Technical Guide

Design of Continuously Reinforced Concrete Pavement using Glass Fibre Reinforced Polymer (GFRP) Bars at Traffic Loop Locations

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About this release

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Transport for NSW (2020) *Technical Guidance: TSI-TG-009 Induction Loop Use in CRCP - Reinforcing Steel replaced by GFRP*. Issue 1.0. Date of Publication: 16/09/2020.

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1. Introduction

The current practice of installing traffic loops in continuously reinforced concrete pavements (CRCP) is by saw cutting and sealing with a sealant. This method of installation has its drawbacks in terms of long term performance of the pavement due to the risk of crack initiation from the saw cuts and also the volume expansion of steel reinforcement caused by corrosion.

The purpose of this Technical Guide is to give Designers an acceptable design approach to install GFRP reinforcement at locations where traffic loops are to be installed in CRCP. GFRP-reinforced concrete slabs have been used in light rail projects (e.g. Sydney and the Gold Coast) so there is evidence that this technology can be extended into CRCP construction. For installation of traffic loops in CRCP where steel reinforcement has been replaced by GFRP bars, refer to TfNSW Technical Guidance TSI-TG-009 (2020).

This Guide has been prepared following the review of the State-of-the-Practice in Australia on the use of GFRP bars in concrete structures (Manalo et al.,2020).

2. Design Methodology

The proposed methodology follows the Austroads approach provided in Section 9.5 of Austroads (2017), so the action of the longitudinal reinforcement induces transverse cracking by providing restraint to shrinkage of the concrete. The longitudinal reinforcement holds cracks tightly together to limit their growth and opening, reducing the likelihood of potential pavement damage and distress over its service life.

2.1 Material Properties

Most of the recent technological research in GFRP has been carried out in Canada. In this Guide, Canadian standard CSA S807:19 has been adopted for material compliance. For CRCP reinforcement, GFRP bars must be electrically non-conductive and splinter free complying with the material requirements that have been adapted from CSA S807 Grade III as shown in Table 2-1 below.

Table 2-1 – Cross Sectional Area and Guaranteed Tensile Strength for Various GFRP Bar Sizes

Bar Designation	Nominal bar diameter (mm)	Cross sectional Area (mm^2)			Guaranteed tensile strength (MPa)
		Nominal	Minimum	Maximum	
G8	8	50	48	79	1,200
G10	10	71	67	104	1,200
G13	13	129	119	169	1,200
G15	15	199	186	251	1,000
G20	20	284	268	347	1,000
G22	22	387	365	460	900
G24	24	450	430	540	900
G25	25	510	476	589	800

Notes:
1. The guaranteed tensile strength is defined as the average strength minus three times the standard deviation. GFRP bars with different nominal diameters shall have the following minimal tensile strength confirmed by the appropriate test method according to CSA S806-12.
2. For reinforcement calculation purposes, at the concept design stage; the minimum cross sectional area must be used for a nominal bar diameter. During the detailed design stage, the actual cross sectional area of approved registered bars can be used. The properties of the bars used in the detailed design must be shown in the drawings.

The GFRP bars must also conform to the requirements for moderate durability class D2 and must:

a) Meet the requirements for D2 in Table 8 of CSA S807:19; and

b) Be made with glass fibre reinforcement with polyester, vinylester, or epoxy resin.

For a list of standard test methods and recommended material property limits, refer to Table A-1 in Appendix A.

Likewise, for a complete list of referenced standards and test methods refer to Table A-2 in Appendix A.

2.2 Design Approach

The design principles provided in Section 9.5 of Austroads (2017) have been adapted to incorporate material properties of GFRP bars.

The percentage of longitudinal GFRP bar reinforcement to be adopted in the design must be the highest percentage determined for the following criteria:

a) Design based on crack width (refer to Equation 1)
b) Design based on creep control (refer to Equation 2)

A design process flowchart is shown in Appendix B.

