BEI-2019
July 22-25, 2019
Honolulu, Hawaii, USA

July 21, 2019 Seminar for HDOT

BFRP-RC Standardization of Design & Materials

FHWA Project: STIC-0004-00A
(Phase 3 - Technology Transfer)

STIC
State Transportation Innovation Councils

FRP-RC Design - Part 2

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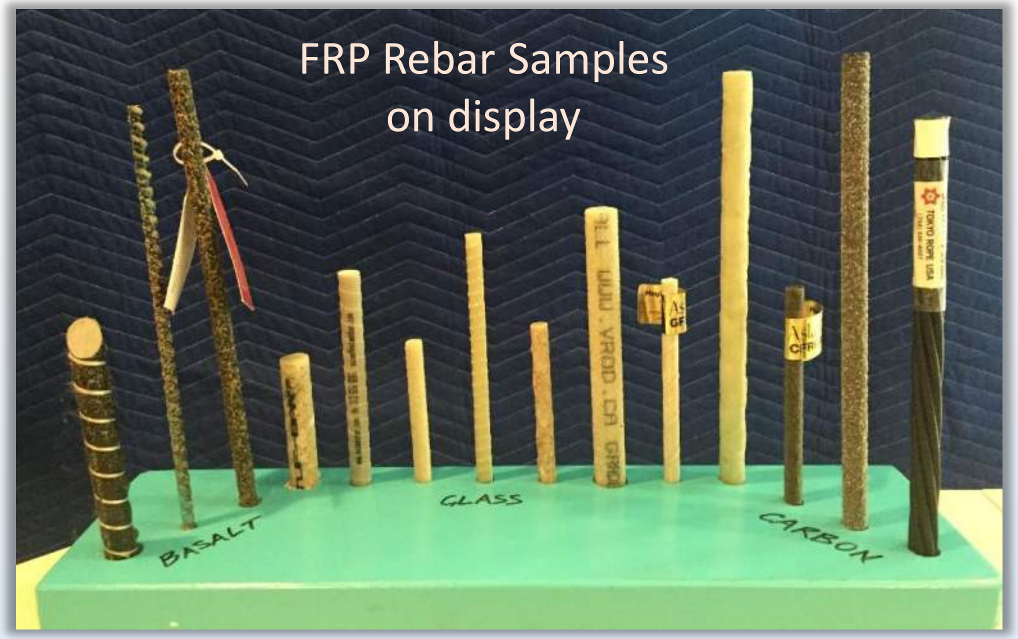
FAMU-FSU Engineering
MIAMI
FDOT

Seminar Description

Fiber-reinforced polymer (FRP) materials have emerged as an alternative for producing reinforcing bars for concrete structures. Due to other differences in the physical and mechanical behavior of FRP materials versus steel, unique guidance on the engineering and construction of concrete structures reinforced with FRP bars is necessary.



Learning Objectives

Part 1

- Understand the mechanical properties of FRP bars
- Describe the behavior of FRP bars

Part 2

- Describe the design assumptions
- Describe the use of internal FRP bars for serviceability & durability design including long-term deflection

Part 3

- Describe the flexural/shear/compression design procedures of concrete members internally reinforced with FRP bars

Part 4

- Review the procedure for determining the development, splice length, and bends for FRP bars.

Content of the Complete Course

FRP-RC Design - Part 1, (30 min.)

This session will introduce concepts for reinforced concrete design with FRP rebar. Topics will address:

- Materials & Design Specifications;
- Design & Typical Applications;
- FRP Rebar Properties;
- New Developments and Solutions;

FRP-RC Design - Part 2, (45 min.)

This session will introduce Basalt FRP rebar that is being standardized under FHWA funded project ***STIC-0004-00A*** with extended FDOT research under BE694, and provide training on the flexural design of beams, slabs, and columns for:

- Design Assumptions and Material Properties
- Ultimate capacity and rebar development length under strength limit states;
- Crack width, sustained load resistance, and deflection under service limit state;

Content of the Complete Course

FRP-RC Design - Part 3, (45 min.)

This session continues with Basalt FRP rebar from Part 2, covering shear and axial design of columns at the strength limit states for:

- Flexural Behavior and Resistance (Session 3a);
- Shear Behavior and Resistance of beams and slabs (Session 3b);
- Axial Behavior of columns & Combined axial and flexure Resistance (Session 3c).

FRP-RC Design - Part 4, (30 min.)

This session continues with FRP rebar from Part 3, covering detailing and plans preparation:

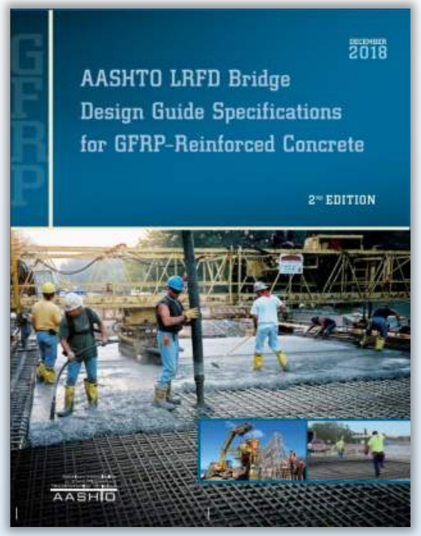
- Fatigue resistance under the Fatigue limit state
- Minimum Shrinkage and Temperature Reinforcing
- Bar Bends and Splicing

Session 2: Design Assumptions and Material Properties

- FRP bar is anisotropic
  - High strength only in the fiber direction
  - Anisotropic behavior affects shear strength, dowel action and bond performance
- FRP bar does not exhibit yielding: is elastic until failure
  - Design accounts for lack of ductility

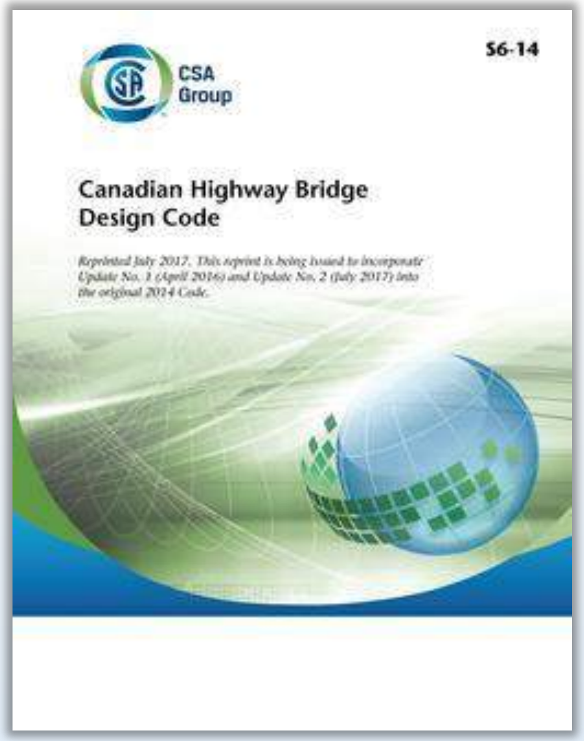
Session 2: Design Assumptions and Material Properties

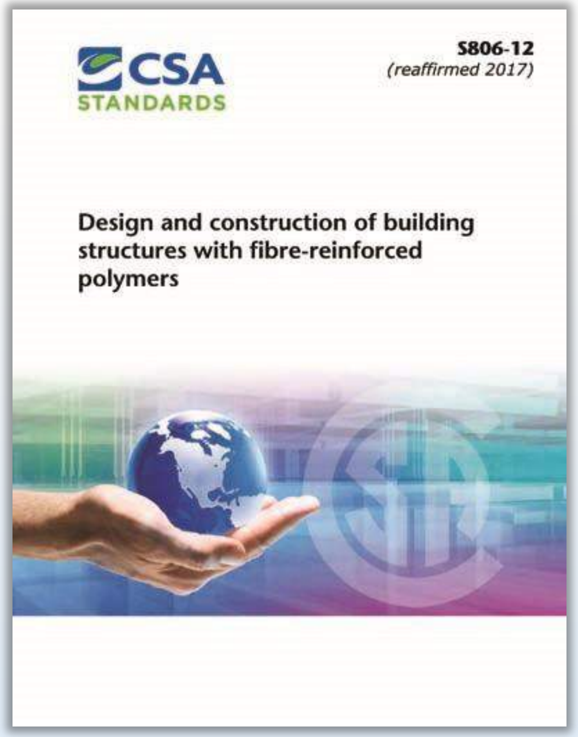
1. **AASHTO-GGS2**: “LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridges 2nd *Edition (2018)*
2. **FDOT Construction and Materials Specifications:** Section 932-3 “Fiber Reinforced Polymer (FRP) Reinforcing Bars” *(2019) (BFRP-2020)*
3. **ASTM D7957-17**: “Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement“. *1st Edition (2017)*
4. **ICC-ES AC454**: “Acceptance Criteria for Fiber-Reinforced Polymer (FRP) Bars for Internal Reinforcement of Concrete Members *(Feb 2017) (2016 update included BFRP)*

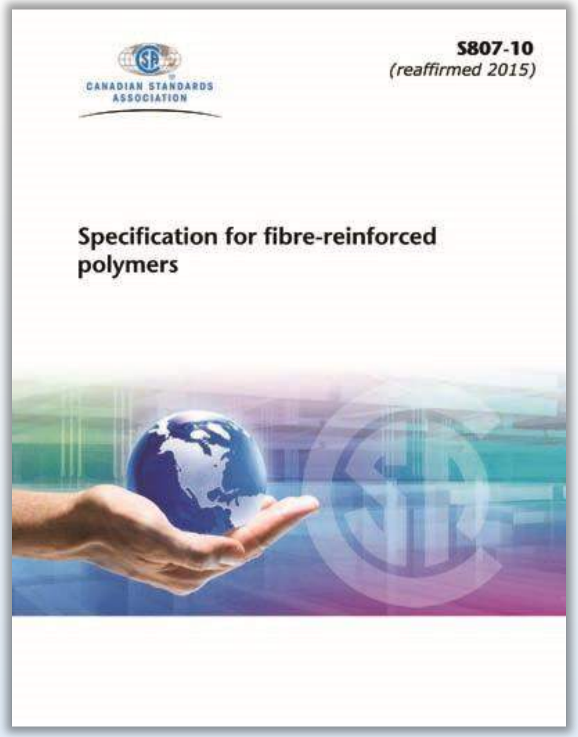


Session 2: Design Assumptions and Material Properties

1. **CAN/CSA-S6:** Canadian Highway Bridge Design Code, Section 16 "Fibre Reinforced Polymers (FRP) Structures".
2. **CAN/CSA-S806:** Design and Construction of Building Components with FRP.
3. **CAN/CSA-S807:** Specifications for Fibre Reinforced Polymers.







Session 2: Design Assumptions and Material Properties

General Standard Philosophy:

These are limit states-based standards

- They follow the same basic procedures as other ***AASHTO*** **or** ***CSA*** structural design standards (concrete structures reinforced with steel bars);
- They are intended primarily for design of concrete structures reinforced internally with FRP bars (and/or grids or externally with sheets and laminates - for repair and retrofit under ***CSA***);
- The standards cover areas for which adequate theoretical and experimental evidence is available to justify the relevant provisions
- The design provisions are intended to be on the conservative side.

