7.5
The rate of temperature increase shall not be more than 5 °C/min.

K.7.6
The compressive stress acting on the test specimen shall be 4 ± 0.5 MPa.

K.8 Calculations

K.8.1
The coefficient of thermal expansion of the test specimen within the measured temperature range (T_1,T_2) shall be calculated in accordance with Equation (K-1):

$$\alpha_{sp} = \alpha_{set} + \left(\Delta L_{spm} - \Delta L_{refm}\right) \Big/ \left[L_o \times \left(T_2 - T_1\right)\right] \quad \textbf{(K-1)}$$

K.8.2
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}).

K.9 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 L (informative)
Test method for shear properties of FRP rods

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

L.1 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.

L.2 Symbols

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
W_0 = initial mass of the dried specimen before immersion
W_1 = mass of the specimen after immersion
W_2 = mass of the dried specimen after immersion

L.3 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.

L.4 Specimen preparation

L.4.1

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.

L.4.2

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.

L.4.3

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 300 mm.

L.4.4
The number of test specimens shall be as specified in CSA S807. 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.

L.5 Test equipment and requirements

L.5.1
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.

L.5.2
The two parts of the machine are the push-in cutting device and a test specimen holder.

L.5.3
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 L.1).

L.5.4
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.

L.6 Test method

L.6.1
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.

L.6.2
The specified loading rate shall be such that the shearing stress increases at a rate of 30 to 60 MPa/min. The load shall be applied uniformly without subjecting the test specimen to shock.

L.6.3
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.

L.7 Calculations

L.7.1
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.

L.7.2

Shear strength shall be calculated with a precision to three significant digits according to Equation (L-1):

$$\tau = \frac{P}{2A} \qquad \text{(L-1)}$$

L.8 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 its standard deviation for all the test specimens, and shear strength; and
(h) the failure mode of each test specimen.

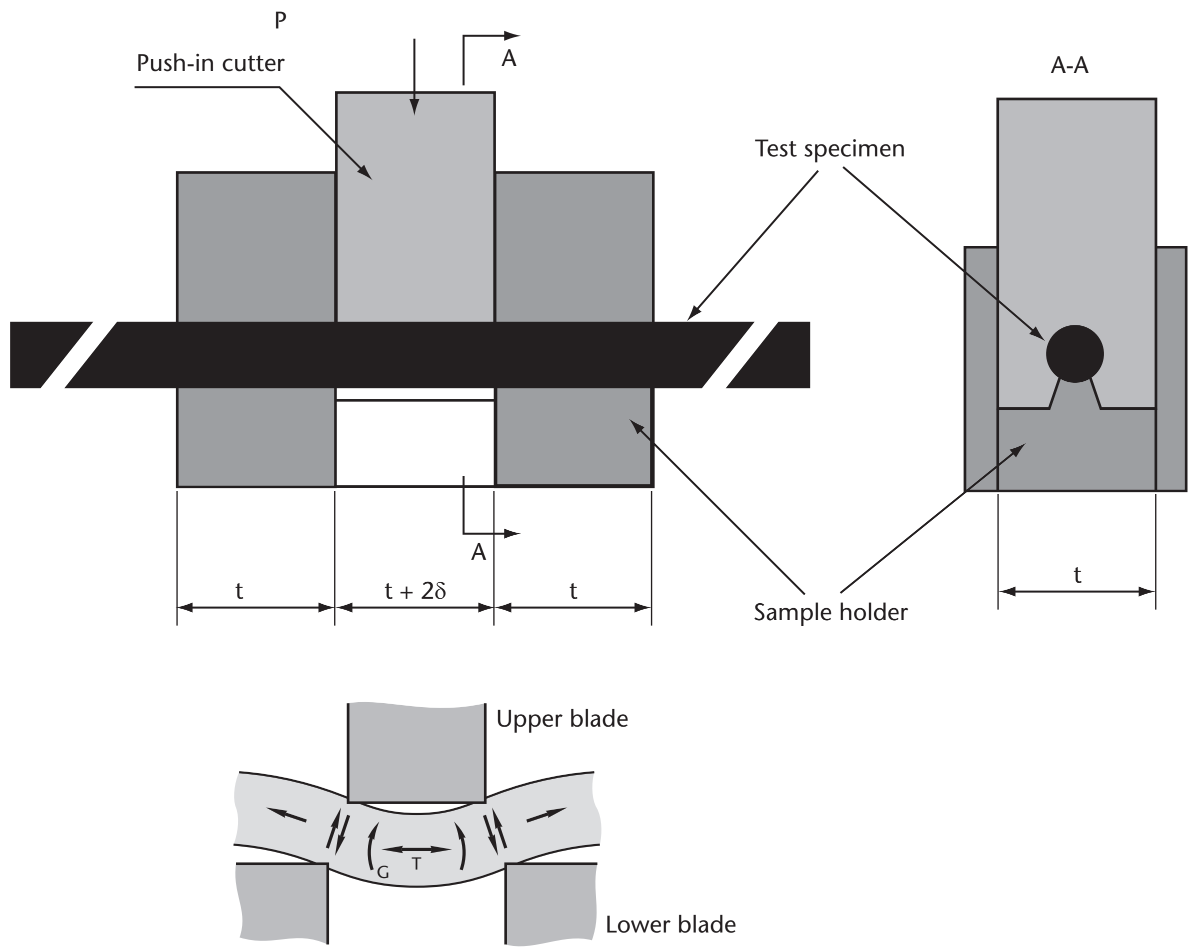


Figure L.1
Double shear testing machine
(See Clause L.5.3.)

Annex M (informative)
Test method for alkali resistance of FRP rods

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

M.1 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.

M.2 Symbols

The following symbols are used in this Annex:

F_{u1} = tensile capacity before immersion, N
F_{u2} = tensile capacity after immersion, N
R_{et} = tensile capacity retention rate, %
W_0 = initial mass of the dried specimen before immersion
W_1 = mass of the specimen after immersion
W_2 = mass of the dried specimen after immersion

M.3 Significance and use

M.3.1

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.

M.3.2

This test method measures tensile capacity retention by measuring the tensile capacity and the weight before and after immersion of an FRP rod.

M.4 Specimen preparation

M.4.1

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.

M.4.2

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.

M.4.3

The length of the test section for tensile testing shall be not 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 be not 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 4560 mm^2, in accordance with ASTM D543.

M.4.4
The number of test specimens for pre- and post-immersion tensile testing shall be as specified in CSA S807. 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.

M.4.5
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.

M.4.6
The test may also be performed on specimens embedded in concrete. The concrete mix and the curing procedure shall be in accordance with ASTM C511. Specimens shall be embedded in concrete for 28 days before testing. Dimensions of the concrete cylinder shall be as shown in Figure M.1.

M.4.7
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.

M.4.8
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.

M.5 Test equipment and requirements

M.5.1
The testing machine and devices shall be in accordance with Annex C.

M.5.2
The test temperature shall be in accordance with Annex C.

M.6 Test method

M.6.1
The pH value of the alkaline solution shall be measured before and after the alkali resistance test.

M.6.2
The specified temperature for immersion shall be 60° ± 3°C.

M.6.3
The test specimen shall be washed in water after removal from the immersion solution.

M.6.4
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.

M.6.5
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).

M.6.6
For the tensile test, the test method shall be in accordance with Annex C.

M.6.7
The samples shall have one-month, three-month, and six-month tests. Test results obtained on specimens without sustained tensile loads and with sustained tensile loads should be reported. Typically, the stress in the sustained load tests should be equal to the stress caused by the dead loads, and any part of the live loads that is sustained. If service load conditions are not known, the sustained tensile stress in glass FRP bars should be set to induce a tensile strain equal to 3000 microstrain. Higher levels of sustained stress can be used as an accelerating condition. The level of sustained stress should be reported.

M.7 Calculations

M.7.1
The mass change of FRP rods shall be calculated according to Equation (M-1) or (M-2):

$$\text{Mass gain (\%)} = \frac{W_1 - W_0}{W_0} \times 100 \qquad \textbf{(M-1)}$$

$$\text{Mass loss (\%)} = \frac{W_0 - W_2}{W_0} \times 100 \qquad \textbf{(M-2)}$$

M.7.2
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.

M.7.3
The tensile capacity retention rate shall be calculated in accordance with Equation (M-3), with a precision to two significant digits:

$$R_{et} = \frac{F_{u1}}{F_{u2}} \times 100 \qquad \textbf{(M-3)}$$

M.8 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.

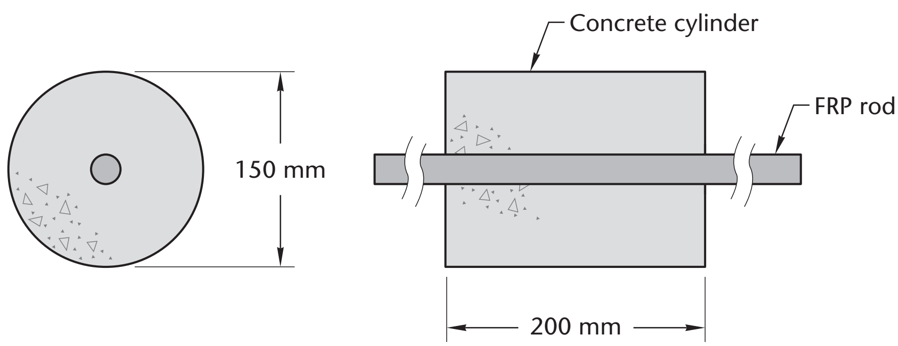


Figure M.1
Dimensions of the concrete cylinder
(See Clause M.4.6.)

Annex N (informative) **Test methods for bond strength of FRP sheet bonded to concrete**

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

N.1 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.

N.2 Symbols

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

N.3 Test method A

N.3.1 Apparatus

N.3.1.1 Testing machine

The machine shall generally conform to ASTM E4. 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 might not have enough clearance to accommodate the relatively long anchors required by specimens of high load capacity. Special testing frames might be required in such cases.*

N.3.1.2 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.

N.3.1.3 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.

N.3.1.4 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.

N.3.2 Specimens

N.3.2.1 General
The test specimen shall be as shown in Figure N.1. 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 N.1. The FRP sheets are bonded on two opposite sides of the prism.

N.3.2.2 Number of specimens
A total of six specimens, one for each bond length, shall be prepared.

N.3.2.3 FRP reinforcement
FRP reinforcement shall be representative of the roll or batch being tested.

N.3.2.4 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.

N.3.2.5 Cross-sectional area
The cross-sectional area of the FRP sheet shall be taken as the width of the sheet multiplied by its thickness.

N.3.2.6 Tensile strength
The tensile strength of the FRP sheet shall be determined in accordance with Annex F.