2.2.1 Design based on crack width

Equation 1 below is based on Equation 61 of Austroads (2017) which has been modified for inclusion of the GFRP bars.

$$p = \frac{(\frac{f_t'}{f_b'})d_b(\varepsilon_s + \varepsilon_t)}{2W} \tag{1}$$

Where,

p =   required proportion of longitudinal reinforcement – this is the ratio of the cross-sectional area of the longitudinal reinforcement to the gross area of the cross-section of the base

$\dfrac{f_t'}{f_b'}$ =   the ratio of the direct tensile strength of the immature concrete to the average bond strength between the concrete and the GFRP bar

d_b =   Nominal bar diameter of longitudinal reinforcing bar (mm)

ε_s =   estimated shrinkage strain (µε) – the shrinkage strain may be in the range 200 to 300µε for concrete with a laboratory shrinkage not exceeding 450µε at 21 days when tested in accordance with AS 1012.13 after three weeks air drying. A shrinkage strain of 250µε should be used in a preliminary design

ε_t =   estimated maximum thermal strain from the peak hydration temperature to the lowest likely seasonal temperature (µε) – a value of 300µε may be assumed, except when the average diurnal temperature at the time of placing concrete is 10°C or less, when a value of 200µε may be assumed

W =   maximum allowable crack width (mm) – a value of 0.3mm should be used in the design

Bond Strength between GFRP bars and concrete

Similar to Equation 1, Equation 63 of Austroads (2017) has been modified for inclusion of the GFRP bars.

The $f't/f'b$ corresponds to 0.5 times the bond coefficient factor (k_b) described in both CSA S806-12 and in ACI 440.1R-15. For GFRP bars having bond behaviour inferior to steel, the value of k_b must be higher than 1.0 and for GFRP bars having bond behaviour superior to steel, k_b must be lower than 1.0.

Therefore, for $f't/f'b$, a default value of 0.5 for deformed bars must be used in the design for bars that report a k_b value of 1.0 or less.

Longitudinal reinforcement

Assuming a total strain (shrinkage and thermal) of 550 µε, a crack width of 0.3mm, the design proportion of longitudinal reinforcing steel using Equation 1 would be as follows:

p = 0.5 x 15 x 550 x 10^{-6} / (2 x 0.3) = 0.69% using G15 bars

p = 0.5 x 20 x 550 x 10^{-6} / (2 x 0.3) = 0.92% using G20 bars

2.2.2 Design based on creep control

The Canadian Standard CSA S806-12 specify that the allowable stress under service load must be adopted as 35% of the guaranteed tensile strength. This limit aims to control potential creep rupture of GFRP bars under sustained loading.

The proportion of longitudinal reinforcing steel is based on working stress principles as reported in the CRCP ME Design Guide (2012) is shown in Equation 2.

$$P = (1.3 - 0.2F)\frac{f_{ct}}{f_s} \times 100 \tag{2}$$

Where

F	=	friction factor of subbase
f_{ct}	=	allowable tensile strength of concrete
f_s	=	allowable working stress of steel reinforcement

In this case, the working stress of the GFRP bars is used in lieu of steel.

The allowable concrete tensile strength is assumed to be equal to 60% of the 28-day concrete flexural strength as suggested in the Austroads (2017):

Assuming a subbase friction factor of 1.5, the proportion of longitudinal GFRP reinforcement would be as follows:

p = (1.3 – 0.2 x 1.5) x (0.60 x 4.5) / (0.35 x 1000) = 0.77%. This percentage is compared with that determined for the control of crack width and the higher percentage is chosen for design.

Therefore, the percentage of longitudinal GFRP reinforcement would be as follows:

p = 0.77% for G15 bars

p = 0.92% using G20 bars

Rounded down to nearest 5mm, the preliminary bar spacing for a 240mm-thick base would be as follows:

G15 @ 100mm which equates to an actual reinforcement ratio of $= \left(\frac{186}{100 \times 240}\right) \times 100 = 0.775\%$

G20 @ 120mm which equates to an actual reinforcement ratio of $p = \left(\frac{268}{120 \times 240}\right) \times 100 = 0.931\%$

The G20 bar spacing must be reduced to 117mm to take into account the cover on both sides of the longitudinal joint.

The G20 reinforcement ratio is similar to the one used on Highway 40 West, Montreal (Benmokrane et al., 2020).

In NSW, most CRCP designs adopt N16 bars spaced in the range of 110 to 130mm. For example, a 240mm-thick base containing 0.72% steel reinforcement ratio would require N16 bars spaced at 115mm. This means that G20 bars will be a better fit in terms of bar spacing. In this case G20 bars at 115mm should be adopted.