Session 2: Design Assumptions and Materials

Load Factors and Load Combinations:

- ***AASHTO-GGS2*** uses the same load factors as in ***AASHTO-LRFD Bridge Design Specifications*** **(Section 3.4.1);**

- ***CSA-S806*** uses the same load factors as in ***CSA A23.3-14*** code. Load combinations are also the same as in ***CSA A23.3-14***, which are based on the ***National Building Code of Canada;***

- ***CSA-S6*** **– Section 16** on FRP Structures - uses the same load factors and load combinations as in the **Section 8** on Concrete Structures of the ***Canadian Highway Bridge Design Code.***

Table 3.4.1-1—Load Combinations and Load F

Load Combination Limit State	*DC DD DW EH EV ES EL PS CR SH*	*LL IM CE BR PL LS*	*WA*	*WS*
Strength I (unless noted)	γ_p	1.75	1.00	—
Strength II	γ_p	1.35	1.00	—
Strength III	γ_p	—	1.00	1.00
Strength IV	γ_p	—	1.00	—
Strength V	γ_p	1.35	1.00	1.00
Extreme Event I	1.00	γ_{EQ}	1.00	—
Extreme Event II	1.00	0.50	1.00	—
Service I	1.00	1.00	1.00	1.00
Service II	1.00	1.30	1.00	—
Service III	1.00	γ_{LL}	1.00	—
Service IV	1.00	—	1.00	1.00
Fatigue I— *LL, IM & CE* only	—	1.75	—	—
Fatigue II— *LL, IM & CE* only	—	0.80	—	—

Session 2: Design Assumptions and Materials

FRP Bar Sizes & Strength:

- ***FDOT 932-3*** and ***ASTM D7957*** force (kips) not stress (ksi)
- ***CSA-S807*** similar but uses stress (MPa)

FDOT

932-3

Table 3-1
Sizes and Tensile Loads of FRP Reinforcing Bars

Bar Size Designation	Nominal Bar Diameter (in)	Nominal Cross Sectional Area (in^2)	Measured Cross-Sectional Area (in^2)		Minimum Guaranteed Tensile Load (kips)	
			Minimum	Maximum	BFRP and GFRP Bars	CFRP Bars
2	0.250	0.049	0.046	0.085	6.1	10.3
3	0.375	0.11	0.104	0.161	13.2	20.9
4	0.500	0.20	0.185	0.263	21.6	33.3
5	0.625	0.31	0.288	0.388	29.1	49.1
6	0.750	0.44	0.415	0.539	40.9	70.7
7	0.875	0.60	0.565	0.713	54.1	-
8	1.000	0.79	0.738	0.913	66.8	-
9	1.128	1.00	0.934	1.137	82.0	-
10	1.270	1.27	1.154	1.385	98.2	-

ASTM D7957-17

TABLE 3 Geometric and Mechanical

Bar Designation No.	Nominal Dimensions				
	Diameter mm [in.]	Cross-Sectional Area mm^2 [in.^{2}]	Minimum	Maximum	Ultimate Tensile Force kN [kip]
M6 [2]	6.3 [0.250]	32 [0.049]	30 [0.046]	55 [0.085]	27 [6.1]
M10 [3]	9.5 [0.375]	71 [0.11]	67 [0.104]	104 [0.161]	59 [13.2]
M13 [4]	12.7 [0.500]	129 [0.20]	119 [0.185]	169 [0.263]	96 [21.6]
M16 [5]	15.9 [0.625]	199 [0.31]	186 [0.288]	251 [0.388]	130 [29.1]
M19 [6]	19.1 [0.750]	284 [0.44]	268 [0.415]	347 [0.539]	182 [40.9]
M22 [7]	22.2 [0.875]	387 [0.60]	365 [0.565]	460 [0.713]	241 [54.1]
M25 [8]	25.4 [1.000]	510 [0.79]	476 [0.738]	589 [0.913]	297 [66.8]
M29 [9]	28.7 [1.128]	645 [1.00]	603 [0.934]	733 [1.137]	365 [82.0]
M32 [10]	32.3 [1.270]	819 [1.27]	744 [1.154]	894 [1.385]	437 [98.2]

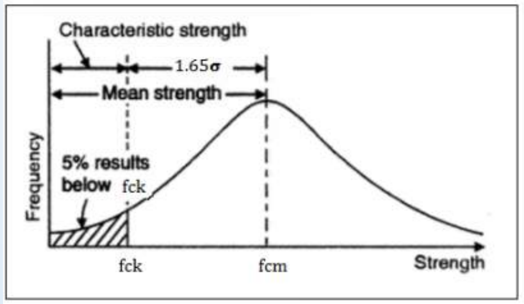
Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior (f_{fu}, E_f)

Tensile Behavior

- The guaranteed (characteristic) tensile strength (f_{fu}) shall be the mean tensile strength minus: 3σ std. deviation (***ASTM D7957*** – *99.9%); or ~1.65σ*** (***CSA-S806 & -S6*** *– 95% confidence);*
- Similarly, the guaranteed (characteristic) rupture tensile strain (ε_{fu}) shall be the mean rupture tensile strain minus three times the standard *deviation (**ASTM D7957**, **CSA-S806 & -S6**);*
- Similarly, the design elastic modulus (E_f) shall be the mean modulus (***ASTM D7957***, ***CSA-S806 & -S6***).

Similar concept to concrete characteristic (f'_c) and mean (f_{ck}) strengths →



$$^{**}\quad F_t = \frac{1 - 1.645 * CoV}{1 + \dfrac{1.645 * CoV}{\sqrt{n}}}$$

Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior (f_{fu}, E_f)

Tensile Strength & Modulus of Elasticity of GFRP Bars

- Tensile strength (f_{fu}) ranges between 77 to 250 ksi (530 to 1,700 MPa); ***FDOT 932-3*** ranges 77 (#2 bars) to 124 (#10 bars) minimum;
- Modulus of elasticity ranges between 5,800 to 9,500 ksi (40 to 65 GPa); ***FDOT 932-3*** $\geq$ 6,500 ksi.

Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior (E_f)

CAN CSA S807-10 – Grades of FRP Bars

© Canadian Standards Association — *Specification for fibre-reinforced polymers*

Table 2
Grades of FRP bars and grids corresponding to their minimum modulus of elasticity, GPa
(See Clause 8.3 and Table 3)

Designation	Grade I		Grade II		Grade III	
	Individual bars	Bars in a grid	Individual bars	Bars in a grid	Individual bars	Bars in a grid
AFRP	50	40	70	60	90	80
CFRP	80	70	110	100	140	130
GFRP	40	30	50	40	60	50

Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior (E_f)

CAN CSA S807-19 *(Public Review Draft)* – Grades of FRP Straight Bars

Table 2A
Grades of FRP straight bars and grids corresponding to their minimum modulus of elasticity, GPa
(See Clauses 8.1.1, 8.3 and 10.1, and Table 3)

	Grade I		Grade II		Grade III	
Designation	**Individual bars**	**Bars in a grid**	**Individual bars**	**Bars in a grid**	**Individual bars**	**Bars in a grid**
AFRP	50	40	70	60	90	80
BFRP	50	40	60	50	70	60
CFRP	80	70	110	100	140	130
GFRP	40	30	50	40	60	50

Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior (E_f)

CAN CSA S807-19 *(Public Review Draft)* – Grades of FRP Bent Bars

Table 2B
Grades of FRP bent bars corresponding to their minimum modulus of elasticity of the straight portion, GPa
(See Clauses 8.1.1, 8.3 and 10.1, and Table 3)

	Grade IB	Grade IIB	Grade IIIB
Designation	Individual bars	Individual bars	Individual bars
AFRP	50	60	65
BFRP	50	55	60
CFRP	80	100	120
GFRP	40	45	50

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Mechanical Properties and Behavior (f_{fu}, E_f)

Lowest

Tensile Properties of V-ROD GFRP bars of **Grade I** (ISIS Canada Manual No. 3)				
Metric size	Nominal diameter (mm)	Nominal Area (mm^2)	Tensile modulus of elasticity (MPa)	Guaranteed tensile strength (MPa)
#3	**10**	**71**	**42500** (6,164 ksi)	**899**
#4	**13**	**129**	**44100**	**825**
#5	**15**	**199**	**42500**	**800**
#6	**20**	**284**	**44500**	**733**
#8	**25**	**510**	**43900**	**654** (95 ksi)

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Mechanical Properties and Behavior (f_{fu} , E_f)

Medium

Tensile properties of V-ROD GFRP bars of **Grade II** (ISIS Canada Manual No. 3)				
Metric size	Nominal diameter (mm)	Nominal Area (mm^2)	Tensile modulus of elasticity (MPa)	Guaranteed tensile strength (MPa)
#3	**10**	**71**	**52500**	**1200**
#4	**13**	**129**	**53400**	**1161**
#5	**15**	**199**	**53600**	**1005**
#6	**20**	**284**	**55400**	**930**
#7	**22**	**387**	**56600**	**882**
#8	**25**	**510**	**53500**	**811**
#10	**32**	**819**	**52900**	**776**

Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior (f_{fu}, E_f)

Highest

Tensile properties of V-ROD GFRP bars of **Grade III** (ISIS Canada Manual No. 3)				
Metric size	Nominal diameter (mm)	Nominal Area (mm^2)	Tensile modulus of elasticity (MPa)	Guaranteed tensile strength (MPa)
#3	**10**	**71**	**65100**	**1734** (251 ksi)
#4	**13**	**129**	**65600**	**1377**
#5	**15**	**199**	**62600**	**1239**
#6	**20**	**284**	**64700**	**1196**
#7	**22**	**387**	**62600**	**1005**
#8	**25**	**510**	**66400** (9,630 ksi)	**1064**
#10	**32**	**819**	**65100**	**1105**

Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior for BFRP A # 3 ***(BDV30 986-01)***

			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957		
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗	
ASTM D 792	Measured Cross-Sectional Area	$in.^2$	0.11	0.15	0.104 – 0.161	✓	0.104 – 0.161	✓	0.104 – 0.161	✓	A_f
ASTM D 2584	Fiber Content	% wt.	75.17	75.17	$\geqslant 70$	✓	$\geqslant 70$	✓	$\geqslant 70$	✓	
ASTM D 570	Moist. Absorption Short Term @50 °C	%	0.2	0.2	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓	
ASTM D 570	Moist. Absorption Long Term @50 °C	%	0.55	0.55	$\leqslant 1.0$	✓	n/a	n/a	$\leqslant 1.0$	✓	
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	29.1	n/a	$\geqslant 22$	✓	$\geqslant 22$	✓	$\geqslant 19$	✓	
ASTM D 4475	Horizontal Shear Stress	ksi	5.75	n/a	n/a	n/a	$\geqslant 5.5$	✓	n/a	n/a	
ASTM D 7205	Min. Guaranteed Tensile Load	kip	13.4	13.4	$\geqslant 13.2$	✓	$\geqslant 13.2$	✓	$\geqslant 13.2$	✓	
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	121.7	105.2	n/a	n/a	n/a	n/a	n/a	n/a	f_{fu}
ASTM D 7205	Tensile Modulus	ksi	7306	6313	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓	E_f
ASTM D 7205	Max. Strain	%	1.66	1.66	n/a	n/a	n/a	n/a	n/a	n/a	ε_{fu}
ACI440. 3R,B.3	Bond-to-Concrete Strength	ksi	3.20	2.64	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓	

Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior for BFRP A # 5 **(BDV30 986-01)**