N.3.2.7 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:

$$L_{ea} = \frac{25\,350}{(t_F \times E_F)^{0.58}} \quad \textbf{(N-1)}$$

The six values of k for the different sheet lengths may be taken in increments of 0.2, from 0.6 to 1.6.

N.3.2.8 Specimen length
The total concrete prism length shall be taken as

$$L_{cp} = 3.2L_{ea} + 50\text{mm} \quad \textbf{(N-2)}$$

N.3.2.9 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 C192/C192M. The slump shall be measured and its ultimate strength determined after 28 days.

N.3.2.10 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.

N.3.2.11 Curing specimens

One day after moulding, the prism shall be demoulded and transferred to a curing environment in accordance with ASTM C192/C192M.

N.3.2.12 Bonding the FRP sheets

On the 28th day after moulding, the FRP sheets shall be bonded in accordance with 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.

N.3.2.13 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.

N.3.3 Test environment

Tests shall be carried out with the room temperature maintained at 20 ± 5 °C and relative humidity at 50 ± 25%.

N.3.4 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.

N.3.5 Test procedure

N.3.5.1 Mounting specimen

The specimen shall be carefully transported, lifted, and mounted on the testing machine in the position shown in Figure N.1. 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.*

N.3.5.2 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.

N.3.5.3 Data recording

If a data acquisition system is used, it shall be started 10 s before the commencement of the loading.

N.3.5.4 Safety measure

Because some specimens can 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.

N.3.5.5 Test termination

The test shall be terminated when either the FRP sheet ruptures or the FRP sheet debonds from the concrete.

N.3.5.6 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.

N.4 Test method B

N.4.1 Apparatus

N.4.1.1 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.

N.4.1.2 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.

N.4.1.3 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.

N.4.2 Specimens

N.4.2.1 General
The isometric view of a test specimen and the set-up is shown in Figure N.2. 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.

N.4.2.2 Specimen dimensions
The specimen dimensions shall be as shown in Figure N.3.

N.4.2.3 Number of specimens
A total of six specimens, one for each bond length, shall be prepared.

N.4.2.4 FRP reinforcement
FRP reinforcement shall be representative of the roll or batch being tested.

N.4.2.5 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.

N.4.2.6 Cross-sectional area
The cross-sectional area of the FRP sheet shall be taken as the width of the sheet multiplied by its thickness.

N.4.2.7 Tensile strength
The tensile strength of the FRP sheet shall be determined in accordance with Annex F of this Standard.

N.4.2.8 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 (N-1). The six values of k for the different sheet lengths shall be taken in increments of 0.2, from 0.6 to 1.6.

N.4.2.9 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 C192/C192M. Slump of fresh concrete shall be measured and its ultimate strength determined 28 days.

N.4.2.10 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.

N.4.2.11 Curing specimens
One day after moulding, the specimen shall be demoulded and transferred to a curing environment as stipulated in ASTM C192/C192M.

N.4.2.12 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.

N.4.3 Test environment
Tests shall be carried out with the room temperature maintained at 20 ± 5 °C and relative humidity at 50 ± 25%.

N.4.4 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.

N.4.5 Test procedure

N.4.5.1 Mounting the specimen
The specimen shall be carefully transported, lifted, and mounted on a flat smooth surface.

N.4.5.2 Rate of loading
The load shall be applied at a bond stressing rate of 0.5 MPa/min.

N.4.5.3 Data recording
If a data acquisition system is used, it shall be started 10 s before the commencement of loading.

N.4.5.4 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.

N.4.5.5 Test termination

The test shall be terminated when either the FRP sheet ruptures or the FRP sheet debonds from the concrete.

N.4.5.6 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.

N.5 Calculations

N.5.1 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%.

N.5.2 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:

$$f_b = \frac{P}{L(w)} \qquad \textbf{(N-3)}$$

where

$L = L_e$ if $L \geq L_e$

$= L$ if $L < L_e$

N.6 Report

The report shall include the following:

(a) properties of the concrete:
- (i) the mix proportions of cement, fine and coarse aggregates, admixtures (if any used), and the water-cement ratio;
- (ii) the slump of freshly mixed concrete as determined in accordance with ASTM C143/C143M;
- (iii) the 28 day strength of control cylinders as determined in accordance with ASTM C138/C138M; 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;

(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
(ix) 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.

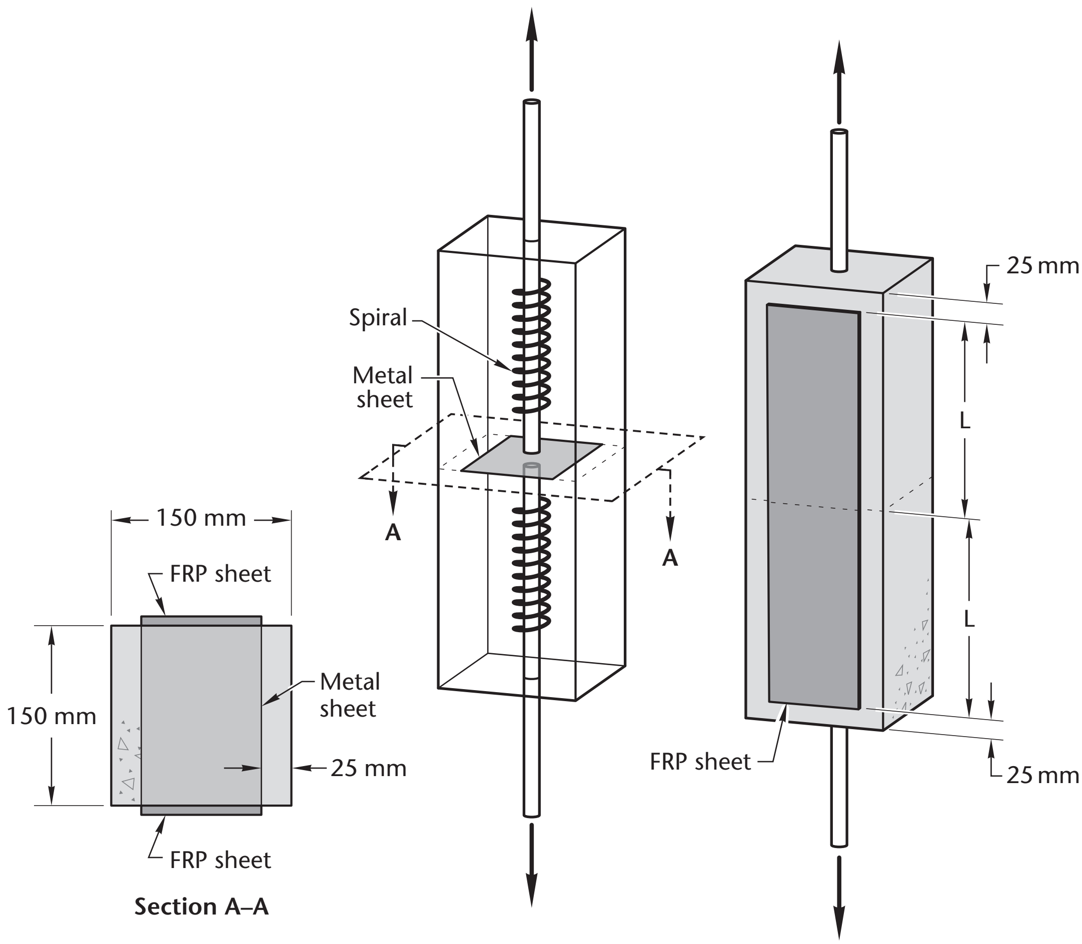


Figure N.1
Pull bond test
(See Clauses N.3.2.1 and N.3.5.1.)

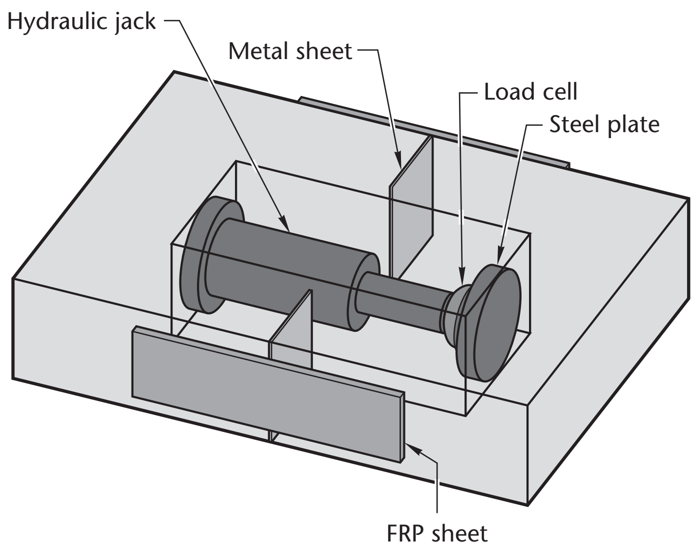


Figure N.2
Push apart bond test — Isometric view
(See Clause N.4.2.1.)

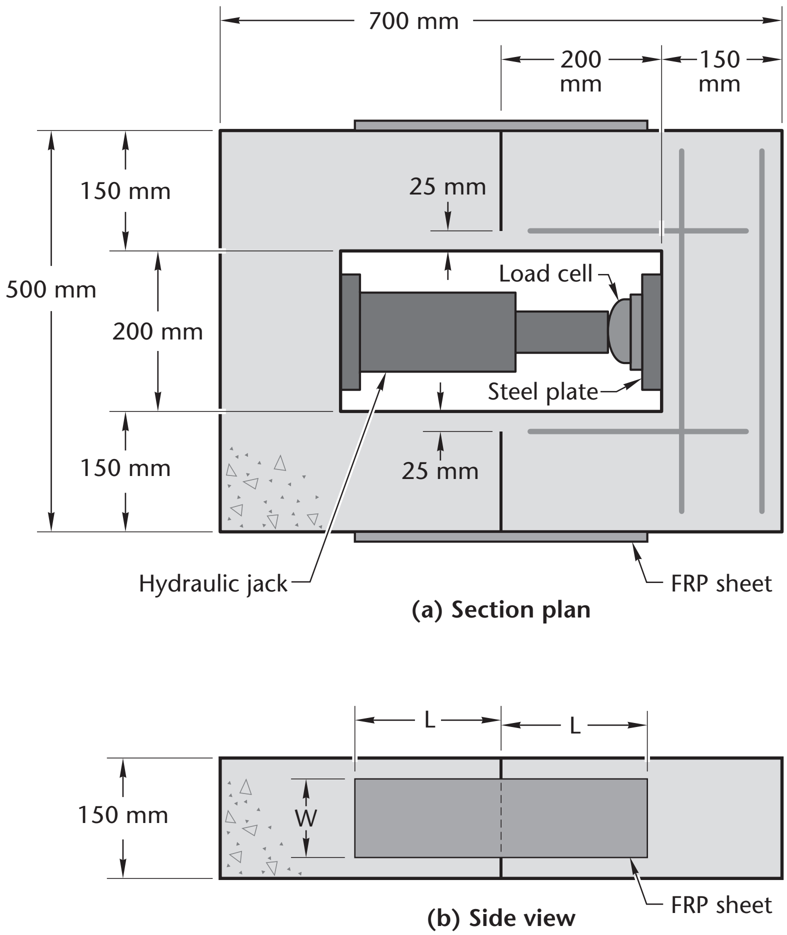


Figure N.3
Push apart bond test
(See Clause N.4.2.2.)