2.2.3 Check for bond area to concrete volume

Ledbetter and McCullough (1961) suggest that the ratio of the bond area to concrete volume should not be less than 0.03 in^2/in^3, which is checked by the Equation 3:

$$Q = \frac{4p}{\emptyset} \tag{3}$$

Where

Q =   the ratio of bond area to concrete volume (in^2/in^3)

p =   percent steel

$\emptyset$ =   nominal bar diameter of longitudinal reinforcing bar (in)

This ratio stipulates that there should be a maximum limit on the ratio of the bond area to concrete volume. This is because the stress transfer from the reinforcement to concrete depends on the bond stress at the interface between steel and concrete, which is a function of Q. The higher the Q, the larger the bond stress and stress transfer. Thus, higher Q values will induce more cracks and smaller crack widths (Won et al., 2012).

In this example

When G15 bars are used, Q = 4 x 0.00775/(15/25.4) = 0.052

When G20 bars are used, Q = 4 x 0.00931/(20/25.4) = 0.047

In both cases Q is higher than 0.03 which is Ok.

Note that the Austroads (2017) intuitively introduces this check by stating the diameter of steel bars should preferably be 16mm and in any case must not exceed 20mm. Where GFRP bars are used, the reinforcement ratio is higher, so it is acceptable to use larger bar sizes as long as the criterion proposed by Ledbetter and McCullough is satisfied.

2.2.4 Theoretical spacing of cracks

The theoretical spacing of cracks in continuously reinforced pavements is estimated by modifying Equation 61 of the Austroads (2017) for inclusion of the GFRP bars. This Equation is adopted for GFRP bars and reproduced as Equation 4.

$$L_{cr} = \frac{f_{ct}^2}{mp^2 u f_b [(\varepsilon_s + \varepsilon_t)E_c - f_{ct}]} \tag{4}$$

Where

L_{cr}	=	theoretical spacing between cracks (mm)
f_{ct}	=	tensile strength of the concrete (MPa) (in this example 0.6 x 4.5 = 2.7MPa)
m	=	ratio of the elastic moduli of GFRP to concrete. For Grade III bars and concrete with a flexural strength of 4.5MPa, m is in the order of 2. The elastic modulus of GFRP bars refers to the longitudinal tensile modulus determined as per Annex C of CSA S806-12
p	=	area of longitudinal GFRP reinforcement per unit area of concrete (in this example 0.92%)
u	=	perimeter of bar per unit area of GFRP which may be simplified to 2 divided by the radius of the bar
f_b	=	bond stress (MPa) – for mature concrete, and when deformed bars are used this may be assumed as $2f$ct,
ε_s	=	estimated shrinkage strain (µε) – the shrinkage strain may be in the range 200 to 300µε for a concrete with a laboratory shrinkage not exceeding 450µε at 21 days when tested in accordance with AS 1012.13 (after three weeks air drying). In this example, 250µε
ε_t	=	estimated maximum thermal strain from the peak hydration temperature to the lowest likely seasonal temperature (µε) – a value of 300µε may be assumed, except when the average diurnal temperature at the time of placing concrete is 10°C or less, when a value of 200µε may be assumed. In this example, 300µε
E_c	=	modulus of elasticity of concrete (MPa). In this example estimated as 30,100 MPa based on a reinforced concrete density of 2,410kg/m^3

For G15 bars:

$$L_{cr} = \frac{2.7^2}{2 \times (\frac{0.775}{100})^2 \times (\frac{2}{0.015/2}) \times (2 \times 2.7) \times [(250+300) \times 10^{-6} \times 30,100 - 2.7]} = 3.04m$$

For G20 bars:

$$L_{cr} = \frac{2.7^2}{2 \times (\frac{0.931}{100})^2 \times (\frac{2}{0.020/2}) \times (2 \times 2.7) \times [(250+300) \times 10^{-6} \times 30,100 - 2.7]} = 2.81m$$

Based on the above the theoretical average spacing between cracks would be about 3m for G15 bars and 2.8m for G20 bars.

Most CRCPs in NSW exhibit an average crack spacing in the order of 1.0 to 1.2m (say 1.1m on average). This means that compared with an equivalent steel reinforced pavement, the frequency of transverse cracks will reduce including the occurrence of clusters of closely spaced cracks.