			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957		
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗	
ASTM D 792	Measured Cross-Sectional Area	in.^{2}	0.307	0.25	0.288 – 0.388	✓	0.288 – 0.388	✓	0.288 – 0.388	✓	A_f
ASTM D 2584	Fiber Content	% wt.	78.4	78.4	⩾ 70	✓	⩾ 70	✓	⩾ 70	✓	
ASTM D 570	Moist. Absorption Short Term @50 °C	%	0.18	0.18	⩽ 0.25	✓	⩽ 0.25	✓	⩽ 0.25	✓	
ASTM D 570	Moist. Absorption Long Term @50 °C	%	0.77	0.77	⩽ 1.0	✓	n/a	n/a	⩽ 1.0	✓	
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	25.7	n/a	⩾ 22	✓	⩾ 22	✓	⩾ 19	✓	
ASTM D 4475	Horizontal Shear Stress	ksi	6.22	n/a	n/a	n/a	⩾ 5.5	✓	n/a	n/a	
ASTM D 7205	Min. Guaranteed Tensile Load	kip	41.2	41.2	⩾ 29.1	✓	⩾ 32.2	✓	⩾ 29.1	✓	
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	137.9	121.0	n/a	n/a	n/a	n/a	n/a	n/a	f_{fu}
ASTM D 7205	Tensile Modulus	ksi	7749	6989	⩾ 6, 500	✓	⩾ 6, 500	✓	⩾ 6, 500	✓	E_f
ASTM D 7205	Max. Strain	%	1.78	1.78	n/a	n/a	n/a	n/a	n/a	n/a	ε_{fu}
ACI440. 3 R,B.3	Bond-to-Concrete Strength	ksi	3.33	2.89	⩾ 1.1	✓	⩾ 1.1	✓	⩾ 1.1	✓	

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Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior (f_{fu}, E_f) for BFRP A,B,& C

(BDV30 986-01)

			Tensile Strength							Elastic		
			Mean μ		Sta. Deviation σ		Guaranteed $\mu - 3\sigma$ f_{fu}			Modulus E_f		
	Rebar size	Lot	ksi	MPa	ksi	MPa	ksi	MPa	%†	ksi	GPa	%†
Rebar A	#3	1	121.7	839	3.82	26.36	110.2	760	92	5482	37.80	84
	#5	1	134.2	925	4.34	29.92	121.3	836	129	7735	53.46	119
Rebar B	#3	1	196.3	1353	4.21	29.03	183.6	1266	153	7808	53.83	120
	#5	1	172.5	1189	9.19	63.33	145.0	999	155	7946	54.79	122
Rebar C	#3	1	183.9	1268	4.80	33.12	169.5	1168	141	7154	49.32	110
	#5	1	161.2	1112	12.85	88.63	122.7	1074	131	5267	36.31	81
	#3	2	169.2	1166	5.03	34.69	154.1	1062	128	7200	49.64	111
	#5	2	147.8	1019	4.04	27.86	135.6	935	145	7480	51.57	115

† Percentage comparison based on FDOT specifications section 932, where 100 % is GFRP rebar acceptance criteria .

Figure 5.31: #3 rebar final failure pattern after tensile test

Session 2: Design Assumptions and Materials

Mechanical Properties and Behavior (cont.) for BFRP A,B,& C

(BDV30 986-01)

(a) Type A #3

(c) Type B #3

			Transverse Shear Strength			Horizontal Shear Strength			Bond-to-Concrete Strength		
	Rebar size	Lot	ksi	MPa	%†	ksi	MPa	%†	ksi	MPa	%†
Rebar A	#3	1	35.20	242.7	160	7.00	48.31	n/a	2.33	16.09	212
	#5	1	33.74	232.7	153	6.41	44.16	n/a	2.96	20.41	269
	#3	2	37.67	259.7	171	6.49	44.71	n/a	1.92	13.22	174
	#5	2	36.48	251.6	166	6.41	44.15	n/a	1.65	11.41	150
Rebar B	#3	1	31.39	216.3	143	6.42	44.22	n/a	2.79	19.23	254
	#5	1	26.51	182.8	120	6.53	45.00	n/a	2.88	19.85	262
Rebar C	#3	1	34.48	237.2	157	5.56	38.38	n/a	3.77	26.00	343
	#5	1	31.69	218.5	144	6.64	45.77	n/a	3.77	26.01	343

† Percentage comparison based on FDOT specifications section 932, where 100 % is GFRP rebar acceptance criteria .

(d) Type B #5

(f) Type C #5

rebar after horizontal shear test

Session 2: Design Assumptions and Materials

Tensile Strength of the FRP at Bend (f_{fb})

FRP bars can be fabricated with bends, however the tensile strength is reduced:

AASHTO-GGS2, CSA S6 and CSA S806 Codes

$$f_{fb} = \left(0.05\left(\frac{r_b}{d_b}\right) + 0.3 \right) f_{fu} \leq f_{fu}$$

r_b = bend radius

d_b = diameter of reinforcing bar

f_{fu} = design tensile strength of FRP

FDOT 932-3 Table 3-3

f_{fb} > 60% f_{fu} *(straight bars)*

FDOT

Session 2: Design Assumptions and Materials

Compression Behavior of the FRP:

- FRP compression reinforcement is considered in ***AASHTO-GGS2***, ***CSA-S806*** and ***CSA-S6*** ***(pending 2019 edition)***

- For the purpose of design, assume zero compression strength and stiffness. (see *GGS2 - 2.6.4*)

Note however, that recent testing by researchers shows that there is definitely an axial strength contribution from GFRP bars (approx. 10%)

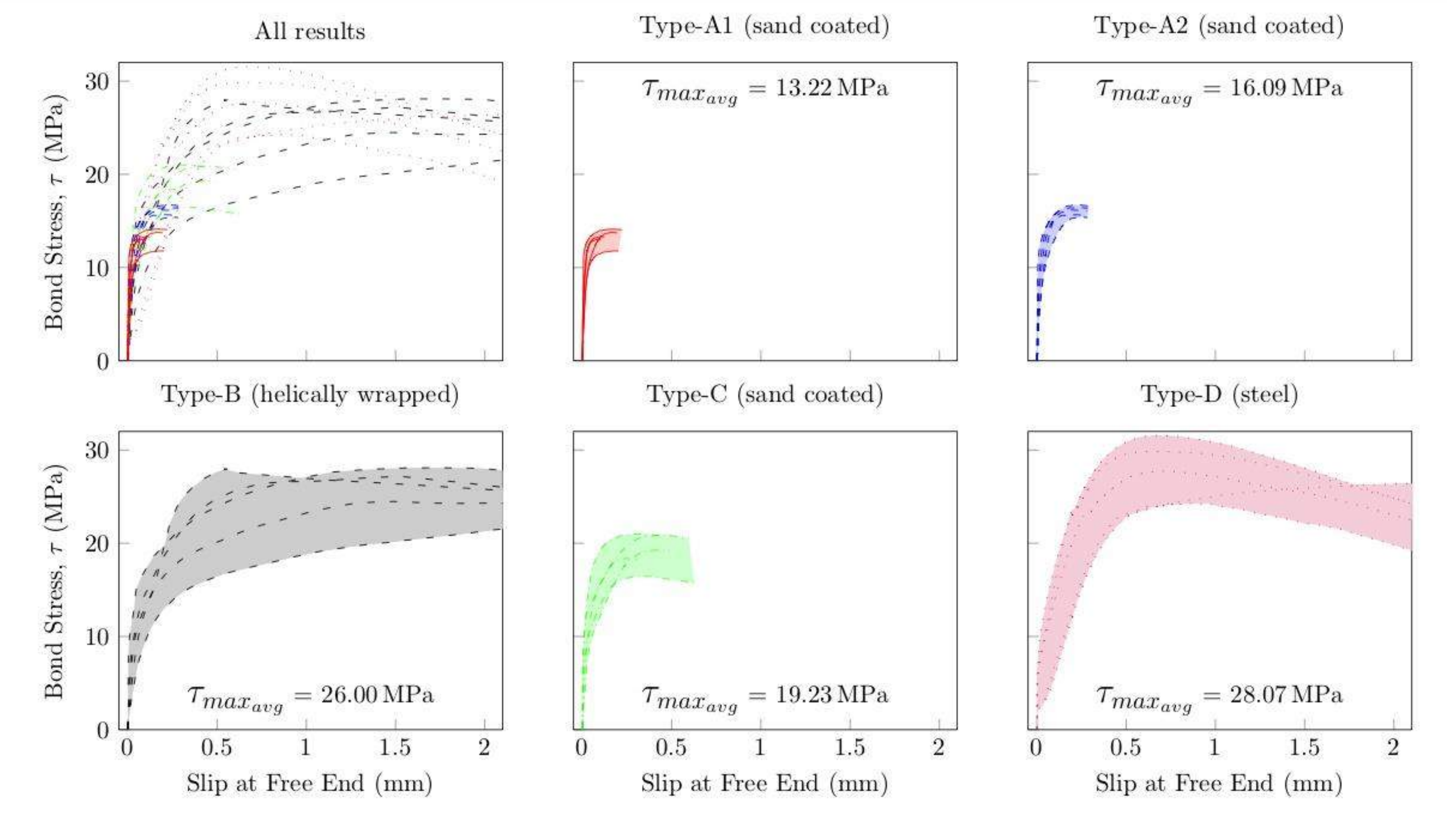
Session 2: Design Assumptions and Materials

Bond Behavior

- Bond strength is a function of:
  1) The bar design and surface roughness
  2) Mechanical properties of the bar itself
- Bond Force can be transmitted by:
  1) Adhesion resistance at bar interface (chemical bond)
  2) Frictional resistance of interface (friction bond)
  3) Mechanical interlock due to surface irregularity
- Adequate cover is essential
- f_c' of the concrete affects bond.
- In general the bond of FRP bars to concrete is similar to the bond of steel bars (***FDOT 932-3*** $\geq$ 1.1 ksi & for hooks f_{fb} > 60% f_{fu} straight bars)

Add charts here from Kampmann and Ruiz

Session 2: Design Assumptions and Materials



From Phase 1: ***BDV30 986-01*** @ *https://www.fdot.gov/structures/innovation/FRP.shtm#link10*

Session 2: Design Assumptions and Materials

Time Dependent Behavior – Creep Rupture

- FRP reinforcing bars subjected to a sustained load over time can fail after a time period called the **endurance time**.
- This phenomenon is known as **creep-rupture** (or **static fatigue**)
- The higher the stress, the shorter the lifetime
- GFRP –> BFRP –> AFRP –> CFRP (least susceptible)

Add charts here from Hartman (OC)


QUEEN'S UNIVERSITY BELFAST

International Institute for FRP in Construction

FRPRCS-14, Belfast - June 2019

Improved Endurance Limits for GFRP Reinforcement of Concrete

Nolan, S.[1], Knight, C.[2], Nagarajan, M.[3], Hartman, D.[3]