Annex O (informative)
Test method for overlap splice tension test

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

O.1 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° and continuous bidirectional fabrics at 0/90°.

O.2 Symbols

The following symbols are used in this Annex:

f_{su} = average tensile shear strength
l = overlap length
P = failure load
w = specimen width

O.3 Summary of test method

The tension specimen shown in Figure O.1 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.

O.4 Test apparatus

The test apparatus shall be in accordance with ASTM D3039/D3039M.

O.5 Specimen preparation

O.5.1 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.

O.5.2 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.

O.5.3 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.

O.5.4 Geometry

The test specimen shall be as shown in Figure O.1, 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 O.1 shows nominal specimen geometry for various overlap lengths. Variations in specimen width and thickness shall not be greater than ± 1%.

O.5.5 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.

O.6 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.

O.7 Test procedure

O.7.1

The width and length of the overlap joint shall be measured. The surface area of the joint shall be measured.

O.7.2
The maximum load sustained by the specimen during the test and the failure mode of the specimen shall be recorded, 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 failure modes specified in Items (a) to (d).

O.7.3
The average tensile shear strength shall be calculated using the following equations, and the results reported with a precision of two significant figures:
(a) for single lap:

$$f_{su} = \frac{P}{wl} \qquad \textbf{(O-1)}$$

(b) for double lap:

$$f_{su} = \frac{P}{2wl} \qquad \textbf{(O-2)}$$

O.7.4
For each series of tests, the average value, standard deviation, and coefficient of variation shall be calculated.

O.8 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 O.1
Width and gauge lengths of specimens
(See Clause O.5.4.)

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°.*

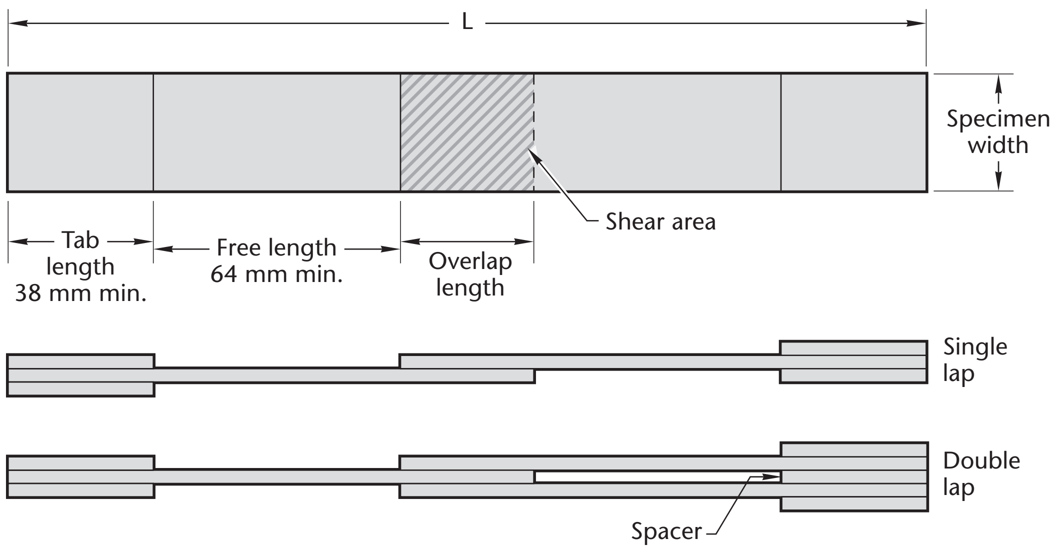


Figure O.1
Overlap tension specimen
(See Clauses O.3 and O.5.4.)

Annex P (informative)
Fibre-reinforced concrete cladding

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

P.1 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.

P.2 Materials and composition of FRC

P.2.1 General

The cementitious matrix shall consist of Portland cement or Portland-limestone 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.

P.2.2 Concrete materials

P.2.2.1 Cement

Portland cement, Portland-limestone cement, and cementitious material conforming to CAN/CSA-A3000 should be used 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 or white Portland-limestone 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.

P.2.2.2 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 A23.1 and CSA 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 can influence the final appearance. Weathering of certain aggregates can influence their appearance over time.

Differential movements of facing materials can 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 should be used with natural stone in order to minimize panel bowing or high stresses in the FRC skin.

P.2.2.3 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 C144.

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.

P.2.2.4 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 C494/C494M, Types A, B, D, F and G, and air-entraining admixtures to ASTM C260. In addition, the use of a combination of admixtures shall be evaluated with the cement intended for use on the job.

P.2.2.5 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 A23.1, Clause 4.)

P.2.3 Reinforcements

P.2.3.1 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 P.1 and P.2. It is noted that alkali-resistant glass fibre-reinforced concrete is by far the most widely used system for the manufacture of GFRC products.

P.2.3.2 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 P.1 and P.2).

P.2.3.3 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 might be justified.

The most common trade name for these fibres is Kevlar®. Mechanical properties of aramid fibres are shown in Table P.3.

P.2.3.4 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 P.4.

P.2.3.5 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 P.5.

P.2.3.6 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 P.6.

P.3 Testing

P.3.1 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.

P.3.2 Acceptance testing of materials

P.3.2.1 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 CAN/CSA-A3000.

P.3.2.2 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 P.1. Certificates shall be kept on file.

P.3.2.3 Sand

Sieve analyses shall be conducted in accordance with CSA A23.2, Method A23.2-2A, on samples taken from each shipment received at the plant.

P.3.2.4 Facing aggregates

Fine and coarse aggregates shall be regarded as separate ingredients, and each shall conform to the requirements for facing aggregates.

P.3.2.5 Water

Water for use in precast concrete shall conform to the requirements of CSA A23.1, Clause 4.

P.3.2.6 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 A23.1.

P.3.2.7 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.

P.3.2.8 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.

P.3.2.9 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 the relevant requirements of CSA A23.1 and CSA 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.

P.3.3 Production testing

P.3.3.1 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.

P.3.3.2 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.

P.3.3.3 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.

P.3.4 Production testing of aggregates
Aggregates for use in precast concrete shall conform to the requirements of CSA A23.1 and CSA A23.4 and to Clause P.3 of this Standard.

P.3.5 Production testing — Wet

P.3.5.1 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.

P.3.5.2 Slurry unit weight
The unit weight test (see ASTM C138/C138M) 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.

P.3.5.3 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 +1 °C shall remain in the sample until the reading becomes stable. This is an advisory test performed at the discretion of the manufacturer.

P.3.5.4 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.

P.3.5.5 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.

P.3.5.6 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.

P.3.5.7 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.

P.3.5.8 Face mix

Air content tests shall be conducted daily on mixes containing air-entraining admixtures.

P.3.6 Production testing — After curing

P.3.6.1 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.

P.3.6.2 Face mix strength tests

Compressive strength tests of the face mix shall be conducted weekly in accordance with ASTM Standard C39/C39M.

P.3.6.3 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.

P.3.6.4 Flex Anchor and gravity anchor pull-off or shear tests
Anchor connection tests shall be conducted on 300 × 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.

P.3.7 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 PCI MNL-128.

P.3.8 Fabrication and placement of reinforcement
Fabrication and placement of reinforcement and prestressing tendons shall conform to the relevant requirements of CSA A23.1 and CSA A23.4.

P.3.9 Tolerances

P.3.9.1 General
The tolerances of precast concrete work shall conform to the requirements of CSA A23.4.

P.3.9.2 Wall panels
For wall panels, see the relevant clauses of CSA A23.4.

P.3.9.3 Joints
For tolerances in joints, Clause 10.6 in CSA 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/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 E119. Joint details can be found in Chapter 4 of the CPCI *Design Manual*.

P.3.10 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 or Portland-limestone 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 in accordance with the following Standards:

(a) ULC CAN/ULC-S102.2;
(b) ASTM E84;
(c) ASTM C518;
(d) ASTM C531;
(e) ASTM C1185; and
(f) ASTM D1037.

Information on panel sizes, thicknesses, shapes, and colours, as well as installation instructions, are available from the manufacturers.

P.3.11 Forms

Forms for precast concrete shall conform to the requirements of CSA A23.4.

Table P.1
Chemical composition of selected glasses, %
(See Clauses P.2.3.1, P.2.3.2, and P.3.2.2.)

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 P.2
Properties of selected glasses
(See Clauses P.2.3.1 and P.2.3.2)

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 P.3
Mechanical properties of aramid fibres
(See Clause P.2.3.3.)

Fibre	Tensile strength, MPa	Modulus of elasticity, MPa	Elongation at break, %
DuPontTM Kevlar® 29	3620	62 000	3.6
DuPontTM Kevlar® 49	3620	117 200	2.5
Teijin Technora®	3030	70 300	4.4

Table P.4
Typical properties of polypropylene fibre
(See Clause P.2.3.4.)

Fibre	Specific gravity	Tensile strength, MPa	Modulus of elasticity, MPa
Polypropylene	0.9	550–690	3540

Table P.5
Typical properties of polyethylene fibre
(See Clause P.2.3.5.)

Fibre	Specific gravity	Tensile strength, MPa	Modulus of elasticity, MPa
Polyethylene	0.96	200	5000

Table P.6
Typical properties of polyester fibre
(See Clause P.2.3.6.)

Fibre	Specific gravity	Tensile strength, MPa	Modulus of elasticity, MPa
Polyester	1.34	900–1100	17 200

Annex Q (informative) ***FRP nonstructural components***

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

Q.1 Fibre-reinforced polymer nonstructural components

The term "fibre-reinforced polymer composites" refers to thermoset resins, additives, catalysts, and reinforcements used 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.

Q.2 Materials and composition of reinforced polymer composites

Q.2.1 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.

Q.2.2 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.

Q.3 Physical properties

Q.3.1 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.

Q.3.2 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.

Q.3.3 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 can be of concern in clamped joint designs.

Q.3.4 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.