3 Recommendations for Implementation

3.1 Longitudinal Lap Length

It is expected that longitudinal GFRP reinforcement will be used in areas where traffic loops will be installed in the concrete base. Therefore, for field implementation, the GFRP bars must be lap-spliced together with the 16mm steel bars (i.e. matching the bar spacing of the longitudinal steel reinforcement). The calculated spacing of the longitudinal GFRP bars must not be less than the specified spacing of longitudinal steel reinforcement.

The data presented by Mohamed & Benmokrane (2011) for standard GFRP bars supplied by V•ROD has been plotted and shown and in Figure 3-1. These bars have a bond-dependent coefficient (k_b) of 1.0 or less so they can provide indicative development lengths of GFRP bars that have a bond behaviour equal or superior to steel reinforcing bars. The development length was calculated using the methodology presented in Section 9.3.2 and 9.3.3 of Canadian Standard CSA-S806-12.
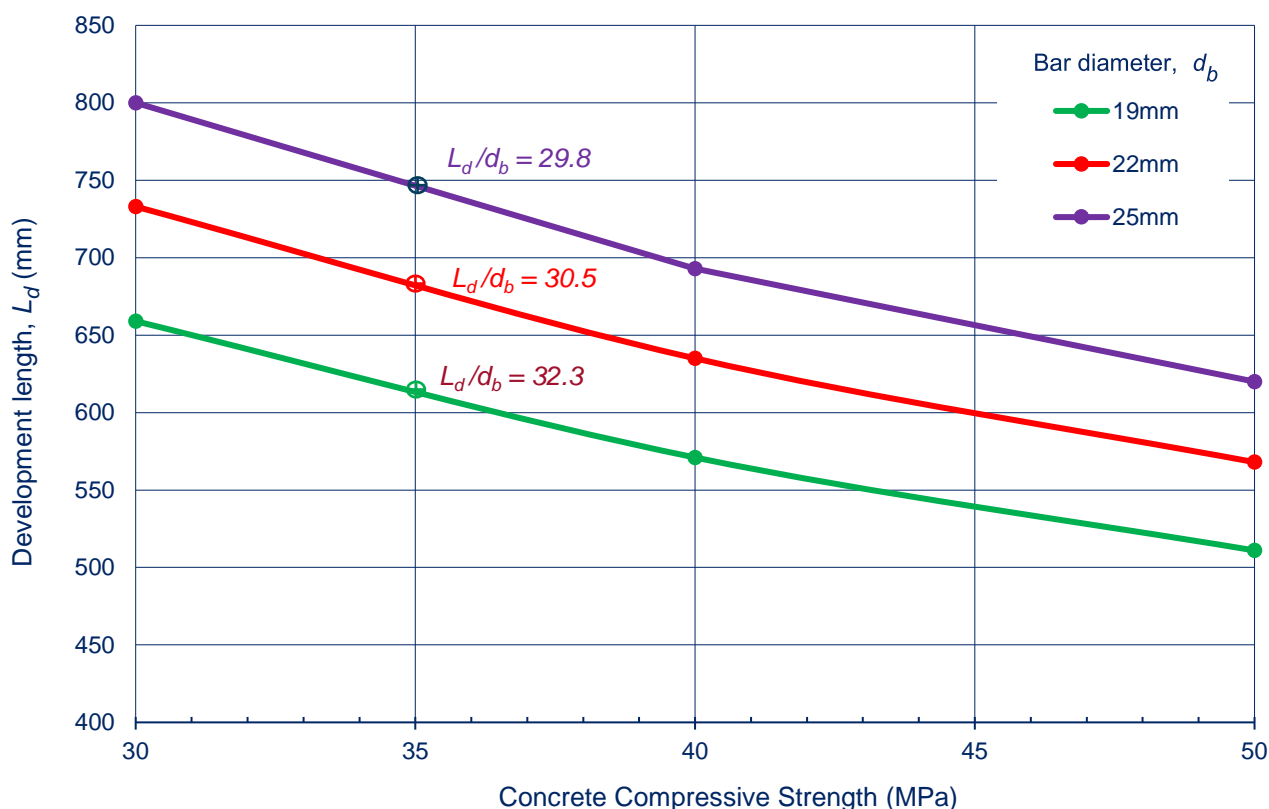
Figure 3-1 - Development Length for Typical GFRP bars

From Figure 3-1, the average development length is 31 times the GFRP bar diameter (db) for a concrete compressive strength of 35MPa. Note that the FHWA CRCP Manual (2016) states that for splicing length, the development length used in the US varies from 25 to 33 times the bar diameter.