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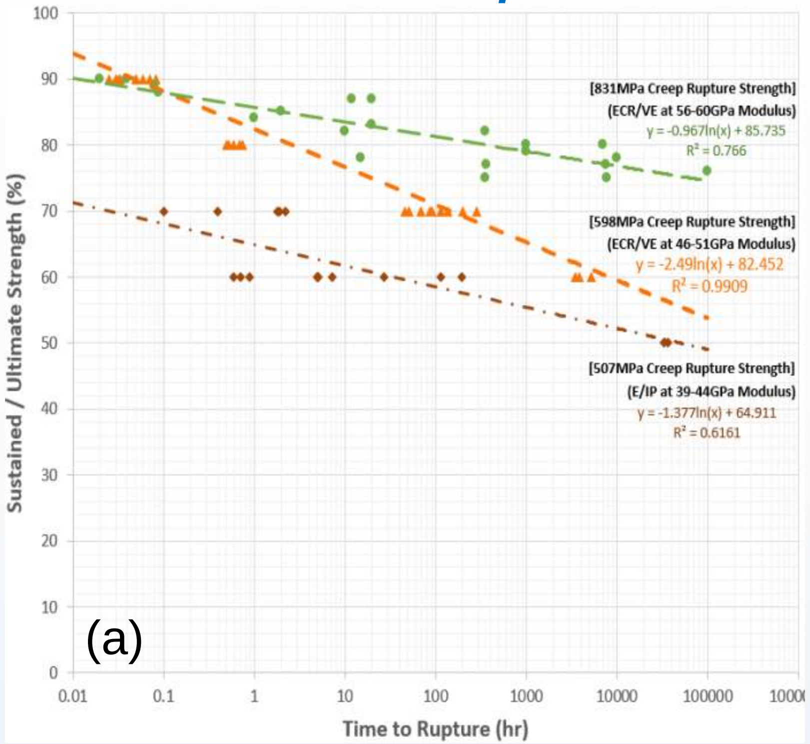
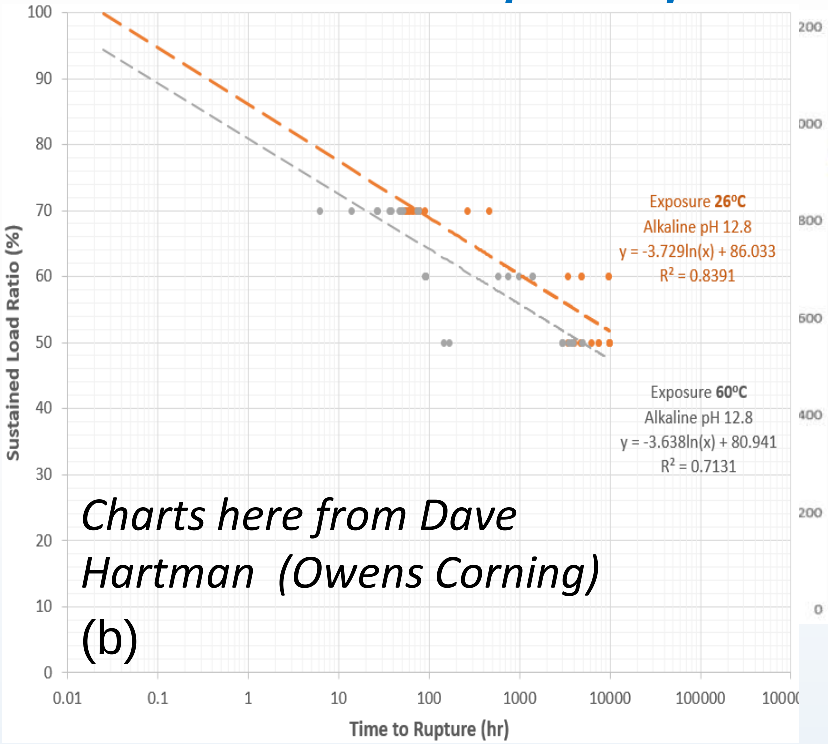
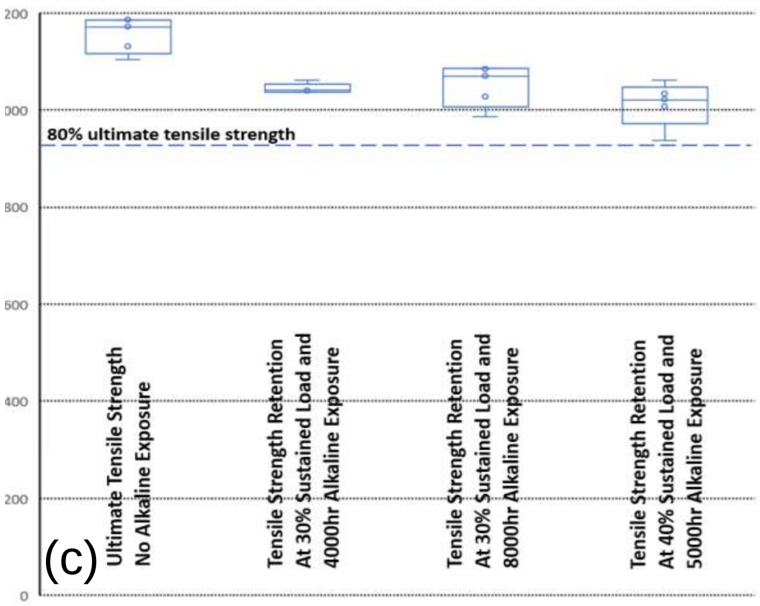
Session 2: Design Assumptions and Materials

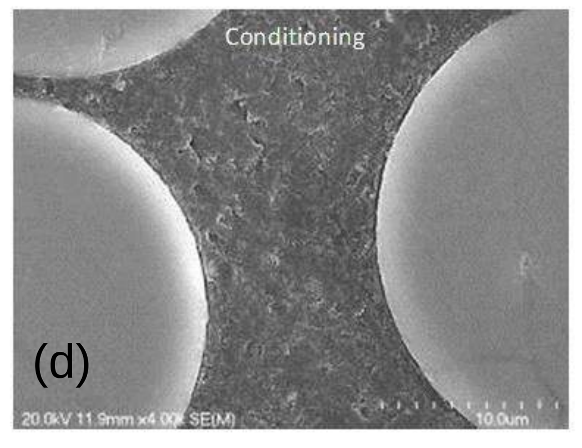
Time Dependent Behavior – Creep Rupture for E-CR GFRP rebar





Charts here from Dave Hartman (Owens Corning)





Figures: Calculated 100-year creep rupture strength to *ACI 440.3R B.8*

a) by glass/resin type and glass content (tensile elastic modulus)
b) with alkaline pH12.8 solution at 26°C and 60°C
c) tensile strength retention after exposure;
d) d) ECR/VE SEM after 5000hr pH12.8 60°C

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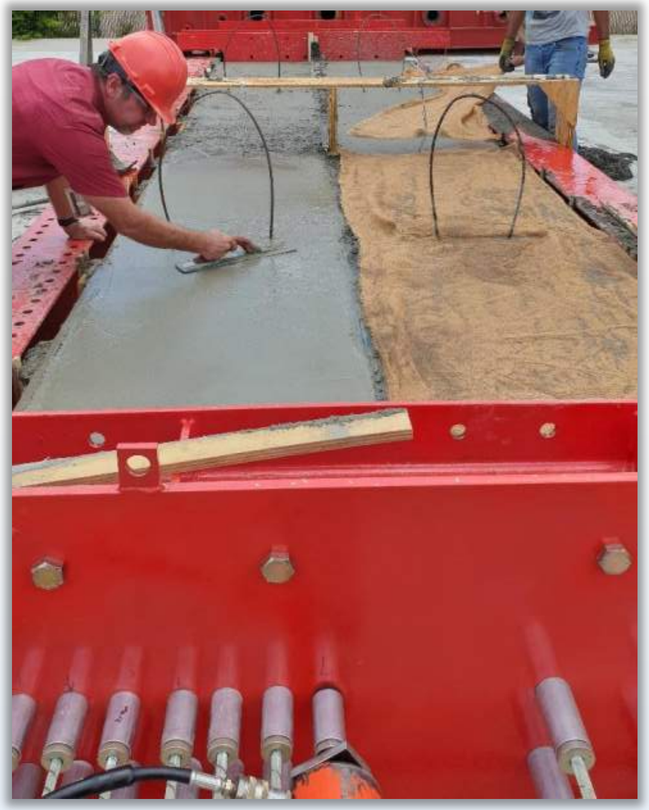
(a)

(b)

(c)



(d)

Photos: *NCHRP IDEA Project #207* – MILDGLASS

(a) GFRP Transverse stirrups surround longitudinal prestressed GFRP Bars; (b) jacking of bars to 40%-50% f_{fu}; (c) Pretensioned GFRP-PC sheet pile specimen ready for casting ; (d) casting completed 7/19/2019.

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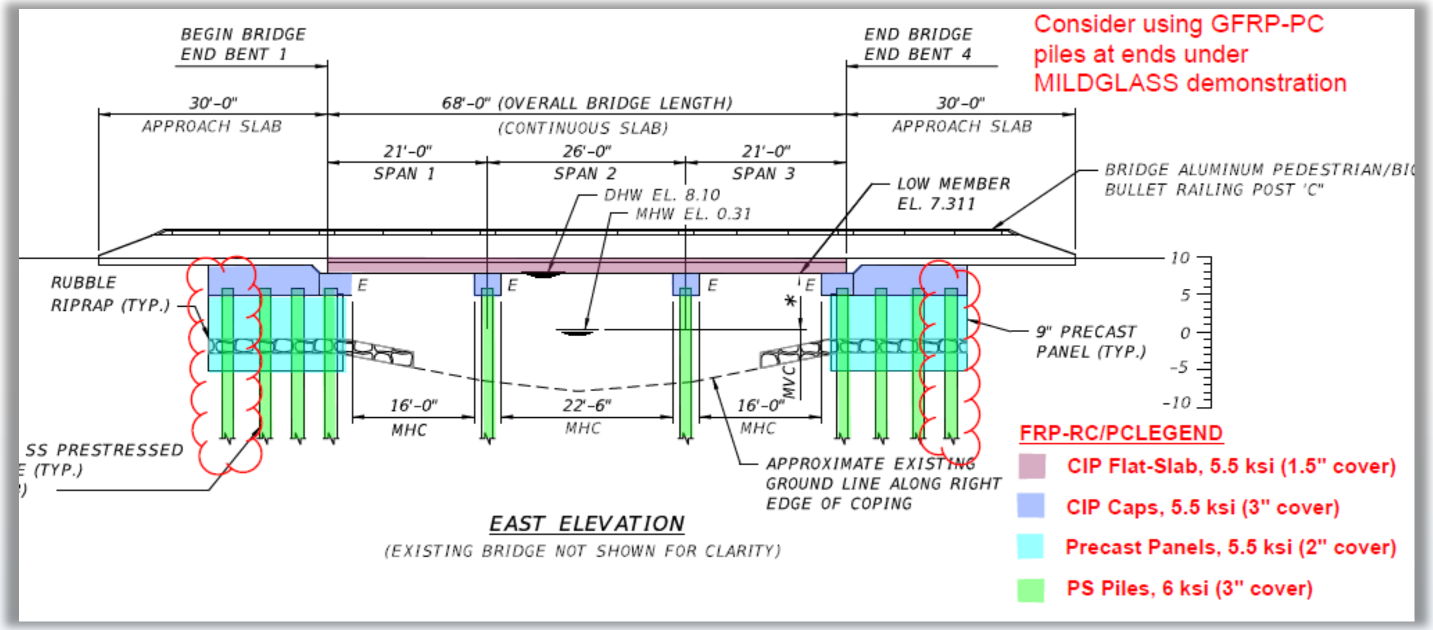
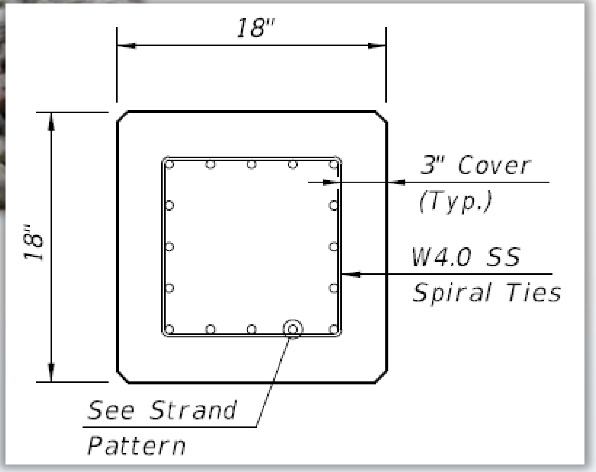
Time Dependent Behavior – Creep Rupture for E-CR GFRP rebar



(a)

(b)



(c)

Photos: *NCHRP IDEA Project #207* – MILDGLASS

(a) Future demonstration project in planning phase;
(b) Sample thermo-plastic (recyclable & post production-formability);
(c) Pretensioned GFRP-PC soldier pile typical section.