Q.3.5 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.

Q.3.6 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.

Q.3.7 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.

Q.3.8 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.

Q.3.9 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.

Q.3.10 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.

Q.3.11 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.

Q.3.12 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.

Q.3.13 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.

Q.3.14 Thermal conductivity

The typical range of thermal conductivity is from 1.7×10^{-3} to 2.3×10^{-3} (W/cm•K). It is noted that low-density cores in FRP laminates can greatly reduce thermal conductivity.

Q.3.15 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.

Q.3.16 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 D3164.

Q.3.17 Test methods for FRP materials
The test methods outlined in Table Q.1 shall be used, as needed.

Q.4 Exterior cladding

Q.4.1 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.

Q.4.2 Panels

Q.4.2.1 FRP Sheets
FRP panels shall be manufactured and tested in accordance with ASTM D3841, 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 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.

Q.4.2.2 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 Q.1
Test methods for FRP materials
(See Clause Q.3.17.)

Test description	ASTM Standard or other method
Mechanical properties	
Tensile strength	ASTM D638
Tensile modulus	ASTM D638
% elongation	ASTM D638
Flexural strength	ASTM D790
Flexural modulus	ASTM D790
Flexural strength-cored laminate	ASTM C393/C393M
Compressive strength	ASTM D695
Bearing load test	ASTM D1602
Punch shear test	ASTM D732
In-plane shear	ASTM D3846 or D3914
Short beam shear	ASTM D2344/D2344M
Izod impact	ASTM D256
Charpy impact	ASTM D256
Environmental	
Accelerated weathering test	ASTM G154 or D4329
Humidity exposure	ASTM D2247
Corrosion testing	ASTM C581
Fire	
Surface burning characteristics	ASTM E84
Oxygen index	ASTM D2863
NBS smoke test	ASTM E662
Surface testing	
Gravelometer	SAE J-400
Gardner gloss meter	Gardner
Stain resistance	ANSI Z124
Physical properties	
Specific gravity	ASTM D792
Water absorption	ASTM D570
Barcol hardness	ASTM D2583
Materials properties	
Resin viscosity	Brookfield
Ignition loss of cured reinforced resin	ASTM D584
Gel time	Room temp./Cup
Weight per gallon	Gardner

Annex R (informative) ***Procedure for the determination of a fire-resistance rating for concrete slabs reinforced with FRP and concrete members strengthened with FRP***

Note: *This informative (non-mandatory) Annex has been written in normative (mandatory) language to facilitate adoption where users of the Standard or regulatory authorities wish to adopt it formally as additional requirements to this Standard.*

R.1 Fire Resistance of concrete slabs reinforced with FRP

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*). While the heat transfer behaviour of FRP reinforced concrete slabs during exposure to a standard fire is similar to slabs reinforced with steel bars, the reinforcement type has an influence on fire resistance. Concrete slabs reinforced with FRP bars may have lower fire resistances as compared with slabs reinforced with conventional steel (Bisby and Kodur 2007). The type of reinforcement, aggregate type, and concrete cover thickness have an influence on the fire performance of FRP-reinforced slabs. The load and resistance factors and serviceability criteria used during the design process also affect fire performance. As such, design of FRP-reinforced concrete members for fire safety should be performed with an understanding of the appropriate structural fire endurance criteria applicable to the buildings in which they are proposed. The designer should also be aware that the bond between FRP bars and concrete is more sensitive to the effects of elevated temperature than it is for conventional deformed steel reinforcing bars. The general approach to fire endurance tests given in UL CAN/ULC-S101 should be performed, even though CAN/ULC-S101 does not specifically mention FRP materials. When conducting fire tests using CAN/ULC-S101 for FRP reinforced concrete members, the critical temperature approach should not be taken for the FRP reinforcement. Instead, the concrete slab shall be tested in a loaded condition and the fire endurance shall be determined based on strength and deflection limits rather than on the temperature in the FRP. Temperature limits in the concrete (i.e., on the unexposed surface) shall still apply.

Kodur and Baingo (1998) and Bisby and Kodur (2007) performed a parametric study using a one dimensional heat transfer model to investigate the potential impacts of fire on unloaded FRP reinforced concrete slabs and 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 FRP reinforced structural member loses enough of its original capacity such that the loads to be expected during a fire can no longer be supported. Lie (1978) found that for reinforcing steel, the critical temperature is 593 °C. At this critical temperature of 593 °C, steel loses half of its room temperature strength. Thus, for FRP, the critical temperature for strength can be taken as the temperature at which the bar loses 50% of the tensile strength at room temperature. For FRP reinforcement, the critical temperature depends on the type and composition of FRP, and hence it shall be provided by the manufacturer based on tensile tests at elevated temperature on the specific type of FRP bar under consideration. Wang and Kodur (2005) have reported that the critical temperatures for loss of strength, based on a 50% strength reduction criterion, are 325 °C for GFRP and 250 °C for CFRP bars. Other research has shown that the critical temperature for strength can vary between 200 and 500 °C (Bisby et al. 2005a, Weber et al. 2008). Tensile tests on FRP bars to determine the critical temperature shall be performed at different elevated temperatures in accordance with Annex C using a relevant heating chamber (Wang and Kodur 2005; Robert and Benmokrane 2010).

In lieu of actual full scale fire resistance test data, the fire resistance of FRP-reinforced concrete slabs can be established using the figures provided by Kodur and Baingo (see Figures R.1 to R.8) for a given FRP's critical temperature specified by the FRP manufacturer.

Alternatively, these figures may be used to obtain the relevant concrete cover thickness of FRP reinforcement for a required fire resistance rating (again assuming that the critical temperature is known). As an illustration, the required cover of reinforcement to obtain a fire resistance of 1 h in a 250 mm thick FRP reinforced concrete slab, made of carbonate aggregate concrete, and with the critical temperature of FRP as 325 °C, for the purposes of illustration only [based on data presented for glass FRP bars by Wang and Kodur (2005)], is about 40 mm (see Figure R.4). This assumed critical temperature might not be realistic for all FRP bars (strength tests should be conducted to determine the appropriate critical temperature for a given type of FRP bar). Any post-fire evaluation of an FRP reinforced concrete structure should consider the possible impacts of heating on both the mechanical and bond properties of the FRP bars.

R.2 Fire resistance of FRP-strengthened structures

The level of strengthening that can be achieved through the use of bonded FRP reinforcement may be limited by the code-required fire resistance rating for the structure. FRP materials used in structural strengthening applications suffer degradation of mechanical and bond properties at elevated temperatures close to or exceeding the glass transition temperature of their polymer matrix or adhesive (Bisby et al. 2005a). The strength of externally bonded FRP systems is therefore assumed to be lost in a fire unless it can be shown that the FRP temperature will remain below its critical temperature for the required duration during fire. The critical temperature for a specific FRP system shall be defined as the temperature at which sufficient deterioration of the FRP's mechanical or bond properties has occurred to cause failure of the concrete member strengthened with FRP subject to the CAN/ULC S101 standard fire in a loaded condition. Critical temperatures are generally not known for available FRP strengthening systems, and additional research is needed in this area. However, in the absence of specific information on the properties of a given FRP strengthening system at high temperature, the critical temperature for fire resistance calculations of an FRP strengthening system can be taken as the lowest glass transition temperature of all the polymers used in the system (i.e., the primer, matrix, and adhesive).

To demonstrate adequate fire resistance, a concrete member strengthened with FRP shall possess sufficient strength to resist all applicable service loads on the strengthened member during fire, without relying on the strength contribution of the FRP system as required by Clause 5.3.2.3. This can typically be expressed as

$$R_{ne} \geq D + (L + 0.5S) \text{ or } (S + 0.5L)$$

where

R_{ne} = the factored resistance of the member at elevated temperatures (this will be lower than the nominal resistance at room temperature) exposed to the CAN/ULC S101 standard fire for a duration associated with the necessary fire resistance rating of the member

D = dead load effect

L = live load effect

S = snow load effect

D, L, and S, shall be determined using the strengthened load requirements for the structure.

The nominal resistance of the member at elevated temperature shall be determined using accepted structural fire engineering principles. Guidance in this area is available, for example, from ACI 216R or EN 1992-1-2. The nominal resistance shall be calculated based on the properties of the existing member (if the FRP strengthening is meant to address a loss in strength, the resistance should reflect this loss) and shall not account for the contribution of the FRP system unless the FRP temperature can be demonstrated to remain below the critical temperature. The nominal resistance at elevated temperature may alternatively be demonstrated through testing in accordance with the principles of CAN/ULC-S101. Additional guidance in this area is given by Kodur et al. (2006).

The fire endurance of concrete members strengthened with FRP can be improved by applying insulation systems or other methods of fire protection (Bisby et al., 2005a). An insulation system improves the fire rating of such structural members by providing protection to the existing element (i.e., the concrete and reinforcing steel). The insulation system delays temperature-induced strength degradation of the existing structural member and thus increases its fire rating. Such insulation systems also protect the FRP during the early stages of the fire scenario and thus delay combustion of the FRP. Hence, with proper insulation that remains in place during fire, the fire rating of a member can be increased even when the FRP strength contribution is ignored during fire (Bisby et al., 2005b, Kodur et al., 2006, Williams et al., 2006). Such an approach has been demonstrated through testing in accordance with CAN/ULC S101 (e.g., Kodur et al. 2006). This testing has resulted in Underwriters' Laboratories fire-rated, insulated FRP strengthening systems that can achieve fire resistances up to 4 h (Underwriters' Laboratories 2010).

FRP-strengthened members shall comply with all applicable smoke generation and flame spread ratings according to the *National Building Code of Canada*, depending on the classification of the building. Coatings and insulation systems (e.g. Bisby et al. 2005b, Kodur et al. 2006, Williams et al. 2006) can be used to limit smoke generation and flame spread.

R.3 Reference publications

Bisby, L. A and Kodur, V. K. R., 2007. "Evaluating the fire endurance of concrete slabs reinforced with FRP Bars: Considerations for a holistic approach," *Composites, Part B*, 38: 547–558.

Bisby, L. A., Green, M. F., and Kodur, V. K. R., 2005a, "Response to Fire of Concrete Structures that Incorporate FRP," *Progress in Structural Engineering and Materials*, 7(3): 136–149.

Bisby, L. A., Green, M. F., and Kodur, V. K. R., 2005b, "Fire Endurance of Fiber-Reinforced Polymer-Confined Concrete Columns," *ACI Structural Journal*, 102(6): 883–891.

Kodur, V. K. R. and Baingo, D. 1998."Fire Resistance of FRP-Reinforced Concrete Slabs." *Internal Report* No. 178. Institute for Research in Construction, National Research Council Canada.