In NSW, the current CRCP lap length for N16 bars is 525mm which is about 33 times the bar diameter.

Based on current practice to date, it is recommended to keep the current lap length of 33 times the nominal bar diameter.

Though the lap size for G15 should be 495mm, a lap length of 525 has been adopted as it is the standard lap length for N16 bars. In reality the bar diameter of G15 bar corresponds to bar size #5 (US classification for bar size 5/8 inch which is about 15.9mm.)

Therefore, the current lapping options specified in Table 12.2 of the TfNSW standard drawings for CRCP should be modified as shown in Figure 3-2.

GFRP BAR	G15	G20
LAP (mm)	525	660
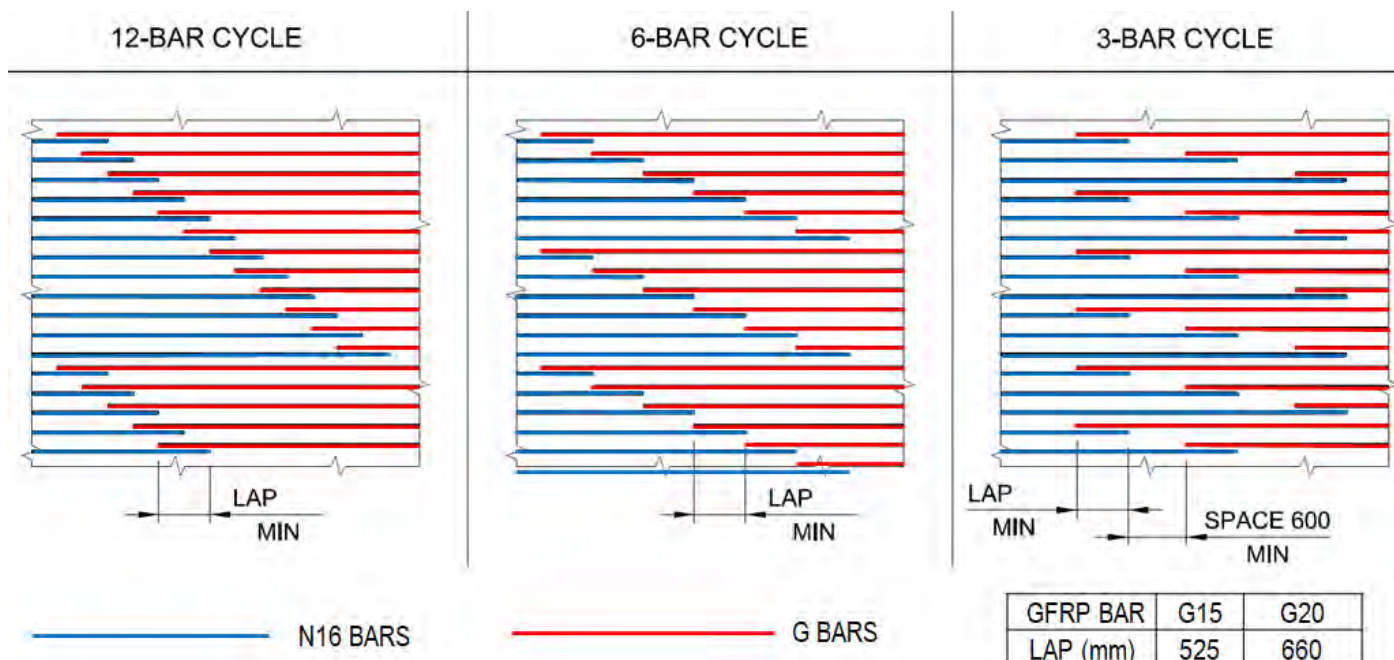
Figure 3-2 - Lap options for B1, B2 and C bars

An example of the 6-bar cycle lap arrangement for the reinforcing steel-free window indicated in Figure 3 of TSI-TG-009 is shown in Appendix C.