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Time Dependent Behavior – Creep & Fatigue Rupture (C_c ,C_f)

The maximum stress in FRP bars (or grids) under loads at serviceability limit state shall not exceed the following fraction of the guaranteed tensile strength ***AASHTO-GS2*** ***(CSA-S806*** & ***CSA-S6)***:

	Creep-Rupture		Cyclic-Fatigue	
• AFRP :	n/a	*(0.35)*	: n/a	*(0.35)*
• CFRP :	C_E*0.65	*(0.65)*	: C_E*0.65	*(0.65)*
• GFRP :	C_E*0.30	*(0.25)*	: C_E*0.25	*(0.25)*
• BFRP :	C_E*0.30 #		: C_E*0.25 #	

(# testing shows these could be higher than GFRP)

*(Also for **CSA** - The maximum strain in GFRP tension reinforcement under sustained service loads shall not exceed 0.002)...for now.*

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Environmental Durability Design (C_E)

- One of the major benefits of FRP bars

- FRP bars do not rust, but are susceptible in degrees to high pH (BFRP & GFRP) or moisture (AFRP)

- Depends on type of fiber, resin used, quality of manufacturing, degree of cure, etc.

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Durability Design

Example of Durability Related Provisions*:*

1. Limit on Constituent Material, e.g.
    - Limits on diluents and certain fillers ***(CSA-S807)***
    - Limits on low-profile additives ***(CSA-S807)***
    - No blended resins
2. Lower Limit on Glass Transition Temperature ($\boldsymbol{T_g}$) & Cure Ratio
    - Minimum cure ratio and $\boldsymbol{T_g}$
3. Material Screening Through Physical & Durability Properties
    - Maximum void content
    - Maximum water absorption
    - Limits on mechanical property loss in different environment conditioning (Alkali)

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Durability and Endurance Design

The *AASHTO-GGS2*, *CSA-S806* and *-S6* address the durablity issue in design of FRP reinforced sections through a common way considering the following:

- The material resistance & environmental reduction factors based on fiber type and exposure conditions
- Concrete cover (fire resistance, splitting, & bend development)
- Limitation of maximum stress under service load
- Limitation of maximum crack-width under service load
- Limitation of maximum stress/strain level under sustained load
- Creep rupture stress limits
- Fatigue stress limits
- Factor for long-term deflection calculation

Environmental

Endurance

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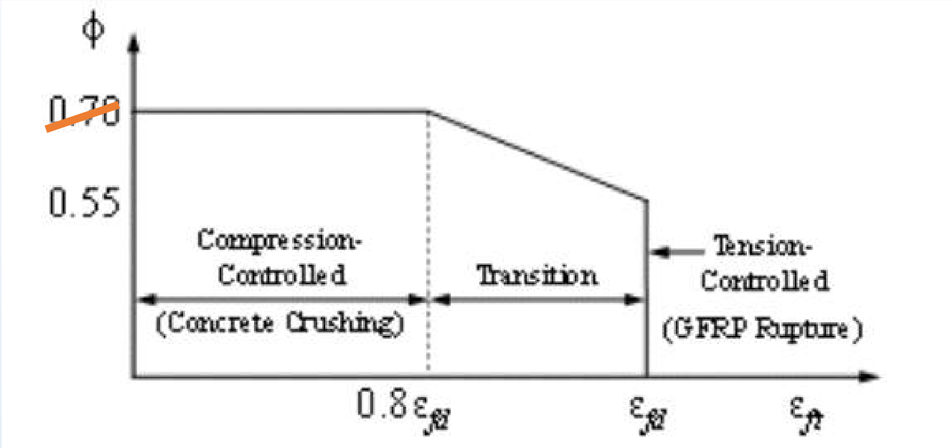
*Resistance factors (**AASHTO-GGS2**, **CSA S806**)*

- For non-prestressed FRP reinforcement, the resistance factor, Φ_F, shall be taken as $\Phi_F = 0.75$ (compression-controlled only in ***AASHTO-GGS2***; For tension-controlled $\Phi_F = 0.55$)
- Concrete and steel resistance factors remain the same.

$\Phi_c = 0.75$



*** Correction need for **GGS-2** commentary*

2.5.5.2—Resistance Factors

The resistance factor, ϕ, shall be taken as:

- For compression-controlled and tension-controlled reinforced concrete sections as specified in Article 2.6.3:

$$\phi = \begin{cases} 0.55 & \text{for} \quad \varepsilon_{ft} = \varepsilon_{fd} \\ 1.55 - \dfrac{\varepsilon_{ft}}{\varepsilon_{fd}} & \text{for} \quad 0.80\varepsilon_{fd} < \varepsilon_{ft} < \varepsilon_{fd} \\ 0.75 & \text{for} \quad \varepsilon_{ft} \le 0.80\varepsilon_{fd} \end{cases} \qquad (2.5.5.2\text{-}1)$$

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Material Resistance Factors

Application ***(CSA-S6)***	*Resistance Factor ø*
AFRP reinforcement in concrete and NSMR	0.65
AFRP in externally-bonded applications	0.55
AFRP and aramid fibre rope tendons for concrete and timber	0.60
CFRP reinforcement in concrete	0.80
CFRP in externally-bonded applications and NSMR	0.80
CFRP tendons	0.80
GFRP reinforcement in concrete *(2019)*	0.55 *(0.65)*
GFRP in externally-bonded applications and NSMR	0.70
GFRP tendons for concrete components	0.55
GFRP tendons for timber decks	0.70

Application ***(AASHTO)***	*Resistance Factor C_E*
CFRP tendons embedded (PC) ***(AASHTO-CFRP-GS)***	1.00
CFRP tendons external (PT) ***(AASHTO-CFRP-GS)***	0.90
GFRP reinforcement in concrete (interior) ***(AASHTO-GGS2)***	0.80
GFRP [& BFRP] reinforcement in concrete (exterior) ***(AASHTO-GGS2)*** **[FDOT]**	0.70

FDOT

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Material Resistance Factors

Resistance factors from ***AASHTO-GGS2***		
Material	**Notation**	**Factor**
Concrete-cast-in-situ	φ_c	0.75
Concrete-precast	φ_c	0.75
Steel reinforcement	φ_s	0.90
CFRP (PC)	φ_f	(0.75)
AFRP	φ_f	n/a
GFRP [& BFRP]	φ_f	0.55 *

Resistance factors from ***CSA***		
Material	**Notation**	**Factor**
Concrete-cast-in-situ	φ_c	0.65
Concrete-precast	φ_c	0.70
Steel reinforcement	φ_s	0.85
CFRP	φ_f	0.75
AFRP	φ_f	0.75
GFRP [& BFRP?]	φ_f	0.75

FDOT

** Future work need to reconcile this low tension-controlled design limit with other low-ductility failure modes*

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Serviceability of FRP Reinforced Concrete Members (Beams & Slabs)

- Deflections under service loads often control design
- Designing FRP-RC beams or slabs for concrete crushing satisfies serviceability criteria for deflections and crack width
- Cracking and deflections are defined as:
  - **Cracking** — Excessive crack width is undesirable for aesthetic and other reasons (for example, to prevent water leakage) that can damage or deteriorate the structural concrete
  - **Deflection** — Deflections should be within acceptable limits imposed by the use of the structure (for example, supporting attached nonstructural elements without damage).
- The substitution of FRP for steel on an equal area basis would typically result in larger deflections and wider crack widths

Session 2: Design Assumptions and Material Properties

Crack Control Reinforcement ***(CSA-S6 , AASHTO-GGS2 similar)***

When the maximum tensile strain in FRP reinforcement under service loads exceeds *0.0015*, cross-sections of the component in maximum positive and negative moment regions shall be so proportioned that the crack-width must not exceed *0.02-in.* (0.5 mm) for member subject to aggressive environments otherwise *0.028-in.* (0.7 mm), where the crack width is given by:

$$w_{cr} = 2\frac{f_{FRP}}{E_{FRP}}\frac{h_2}{h_1}k_b\sqrt{d_c^{\,2}+\left(\frac{s}{2}\right)^2}$$

- The value of k_b shall be determined experimentally, but in the absence of test data it may be taken as;
  - ***CSA*** → 0.8 for sand-coated and 1.0 for deformed FRP bars.
  - ***AASHTO-GGS2*** → $k_b = 1/C_b = 1.2$ for deformed FRP bars.
- For ***CSA*** In calculating d_c, the clear cover shall not be taken greater than 2-in. (50 mm).

Session 2: Crack Control Reinforcement ***(CSA S6)***

- Check crack widths when tensile strain in FRP at SLS exceeds 0.0015 (stress of 60 MPa [8.7 msi] in Grade 1) which is almost always the case.
- Maximum permitted crack widths:

  w_{cr} ≤ 0.50 mm (0.020-in.) for members subject to aggressive environments

  w_{cr} ≤ 0.70 mm (0.028-in.) for members with other exposures
- Maximum permitted crack widths are double what is permitted for reinforcing steel in aggressive environments since GFRP does not corrode.
- Crack width derived from an analytical model:

$$w_{cr} = 2\frac{f_{FRP}}{E_{FRP}}\frac{h_2}{h_1}k_b\sqrt{d_c^{\,2}+\left(\frac{s}{2}\right)^2}$$

Session 2: Crack Control Reinforcement *(CSA S6)*

Maximum crack width to be checked against the limit

Factor to calculate the maximum crack width (1.5 for mean width, 1 for minimum width)

$$w_{cr} = 2\frac{f_{FRP}}{E_{FRP}}\frac{h_2}{h_1}k_b\sqrt{d_c^{\,2}+\left(\frac{s}{2}\right)^2}$$

$f_{FRP}/E_{FRP} = \varepsilon_{FRP}$
is the average strain in FRP reinforcement

Term k_b to account for the bond of the bar to concrete:

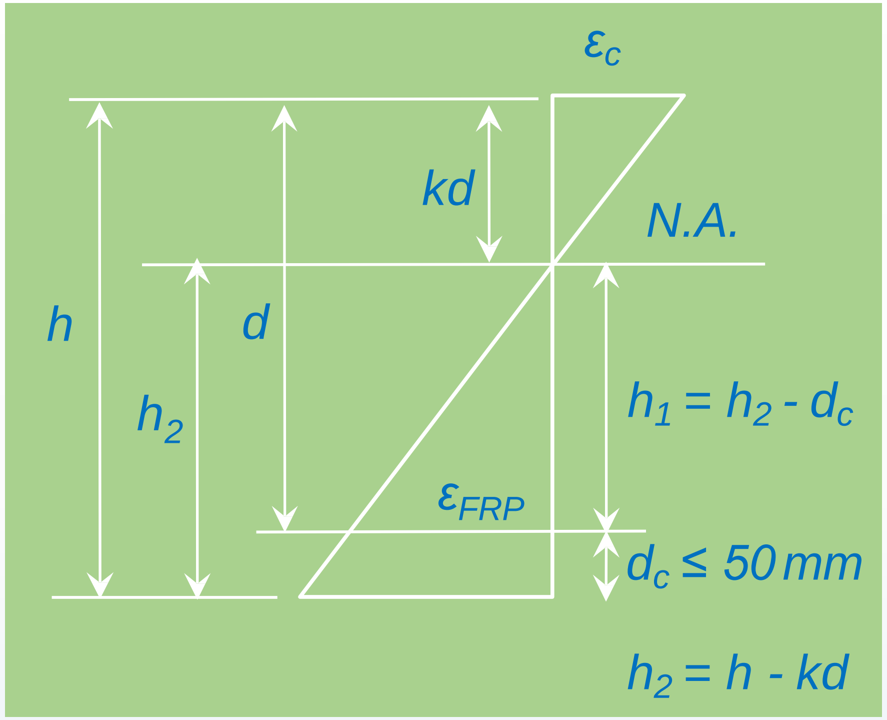
- use k_b = 0.8 for both sand-coated and 1.0 for deformed bars
- *AASHTO-GGS2* 1.2 for all bars

Session 2: Crack Control Reinforcement

Geometrical relationship which accounts for the amplification of the average strain from the FRP bar to the exposed surface of the concrete

$$w_{cr} = 2\frac{f_{FRP}}{E_{FRP}}\frac{h_2}{h_1}k_b\sqrt{d_c^2 + \left(\frac{s}{2}\right)^2}$$