Kodur, V. K. R., Bisby, L. A., Green, M.F., 2006,"FRP Retrofitted Concrete under Fire Conditions — Performance verification of insulated reinforced concrete members," *Concrete International*, 28(12): 37–44.

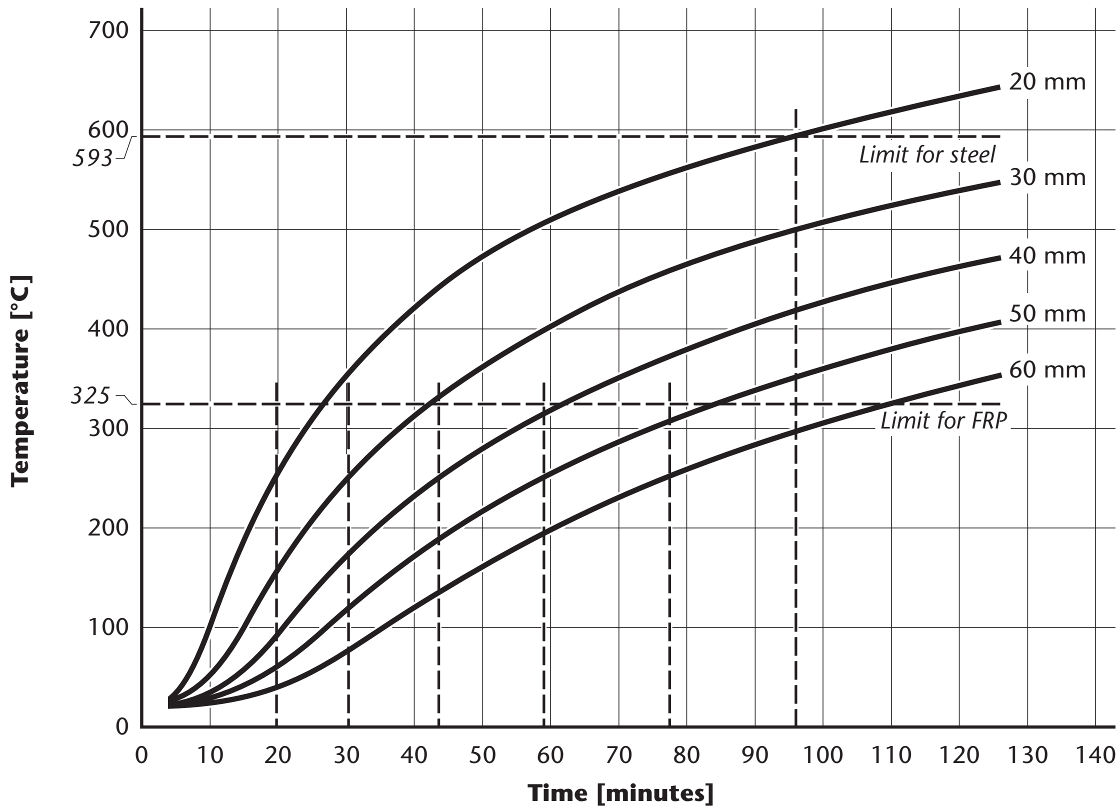
Lie, T. T. 1978. "Calculation of the fire resistance of composite concrete floor and roof slabs." *Fire Technology* 14.1, pp. 26–46.

Robert, M., and Benmokrane, B. 2010. "Behaviour of GFRP Reinforcing Bars Subjected to Extreme Temperature," *ASCE Journal of Composites for Construction*, 14(4): 353–360.

Weber, A.; Christian Witt, C.; and Nadjai, A., 2008, "Composite rebars in RC members in case of fire,"*Proceedings of ACMBS-V*, Winnipeg, Manitoba, 22-24 September, CD-Rom: 8 p.

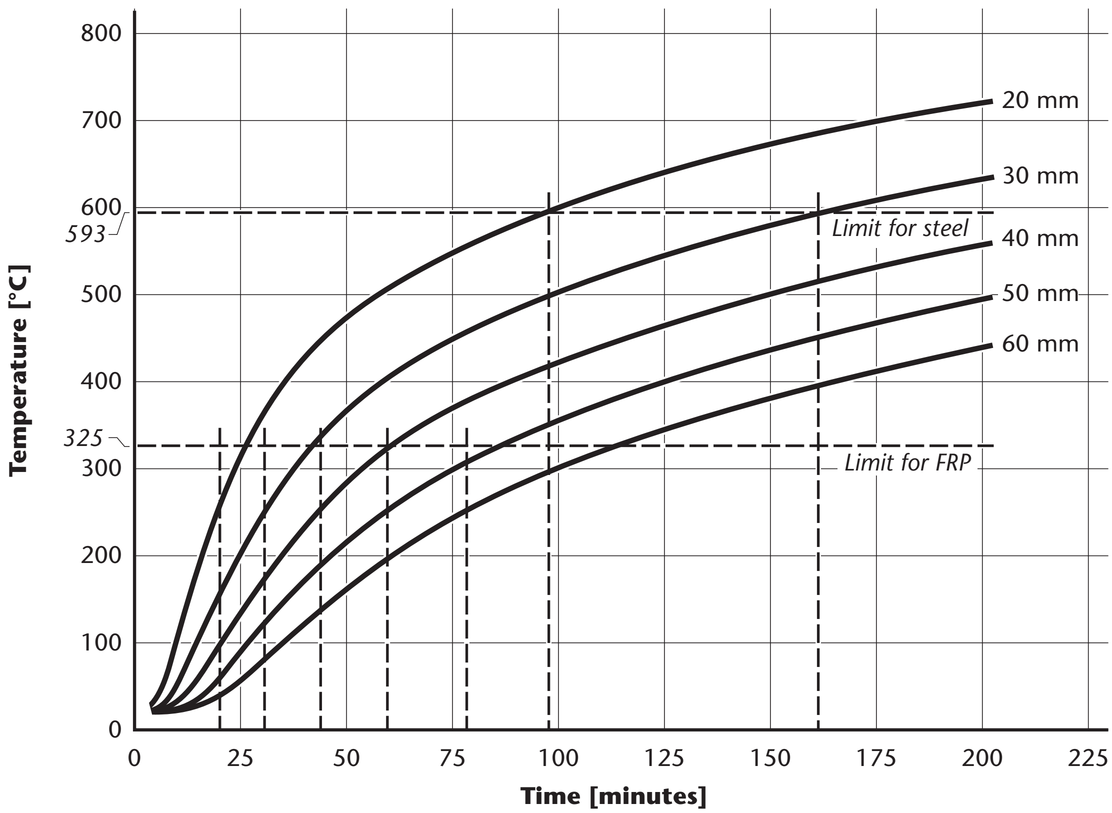
Williams, B.K.; Bisby, L.A.; Kodur, V.K.R.; Green, M.F.; and Chowdhury, E., 2006, "Fire Insulation Schemes for FRP-Strengthened Concrete Slabs," *Composites, Part A*, 37: 1151–1160.

Wang Y. C., and Kodur, V. K. R. 2005. "Variation of Strength and Stiffness of fibre reinforced polymer reinforcing bars with temperature". *Cement Concrete Comp* 27:864–74.



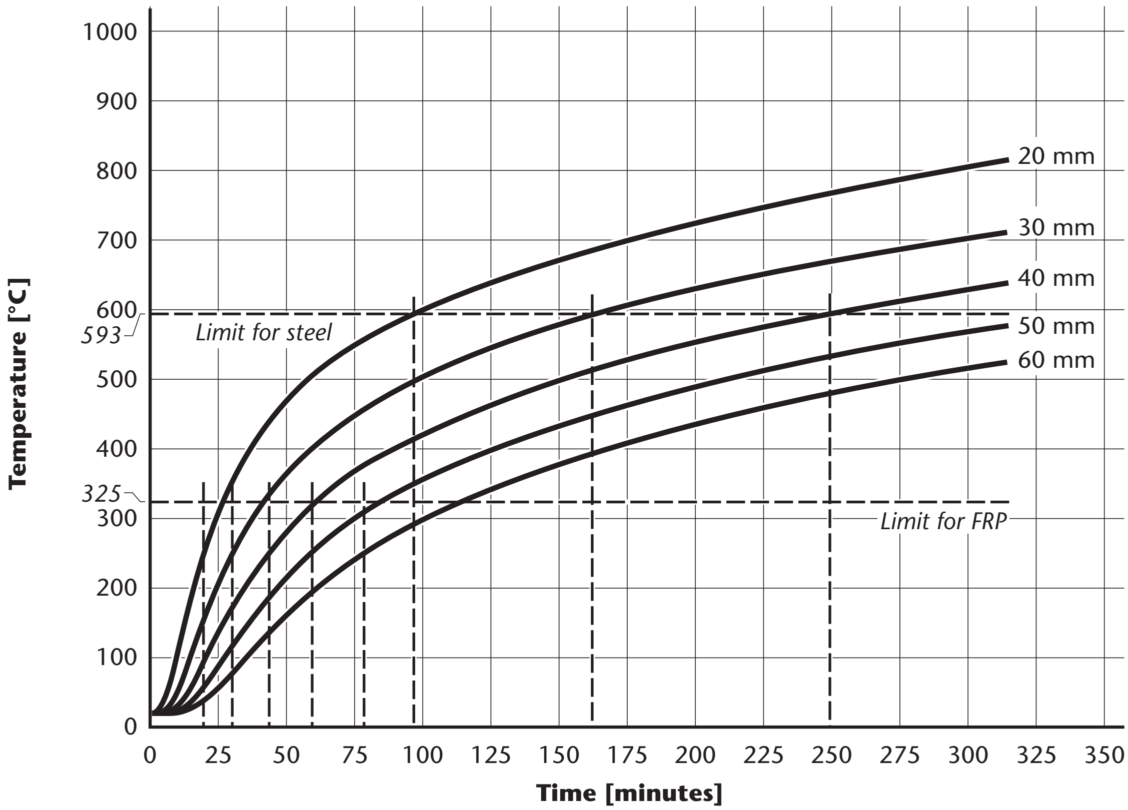
Note: *This figure is based on Kodur and Baingo* (1998).

Figure R.1
Fire resistance of 120 mm concrete slabs
(carbonate aggregate)
(See Clause R.1.)