Effect of the bar spacing and bar cover on the basic crack width



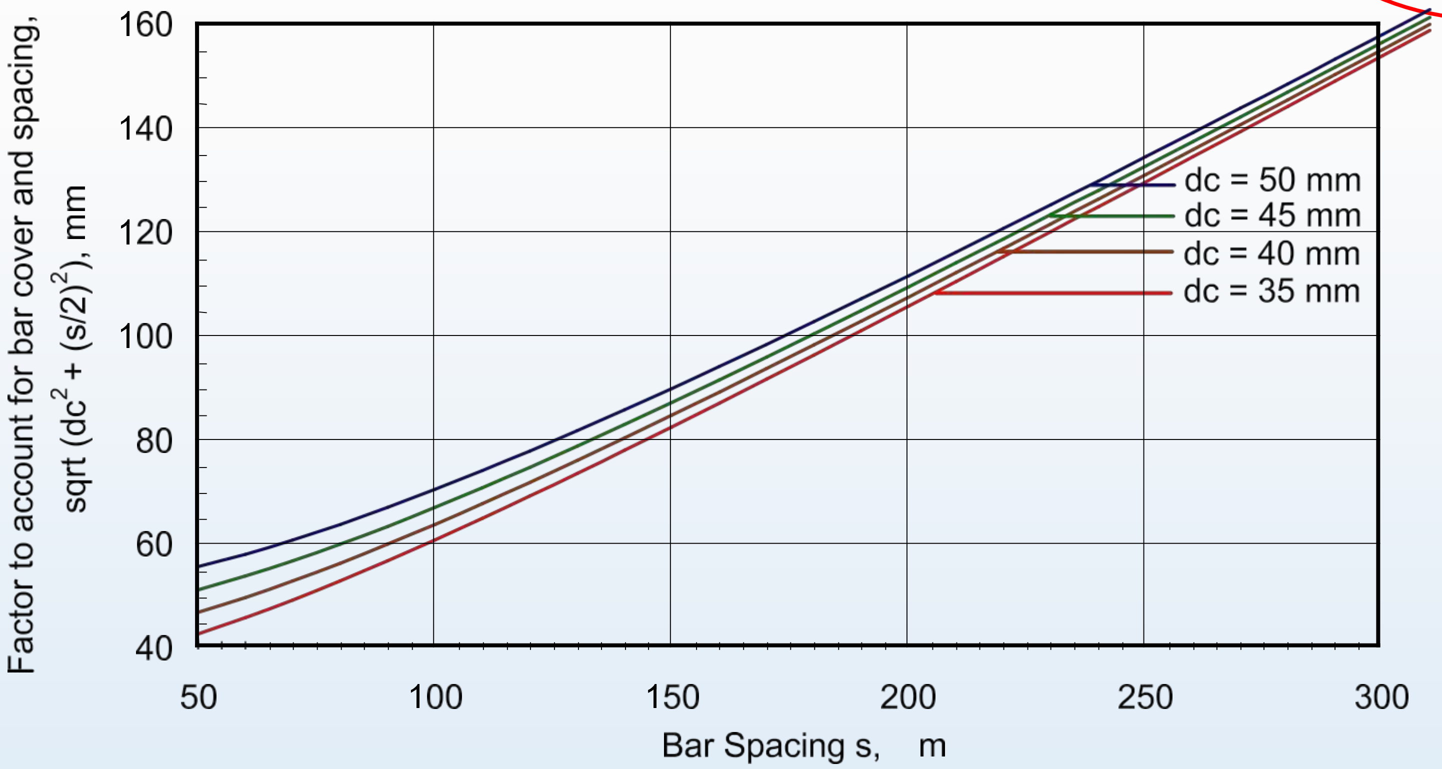
s = bar spacing

d_c = distance from the *centroid* of tension GFRP to the extreme tension surface of the concrete ≤ 2-in. (50 mm)

Session 2: Crack Control Reinforcement

Effect of Bar Spacing and Cover on Crack-Width, w_{cr}

$$w_{cr} = 2\frac{f_{FRP}}{E_{FRP}}\frac{h_2}{h_1}k_b\sqrt{d_c^2 + \left(\frac{s}{2}\right)^2}$$



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*Crack control: (**CSA-S806**)*

The crack control parameter, z:

$$z = k_b \frac{E_s}{E_f} f_f \sqrt[3]{d_c A}$$

$\mathbf{z}$ < 45,000 N/mm [170 kips/in] for interior exposure and 38,000 N/mm [130 kips/in] for exterior exposure.

$f_f < 0.25 f_{fu}$ for GFRP bars. (No f_f limit for ***AASHTO-GGS2***, see sustained load check)

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Deflection Limits of FRP Reinforced Concrete Members (CSA-S806)

Table 11
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	$\ell_n/180$*
Floors not supporting or attached to nonstructural elements likely to be damaged by large deflections	Immediate deflection due to specified live load, L	$\ell_n/360$
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)‡	$\ell_n/480$†
Roof or floor construction supporting or attached to nonstructural elements not likely to be damaged by large deflections		$\ell_n/240$§

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.

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Deflection Calculation ***(CSA-S806 - Refined)***

- Deflection shall be calculated based on moment-curvature (M/EI) relationship
- Integrate M/EI relationship or use moment-area method

$$\delta_A = \int_0^L \frac{mM}{EI} dx$$

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*Deflection Calculation (**AASHTO-GGS2**, **CSA-S806**)*

- Effective moment of inertia (used for Direct Method):
  - When a section is uncracked, its moment of inertia is equal to the gross moment of inertia, I_g

    $$I_g = bh^3 / 12$$

  - When the applied moment, $\boldsymbol{M_a}$, exceeds the cracking moment, $\boldsymbol{M_{cr}}$ cracking occurs, which causes a reduction in the stiffness and the moment of inertia is based on the cracked section, I_{cr}

    $$I_{cr} = \frac{bd^3}{3} k^3 + n_f A_f d^2 (1-k)^2$$

    Where: $$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$$

  - Using n_f as the modular ratio between the FRP reinforcement and the concrete:

    $$n_f = E_{FRP} / E_C$$

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Long-Term Deflection

Long-term deflection under sustained load

The total immediate plus long-term deflection for flexural members shall be obtained by multiplying the immediate deflections from the sustained loads, by a creep factor.

For ***AASHTO-GGS2:*** long-term only → 3.0 for I_{eff} or 4.0 for I_g

For ***CSA:*** → $[1+S]$; S = 2.0 for 5 years or more:

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

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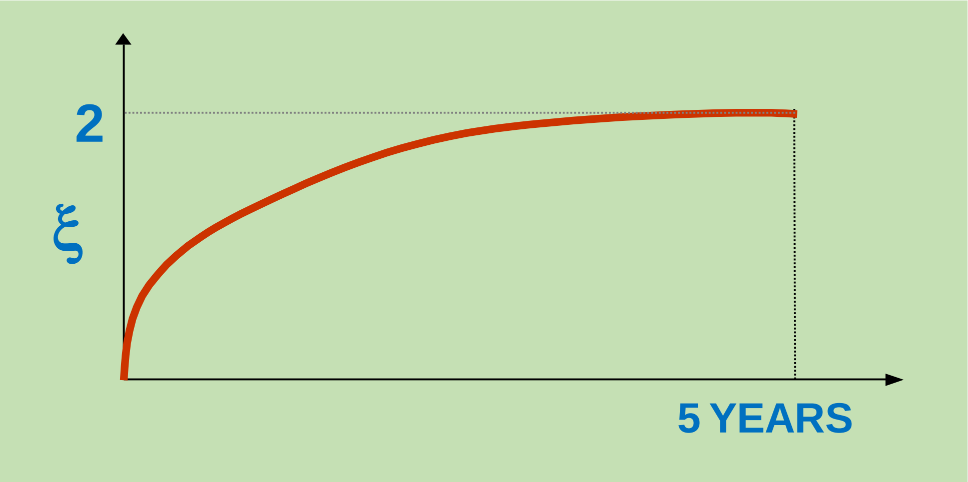
*Long-Term Deflection (**CSA**)*



For same design strength long term deflection is 3 – 4 times greater than members reinforced by steel reinforcement

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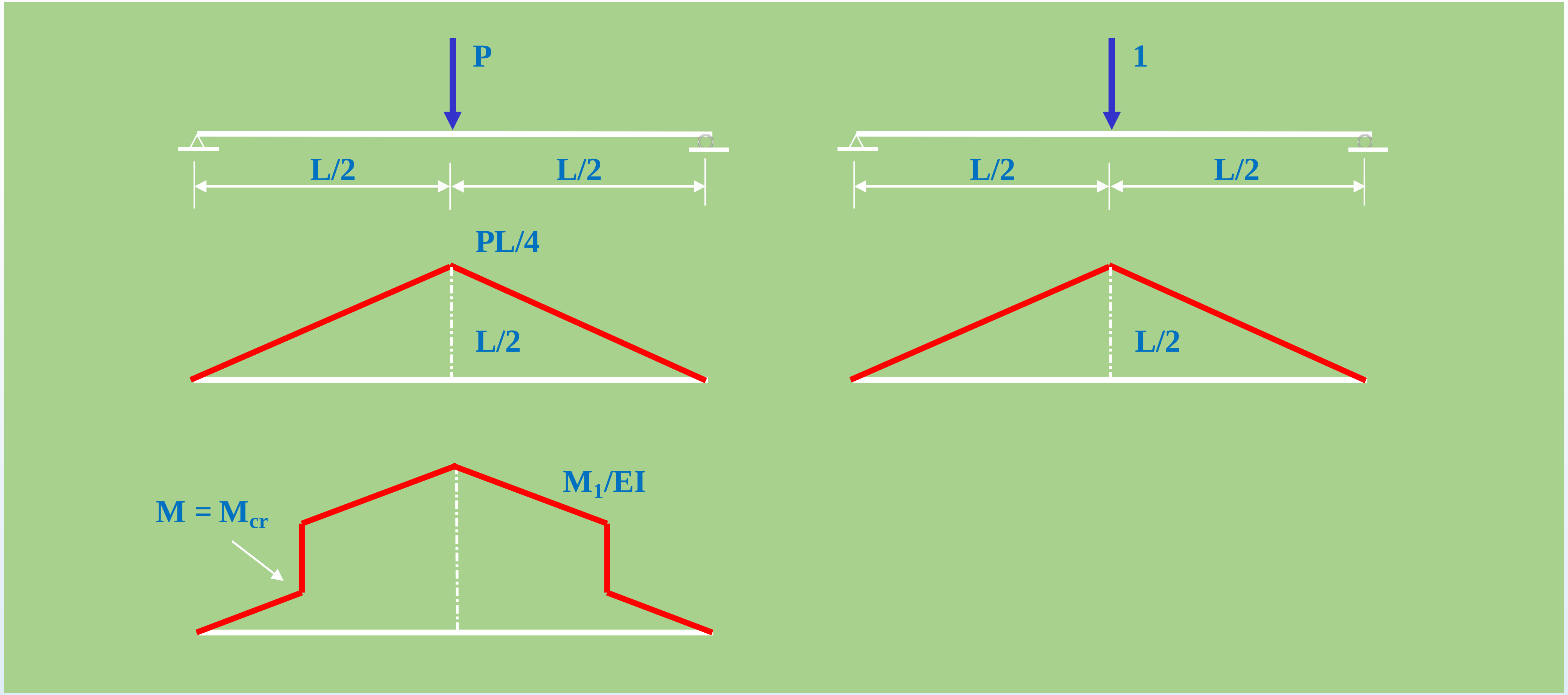
Deflection Calculation



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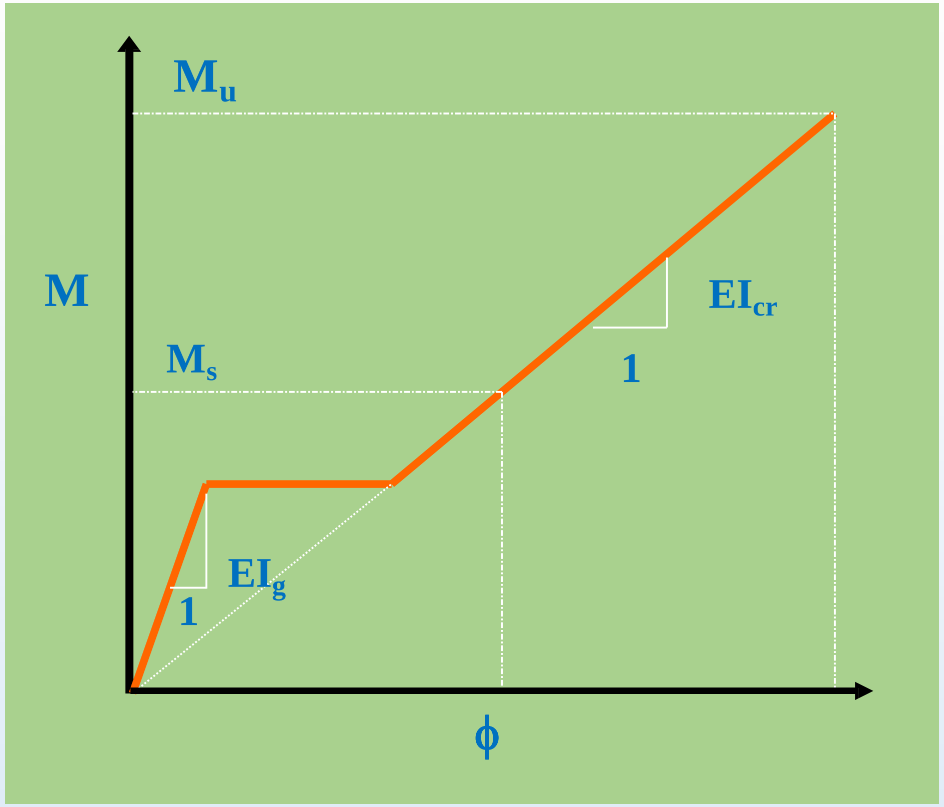
Deflection Calculation

- Moment-Curvature Relationship for FRP Reinforced Section



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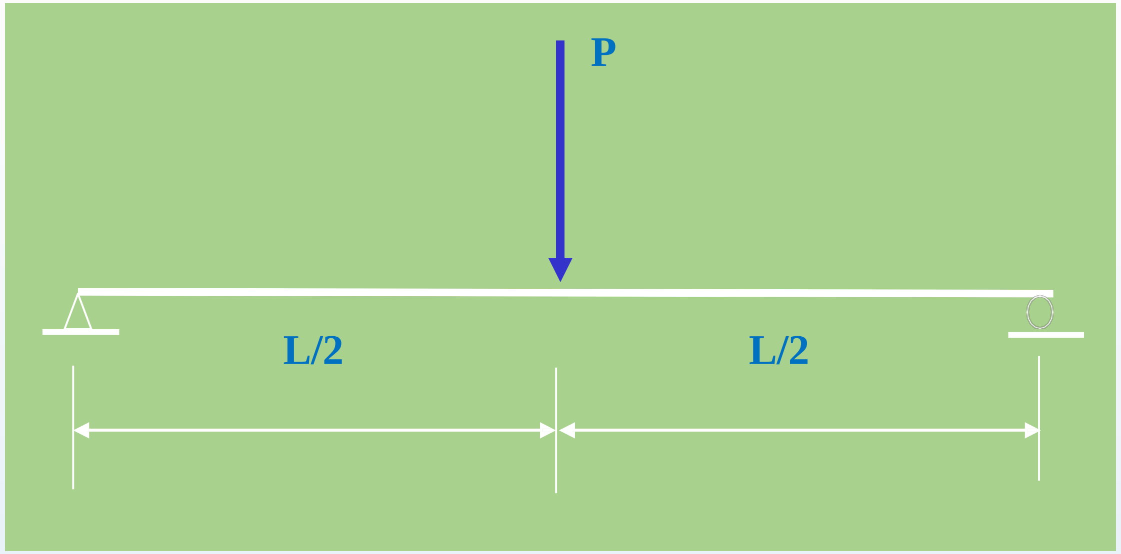
Deflection Calculation

- Example



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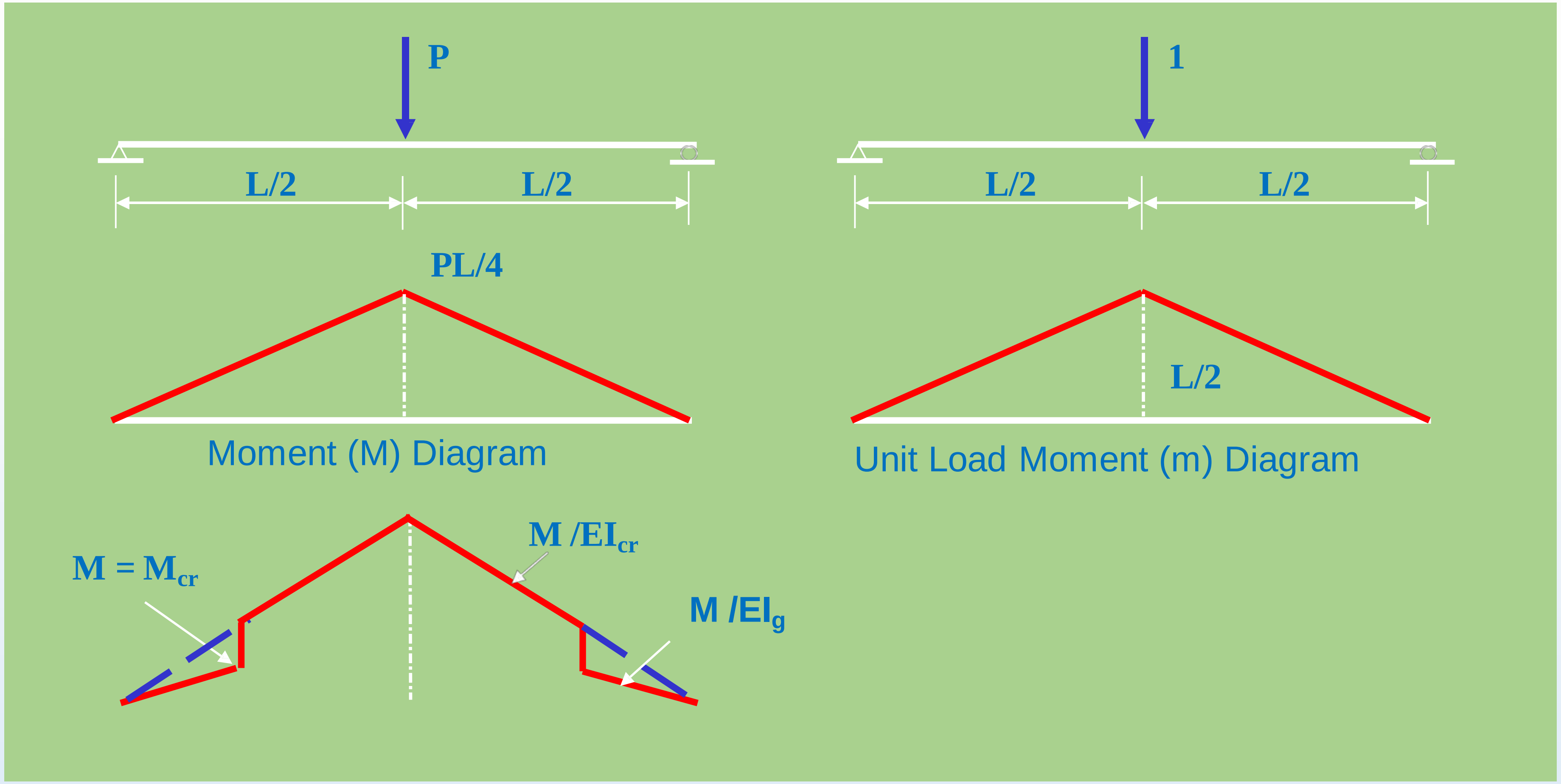
Deflection Calculation



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Deflection Calculation

Maximum Deflection

$$\delta_{\max} = \delta_{cr} - \delta_c$$

Deflection of the fully cracked beam

Correction from the uncracked sections

From Regular Strength of Materials

$$\delta_{cr} = \frac{PL^3}{48E_c I_{cr}}$$

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Deflection Calculation

Correction Term

$$\delta_c = 2\int_0^{Lg} m_1 \eta \frac{M}{EI_{cr}} dx \quad \cong \quad \delta_c = \frac{PL^3}{48E_c I_{cr}} 8\eta \left(\frac{L_g}{L}\right)^3$$

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Deflection Calculation

Maximum Deflection

$$\delta_{\max} = \frac{PL^3}{48E_c I_{cr}}\left[1-8\eta\left(\frac{L_g}{L}\right)^3\right]$$

Where:

$$\eta = (1 - \frac{I_{cr}}{I_g})$$

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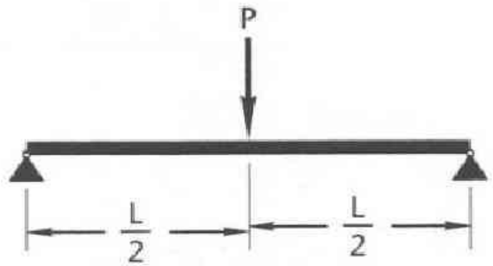
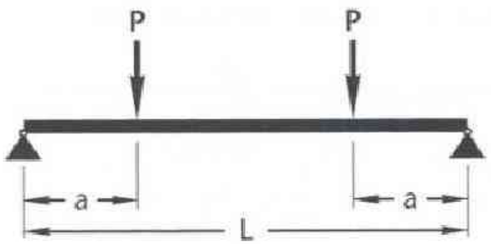
Deflection Calculation

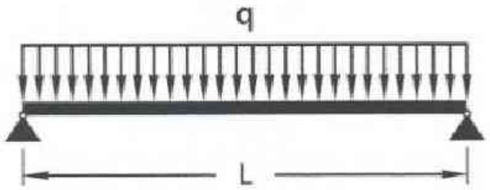
Maximum Deflection of Other Load Cases



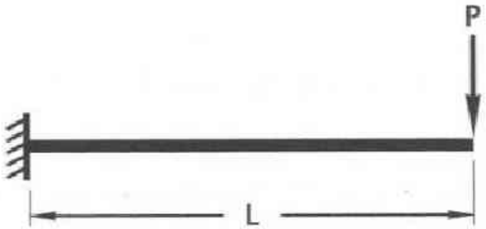
$$\delta_{max} = \frac{PL^3}{48\,E_c I_{cr}}\left[1 - 8\eta\left(\frac{L_g}{L}\right)^3\right]$$



$$\delta_{max} = \frac{PL^3}{24\,E_c I_{cr}}\left[3\left(\frac{a}{L}\right) - 4\left(\frac{a}{L}\right)^3 - 8\eta\left(\frac{L_g}{L}\right)^3\right]$$



$$\delta_{max} = \frac{5qL^4}{384\,E_c I_{cr}}\left[1 - \frac{192}{5}\eta\left[\frac{1}{3}\left(\frac{L_g}{L}\right)^3 - \frac{1}{4}\left(\frac{L_g}{L}\right)^4\right]\right]$$



$$\delta_{max} = \frac{PL^3}{3\,E_c I_{cr}}\left[1 - \eta\left(\frac{L_g}{L}\right)^3\right]$$