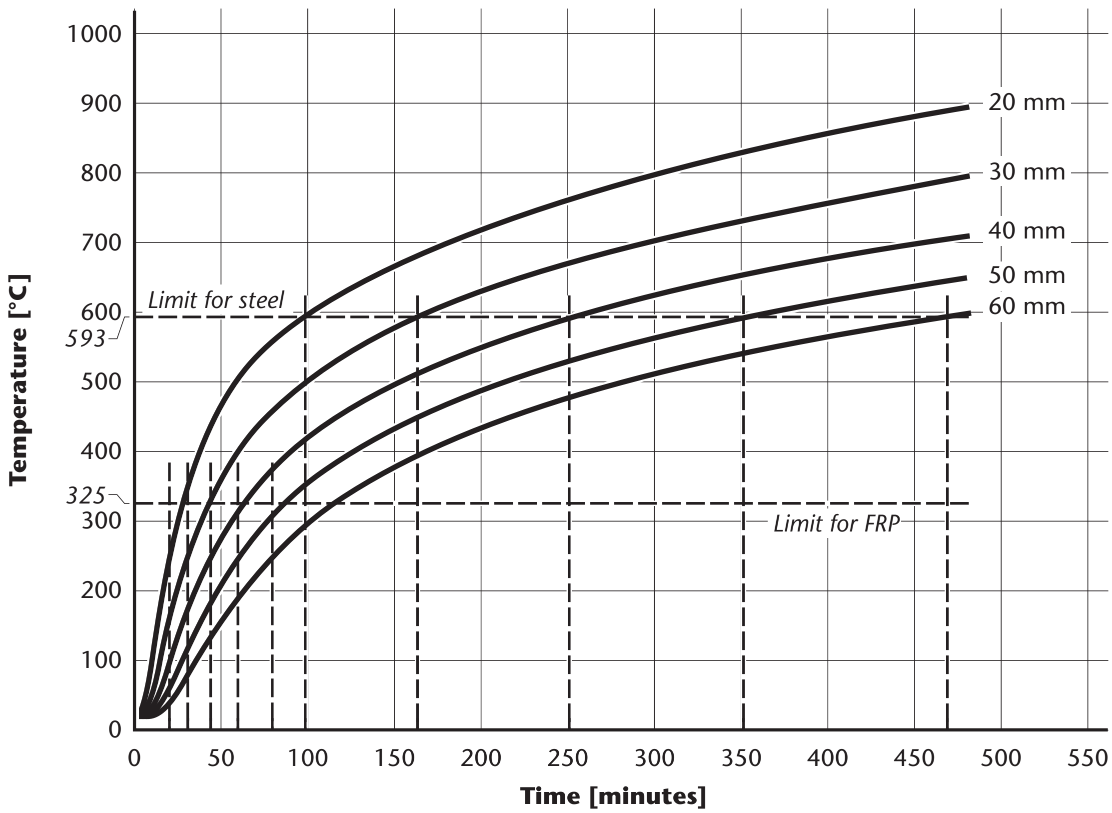
Note: *This figure is based on Kodur and Baingo* (1998).

Figure R.2
Fire resistance of 150 mm concrete slabs
(carbonate aggregate)
(See Clause R.1.)



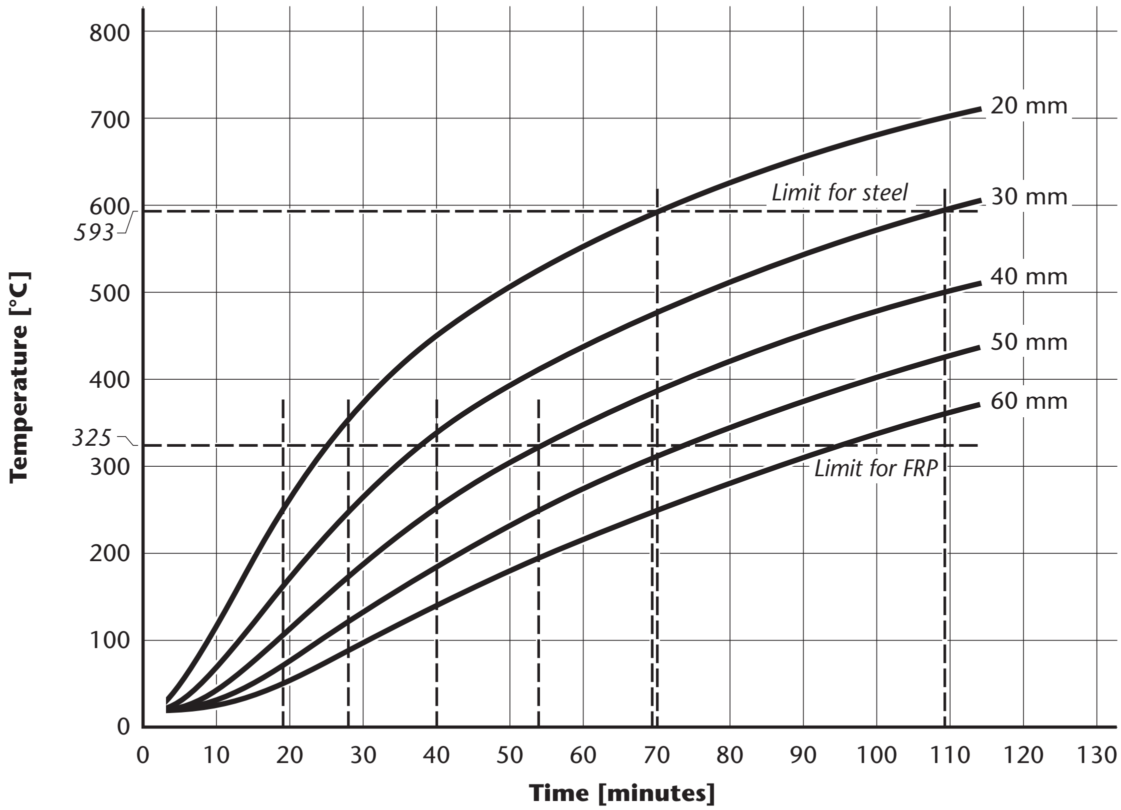
Note: *This figure is based on Kodur and Baingo* (1998).

Figure R.3
Fire resistance of 180 mm concrete slabs (carbonate aggregate)
(See Clause R.1.)



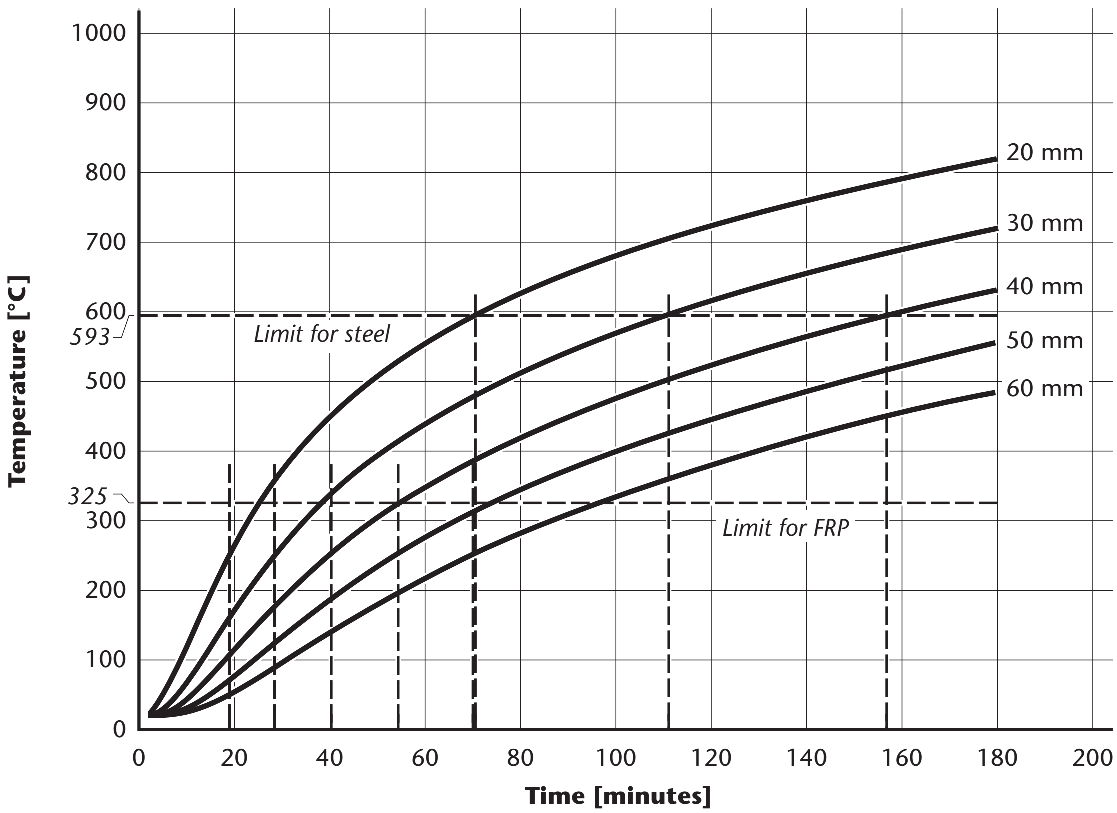
Note: *This figure is based on Kodur and Baingo* (1998).

Figure R.4
Fire resistance of 250 mm concrete slabs
(carbonate aggregate)
(See Clause R.1.)



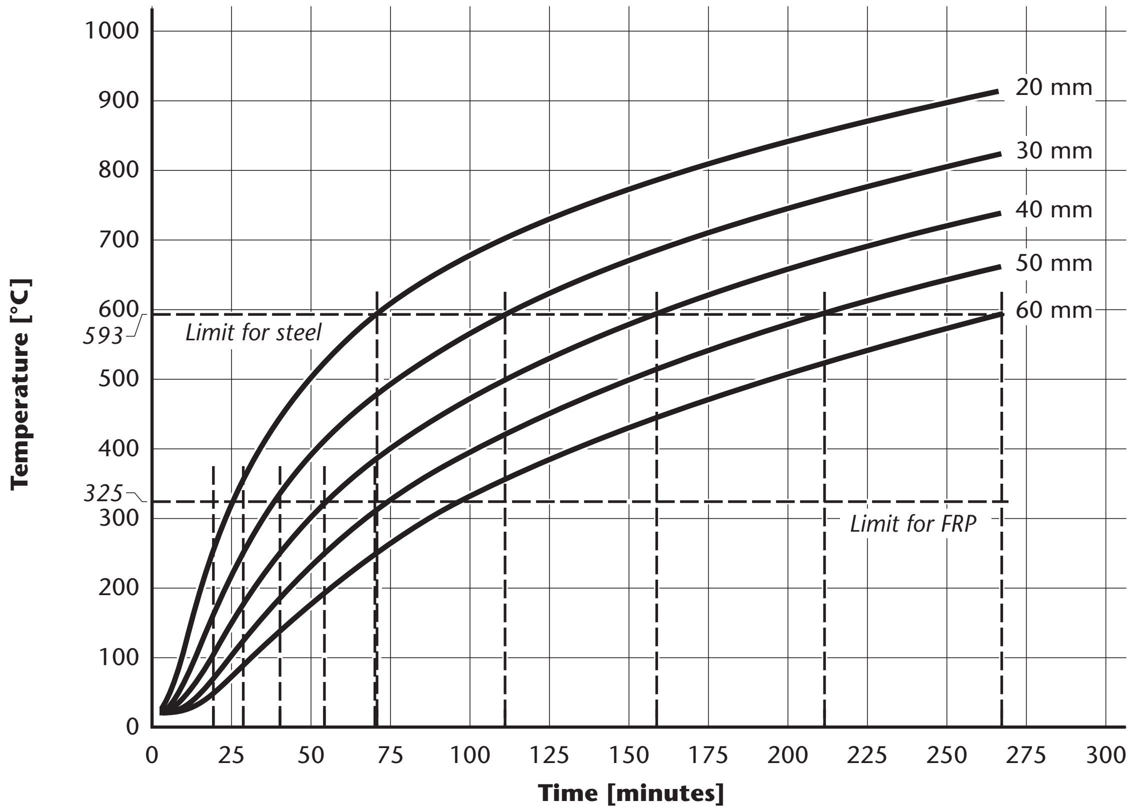
Note: *This figure is based on Kodur and Baingo* (1998).

Figure R.5
Fire resistance of 120 mm concrete slabs (siliceous aggregate)
(See Clause R.1.)



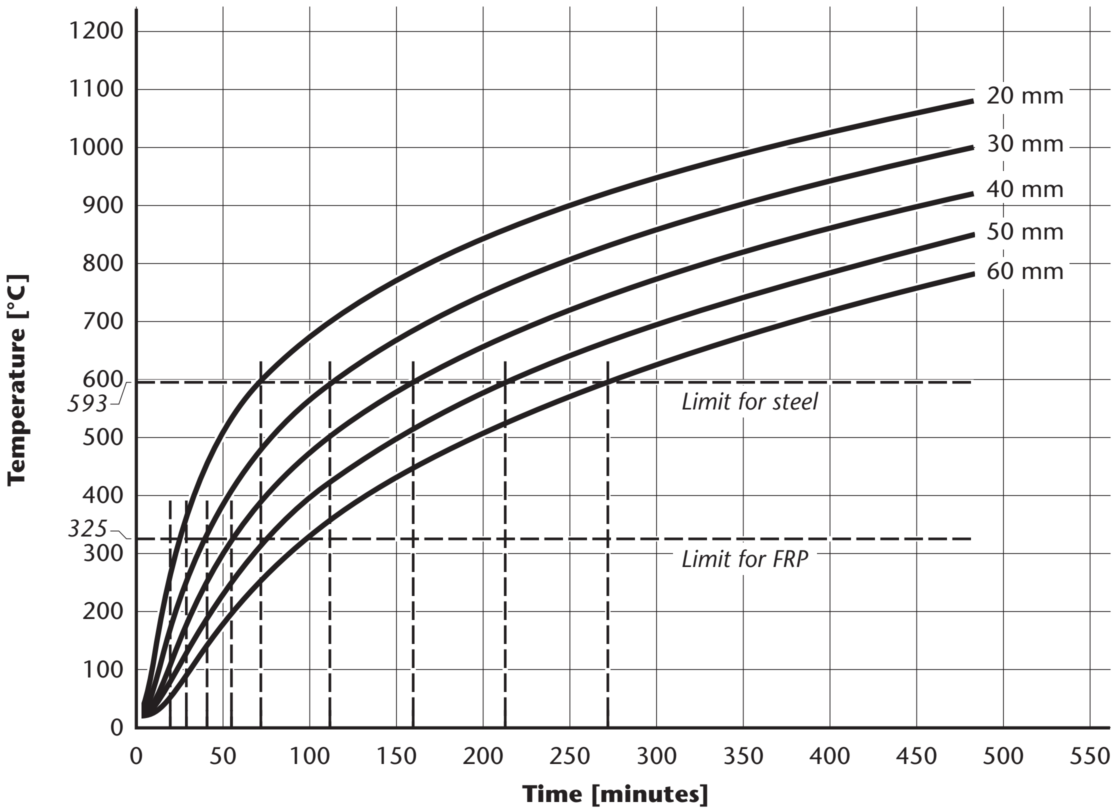
Note: *This figure is based on Kodur and Baingo* (1998).

Figure R.6
Fire resistance of 150 mm concrete slabs (siliceous aggregate)
(See Clause R.1.)



Note: *This figure is based on Kodur and Baingo* (1998).

Figure R.7
Fire resistance of 180 mm concrete slabs
(siliceous aggregate)
(See Clause R.1.)



Note: *This figure is based on Kodur and Baingo* (1998).

Figure R.8
Fire resistance of 250 mm concrete slabs (siliceous aggregate)
(See Clause R.1.)

Annex S (normative)
Test method for determining the bond-dependent coefficient of FRP rods

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

S.1 Scope

S.1.1
This Annex specifies the test requirements for determining the bond- dependent coefficient (k_b) of the FRP rods used as flexural tension reinforcement in concrete members subjected to bending.

S.1.2
This Annex is intended to determine the effects of surface treatment on the bond-dependent coefficient (k_b) of FRP rods. It can be used to test GFRP rods ranging in size from No. 3 to No. 8 and CFRP rods ranging in size from No. 3 to No. 5, using a beam with minimum concrete strength of 28 MPa.

S.2 Significance and use

S.2.1
This Annex is used to determine the bond-dependent coefficient (k_b) of FRP reinforcing rods to be used in flexural members. Thus, this test procedure is based upon beam testing in two points loading.

S.2.2
This Annex is designated to provide bond behavior and strength for material specifications, research and development, quality assurance, and structural design and analysis.

S.2.3
The beams specimens dimensions and reinforcement are designed so that they will not fail in shear prior to concrete crushing, or having bar slip.

S.2.4
This Annex may also be used to determine the conformance of a product or a treatment to a requirement relating to its effect on the bond developed between FRP rod and concrete.

S.3 Definitions

Bond-dependent coefficient (k_b) — factor that accounts for the bond between a bar and concrete.

Development length — length of embedded reinforcement required to develop the tensile capacity.

S.4 Test equipment and requirements

S.4.1
A schematic of a suitable testing system is shown in Figure S.1.

S.4.2
Beams dimensions should be close to L = 3000 mm, b = 200 mm, h = 300 mm.

S.4.3
Shear span, a, should be at least equal to $\ell/3$, or 3 times the height of the beam. Bigger shear span is suitable to reduce shear but the constant bending moment region, x, should not be smaller than 500 mm.

S.4.4
Bar length from the loading point to the bar end shall exceed the development length to avoid any bar slip.

S.4.5
Clear concrete cover for FRP bars is 38 mm for bars #2, #3, #4, and #5 and 50 mm for bars #6, #7, and #8.

S.4.6
The loading system shall be capable of measuring the forces to an accuracy within ±2% of the applied load, when calibrated in accordance with ASTM E4. The load should be applied quasi-statically to the beam at a displacement rate close to 1.2 mm/min.

S.4.7
The hydraulic jack should be fixed between two hinges to ensure that the applied load remains vertical along the test.

S.4.8
Initial crack width of the two first flexural cracks should be measured with instruments capable of 0.01 mm accuracy, such as hand optical or digital microscope as shown in Figure S.2.

S.4.9
Instruments capable of measuring crack opening to an accuracy of 0.01 mm should be installed to measure the continuing crack width growth of the first two flexural.

S.4.10
Initial crack width of the two first flexural cracks should be added in the analysis to the crack width growth measurements to obtain the total crack width.

S.4.11
Mid-span deflection should be measured with a minimum of two displacement metres, one on each side of the beam.

S.4.12
FRP bars strain at mid-span should be measured with a minimum of two strain gages on each bar. Strain gages may be placed 10 mm apart from the centre line of the beam.

S.5 Specimen preparation

S.5.1
FRP rods to be embedded into the specimen should be representative of the lot production being tested.

S.5.2
For each type of bar the set of specimens should be casted in the same batch.

S.5.3
Transverse reinforcement may be placed over the entire length of the beam at a uniform spacing to avoid a shear failure. However, maximum moment region, x, can be transverse-reinforcement-free to avoid confinement effect.

S.5.4
FRP rods used in a given series of tests shall be of the same type and size, and have the same pattern of any deformations or other means of mechanical and frictional interlock with the concrete. The length of the individual rods over the loading point shall be such as to meet the requirements of the test specimens and the expected development lengths.

S.5.5
The concrete should be a standard mix and a minimum of five standard 150 by 300-mm control cylinders should be made for determining compressive strength from each batch of concrete. These cylinders and control tests shall follow ASTM C39/C39M. The concrete mix shall be batched and mixed in accordance with the applicable portions of ASTM C192/C192M. The slump shall conform to the measurements of ASTM C143/C143M.

S.5.6
The concrete should be cast in approximately equal layers, not exceeding 250 mm in depth. Each layer shall be adequately consolidated with an internal vibrator to ensure removal of entrapped air. The specimen may be cast on its side or upside down to control the amount of concrete under the bar during the cast.

S.5.7
The test specimen shall be cured in the forms using a curing compound or a plastic membrane, or both, to prevent rapid evaporation of water for at least 48 h.

S.5.8
Moulds should not be removed from the specimens earlier than 20 h after casting. Immediately after removing the moulds, specimens should be cured in accordance with ASTM C511 until the time of test. Specimens should be tested at an age of 28 ± 3 days, unless k_b at other stages of curing is desired.

S.5.9
Two specimens constitute a set of test specimens. If a specimen is found to have failed prematurely, an additional test shall be performed on a separate specimen using FRP rods taken from the same lot as the failed specimen.

S.6 Test conditions
Unless a different testing environment is specified as part of the experiment, the tests should be conducted at the standard laboratory atmosphere (23 ± 3 $^\circ$C and 50 ± 10 % relative humidity).

S.7 Test method

S.7.1
Beams should be simply supported and tested in two points loading, as shown in Figure S.1.

S.7.2
Load shall be applied until the first flexural crack appears. At that stage loading shall be held constant to measure initial crack width (example see Figure S.2).

S.7.3
The crack width growth measurement system shall be installed at the level of reinforcing bars to monitor the crack width until the end of testing (e.g., see Figure S.3).

S.7.4
Loading shall resume until there is a second flexural crack, and Clauses S.7.1 to S.7.3 as for the first crack shall be repeated.

S.7.5
Loading shall resume until both crack widths have exceeded 1 mm or until beam failure if the ultimate performance is needed.