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

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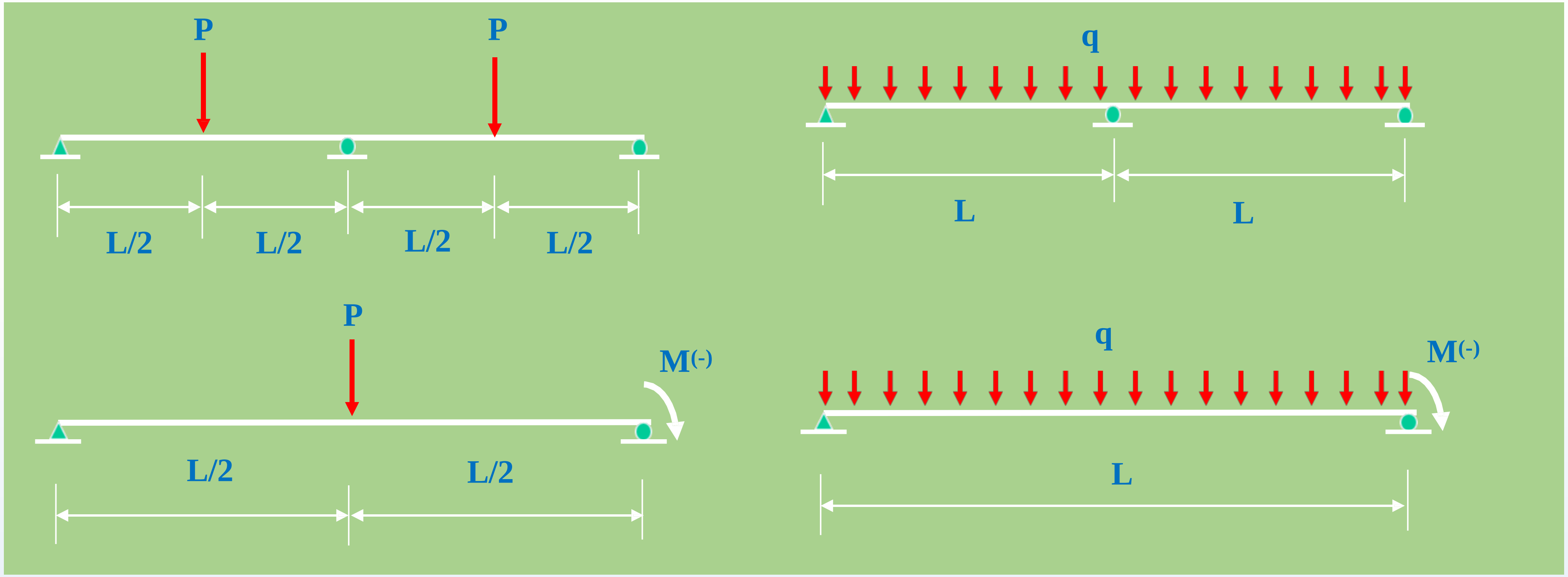
Deflection of Continuous Beams



$$\delta_{max} = \frac{PL^3}{48E_c I_{cr}}\left[\frac{5}{16} - \frac{15}{8}\eta\left(\frac{L_g}{L}\right)^3\right]$$

$$\delta_{max} = \frac{5qL^4}{384E_c I_{cr}}\left[\frac{3}{5} - \frac{36}{10}\eta\left(\frac{L_g}{L}\right)^3\right]$$

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*Development Length and Splice of Reinforcement (**CSA-S806**)*

Development length of FRP bars in tension l_d shall be taken:

$$l_d = 1.15 \frac{k_1 k_2 k_3 k_4 k_5}{d_{cs}} \frac{f_F}{\sqrt{f'_c}} A_b \geq 300mm$$

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
d_{cs} = smaller of :

1. **distance from closest concrete surface to the center of the bar**
2. **two-thirds of the center-to-center spacing d_{cs}**

shall not be greater than 2.5 d_b

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*Development Length and Splice of Reinforcement (**CSA S806**)*

Development length of FRP bars in tension

The maximum permissible value of $(f'_c)^{0.5}$ shall be 5 MPa

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Development Length and Splice of Reinforcement ***(CSA S806, AASHTO-GS2)***

Modification factors:

k_1 (Bar location factor) :1.3; 1.0 *(1.5; 1.0)*

k_2 (Concrete density factor) :1.3; 1.2; 1.0

k_3 (Bar size factor) :0.8; 1.0

k_4 (Bar fibre factor) :1.0; 1.25

k_5 (Bar surface profile) :1.0; 1.05; 1.80

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Development Length and Splice of Reinforcement ***(CSA S806)***

Development of bent bar:

$$165 k_2 \frac{d_b}{\sqrt{f_c'}} \quad for \;\; f_F \leq 520 MPa$$

$$\frac{f_F}{3.1} k_2 \frac{d_b}{\sqrt{f_c'}} \quad for \;\; 520 \leq f_F \leq 1040 MPa$$

$$330 k_2 \frac{d_b}{\sqrt{f_c'}} \quad for \;\; f_F > 1040 MPa$$

- L_d 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 $3d_b$

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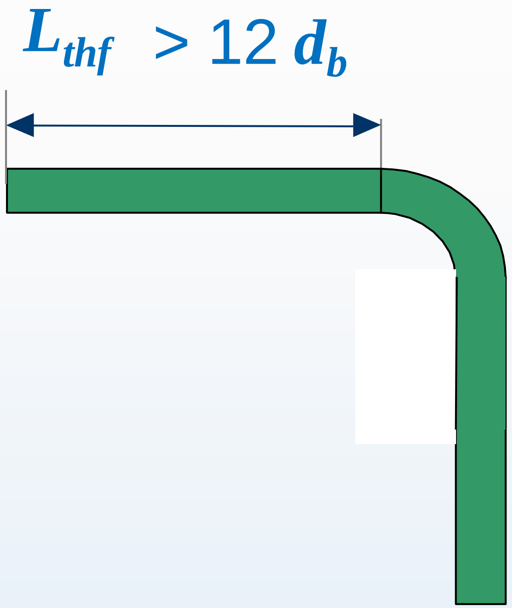
*Development Length and Splice of Reinforcement **(CSA-S806)***

Anchorage of shear reinforcement:

- Web reinforcement shall be carried as close to the compression and tension surfaces of a member as practically feasible. ***(Clause 9.9.1)***
- 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.
- The web reinforcement shall have sufficient development length to develop its design stress at mid-height of the member.

Session 2: Design Assumptions and Material Properties

Detailing of shear stirrups



L_{thf} = length of tail beyond a hook

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Development Length and Splice of Reinforcement ***(CSA S806)***

Splices of reinforcement:

- The lap splice length shall be 1.3l_d, where l_d is the basic development length of the bar ***(Clause 9.10.3; GGS-2, 2.9.7.6);***
- 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 ***(Clause 9.10.4; GGS-2, n/a);***
- Spliced bars in flexural members shall have a transverse spacing not exceeding the lesser of one-fifth of the required lap splice length or 130mm ***(Clause 9.10.5; GGS-2 , 2.9.7.6).***

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*Development Length and Splice of Reinforcement **(CSA S806)***

Mechanical anchorages:

- 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. ***AASHTO-GS2, 2.9.7.5*** ~ 1.25f_{fd})

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Development Length and Splice of Reinforcement ***(CSA-S6)***

The development length, l_d, of FRP bars in tension shall be calculated from:

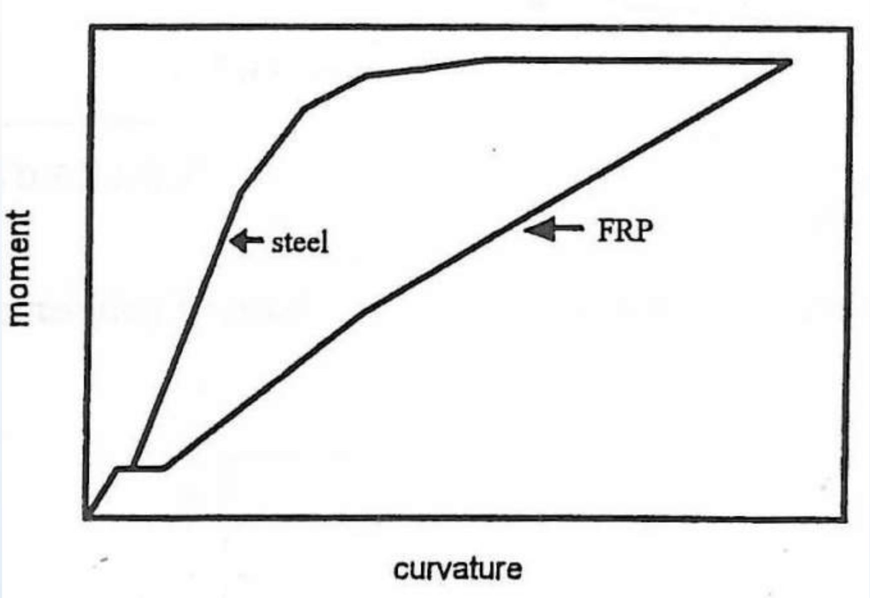
$$l_d = 0.45 \frac{k_1 k_4}{\left(d_{cs} + K_{tr} \frac{E_{FRP}}{E_s} \right)} \left(\frac{f_{FRPu}}{f_{cr}} \right) A$$

The splice length for FRP bars in tension shall be $1.3 l_d$.

Spliced FRP bars shall not be separated by more than 6-in. (150 mm).

Deformability ***(CSA-S6)***

- Deformability takes into account absorbed energy based on deformability, to ensure adequate deformation of members reinforced with FRP.
- The purpose of calculating deformability in an FRP reinforced section is to provide a comparable deformability as expected of a comparably reinforced steel reinforced section.



(Jaeger et al. 1997)

Deformability *(CSA-S6, Not in AASHTO-GGS2)*

- Overall performance factor, J, must be at least 4.0 for rectangular sections and 6.0 for T-sections.

$$J = \frac{M_{ult}\Psi_{ult}}{M_c \psi_c}$$

- M_{ult} and Ψ_{ult} are moment and curvature at ultimate limit state.
  - M_{ult} = moment at ultimate limit state
  - $\Psi_{ult} = \varepsilon_{ult} / kd$
- M_c and Ψ_c are moment and curvature corresponding to a concrete strain of 0.001.
  - $M_c = f_c k\,(1\text{-}k/3)\, bd^2$
  - $\Psi_c = \varepsilon_c / kd$, where $\varepsilon_c = 0.001$
- Use $f_c = \varepsilon_c E_c$ or $f_c = 1.8 f'_c (\varepsilon_c/\varepsilon'_c) / (1+(\varepsilon_c/\varepsilon'_c)^2)$

Deformability *(CSA-S6)*

- For calculating M_{ult} and Ψ_{ult}, repeat the same steps as required to calculate M_r, but with higher resistance factors.
- For calculating M_{ult} and Ψ_{ult} use the following:
  - $\Phi_c = 1.00$
  - $\Phi_{FRP} = 1.00$
- Based on the definition of J as a function of M_c, tension- controlled members may not have adequate deformability.
- Deformability may govern the design of deep members or T-beam members (i.e. pier caps or diaphragms).

How Does GFRP Compare with Steel?

- For typical reinforcement ratios found in a bridge deck slab, factored moment resistance at ULS with GFRP and reinforcing steel is similar (within 30%).
- If the member is subjected to SLS moment:
  - SLS will govern the design of a member with GFRP reinforcement. ULS usually governs the design of a member reinforced with steel.
  - On average, a GFRP design will require 50% to 100% more reinforcement as a design with reinforcing steel.
  - Use the smallest practical bar diametre and bar spacing for an efficient design with GFRP (less of a consideration for design with reinforcing steel).
  - Avoid bar spacing of less than 3”- 4” (75-100 mm) to avoid congestion of bars.

Questions

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