S.8 Calculations

S.8.1
The bond-dependent coefficient, k_b, should be determined from the measured crack widths and strains in the FRP bars (at service stage) during testing and using Equation (S-1) (CAN/CSA-S6-06, ACI 440.1R-06) if strain readings are poor, stress calculated with elastic crack theory may be used:

$$w = 2\frac{f_f}{E_f}\beta \times k_b \times \sqrt{d_c^2 + \left(\frac{s}{2}\right)^2} \quad \textbf{(S-1)}$$

where

w = maximum crack width, mm

E_f = modulus of elasticity of FRP bar, MPa

f_f = stress in FRP reinforcement in tension, MPa

k_b = bond-dependent coefficient

β = ratio of distance from neutral axis to extreme tension fibre to distance from neutral axis to centre of tensile reinforcement

d_c = thickness of concrete cover measured from extreme tension fibre to centre of bar, mm

s = longitudinal FRP bar spacing, mm

S.8.2
In Equation (S-1), w shall be measured experimentally using displacement meter. All other terms in the equation are known values except k_b, which can be then calculated (mean value). The crack width values, w, for calculating k_b shall not exceed 0.7 mm.

S.9 Report

The test report should include the following items:

(a) properties of the concrete;
  - (i) the mix proportions of cement, fine aggregate, coarse aggregate, admixture (if any used), and the water cement ratio;
  - (ii) slump of freshly mixed concrete as determined in accordance with ASTM C143/C143M;
  - (iii) twenty-eight day strength of control cylinders as determined in accordance with ASTM C39/C39M; and
  - (iv) any deviation from the stipulated standards in such aspects as mixing, curing, dates of demolding and testing of control cylinders; and

(b) properties of the FRP rod:
  - (i) the trade name, shape and date of manufacture if available, and lot number of product tested;
  - (ii) type of fibre and fibre binding material as reported by the manufacturer, fibre volume fraction, surface treatment, and pre-conditioning of FRP rod;
  - (iii) designation, diameter, and cross-sectional area;
  - (iv) modulus of elasticity and ultimate tensile strength as determined in accordance with ASTM D7205/D7205M–06;
  - (v) a close-up photograph of the rods showing surface deformations and characteristics;
  - (vi) numbers or identification marks of test specimens;
  - (vii) date of test, test temperature, and loading rate;
  - (viii) dimensions of test specimens, bonded length of FRP rod, clear cover above the FRP test bar, and size, spacing, and type of transverse reinforcement; and
  - (ix) average bond-dependant coefficient, k_b, at service load and its standard deviation.

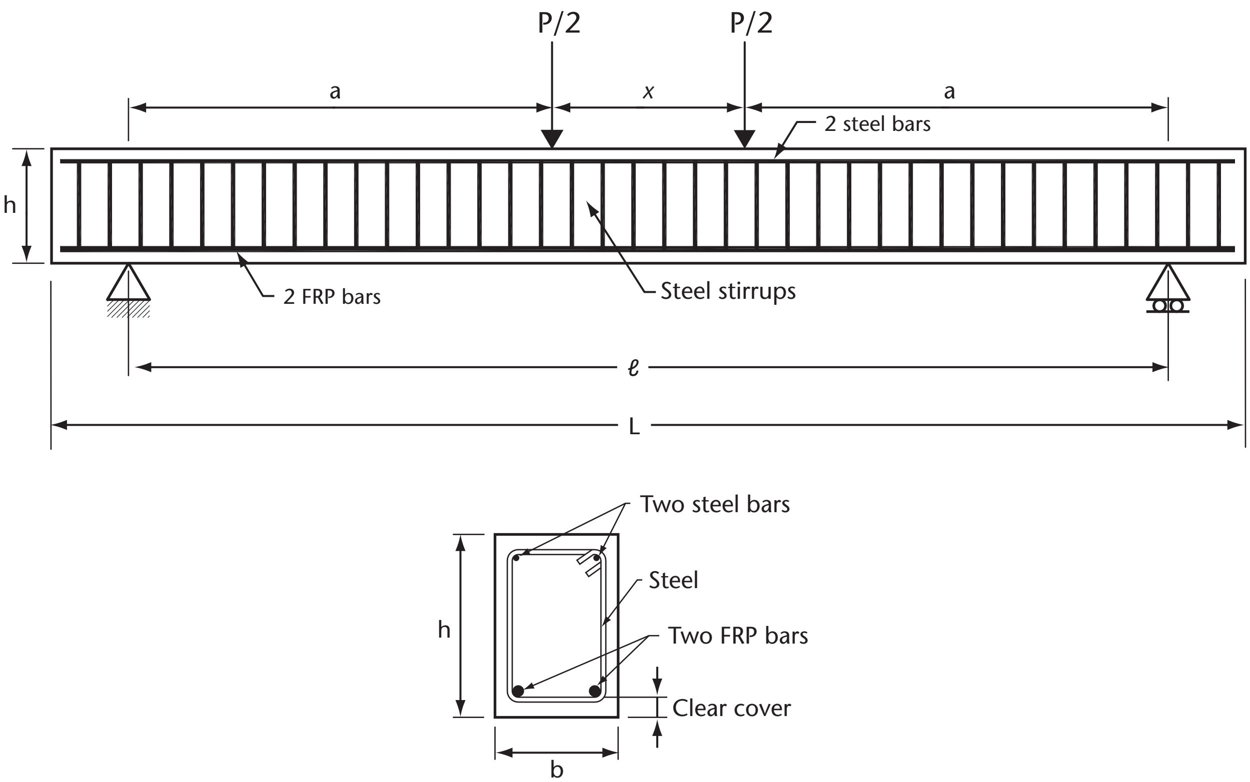


Figure S.1
The dimensions and reinforcement details of the specimens
(See Clauses S.4.1 and S.7.1.)

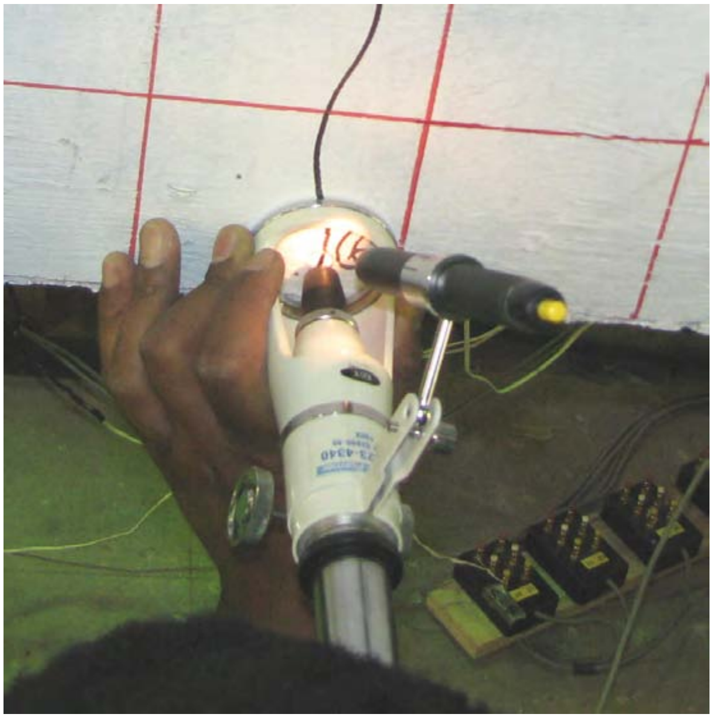


Figure S.2
Hand optical microscope for measuring initial crack-width
(See Clause S.4.8 and S.7.2.)

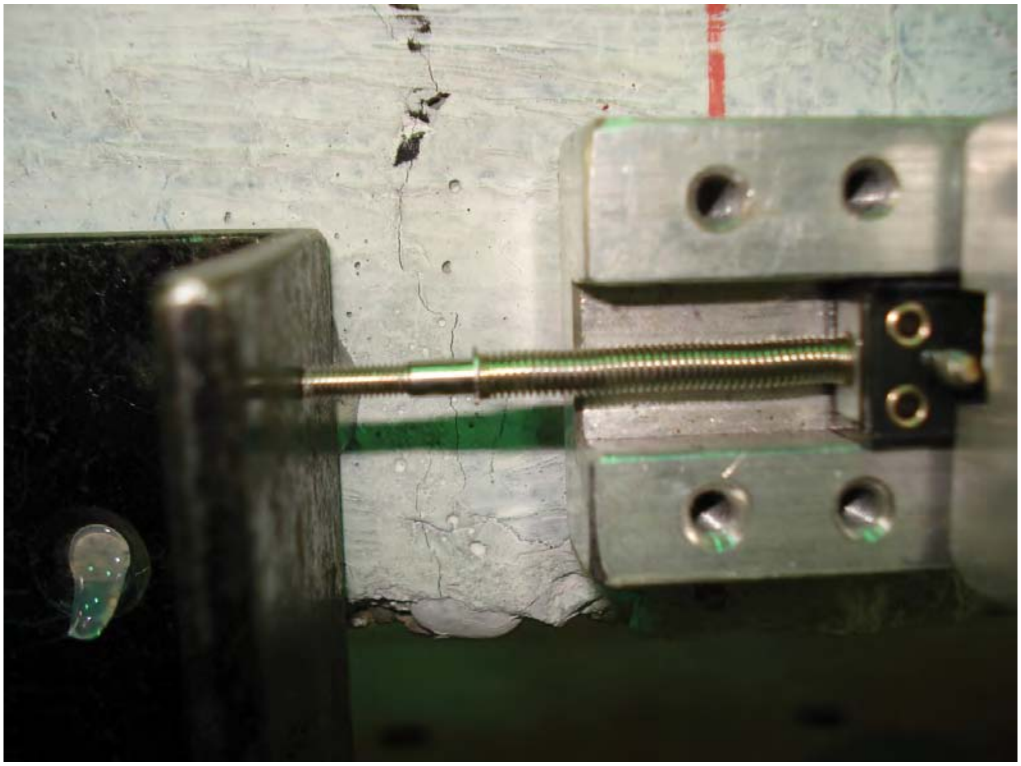


Figure S.3
Monitoring crack–width with displacement meter
(See Clause S.7.3.)

The Canadian Standards Association (CSA) prints its publications on Rolland Enviro100, which contains 100% recycled post-consumer fibre, is EcoLogo and Processed Chlorine Free certified, and was manufactured using biogas energy.

PRINTED IN CANADA IMPRIMÉ AU CANADA

ENVIRONMENTAL CHOICE CHOIX ENVIRONNEMENTAL

PROCESSED CHLORINE FREE PROCÉDÉ SANS CHLORE

100%

BIO GAS ENERGY

ISBN 978-1-55491-931-4