3.2 Transverse Reinforcement

Equation 5 shown below is a modification of Equation 60 of the Austroads (2017) to incorporate the GFRP bars. As per steel reinforcement, the transverse GFRP reinforcement bars should have a maximum spacing of 750mm to prevent sagging in the longitudinal reinforcement.

$$A_G = \frac{\mu \times RED \times \rho \times g \times D}{1000 f_G}$$

(5)

Where

A_G = the required area of GFRP reinforcement (mm² per 1m width of slab)

f_G = the allowable tensile stress of the GFRP reinforcement (MPa). Defined as 0.35 times the guaranteed tensile strength of GFRP reinforcement

g = acceleration due to gravity (m/s²)

D = thickness of the base (mm), including any asphalt surfacing

RED = relief edge distance (m)

ρ = mass per unit volume of the base (kg/m³),

A_G = the required area of GFRP reinforcement (mm^2 per 1m width of slab)

μ = coefficient of friction between the concrete base and the subbase. Refer Austroads (2017) Table 9.10 for indicative values

The cross-sectional area of a nominal G13 bar is 119mm^2 and the guaranteed tensile strength is 1,000MPa.

The allowable tensile load (T) of any GFRP bar can be determined based on working load principles (ie, allowable tensile capacity = Area x allowable tensile strength).

For a G15 bar, the allowable tensile load would be:

T = 119 X (0.35 X 1000) / 1000 = 41.7kN

3.3 Longitudinal Joint Details

In this section there are three relevant joint details from the CRCP Standard Drawings for Construction that need minor modifications to incorporate GFRP bar reinforcement (refer to Figure 3-3, Figure 3-4 and Figure 3-5).

Notation:

- Size of longitudinal GFRP (G) bars: Generally, G15, but G20 but can also be used subject to bar spacing being at least 100mm and not more than 200mm

- Size of transverse GFRP (G) bars: Generally,G13, but G15 bars can also be used.

Figure 3-3 - Proposed Joint Type C1 using GFRP Bars
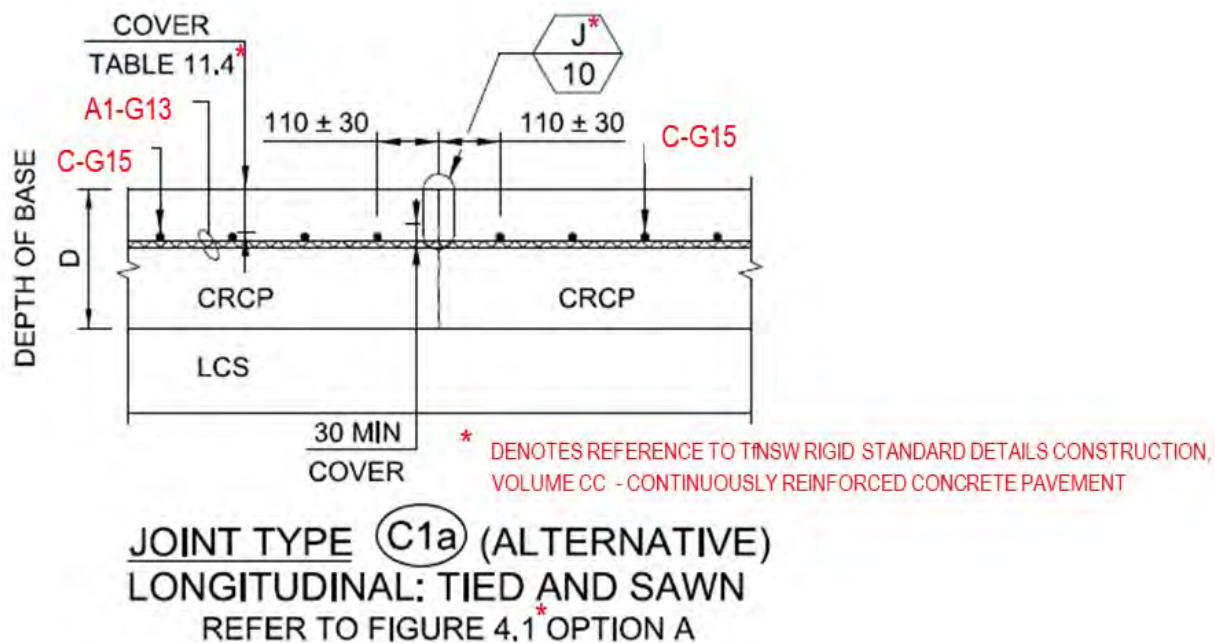
Figure 3-4 - Proposed Joint Type C1a using GFRP Bars
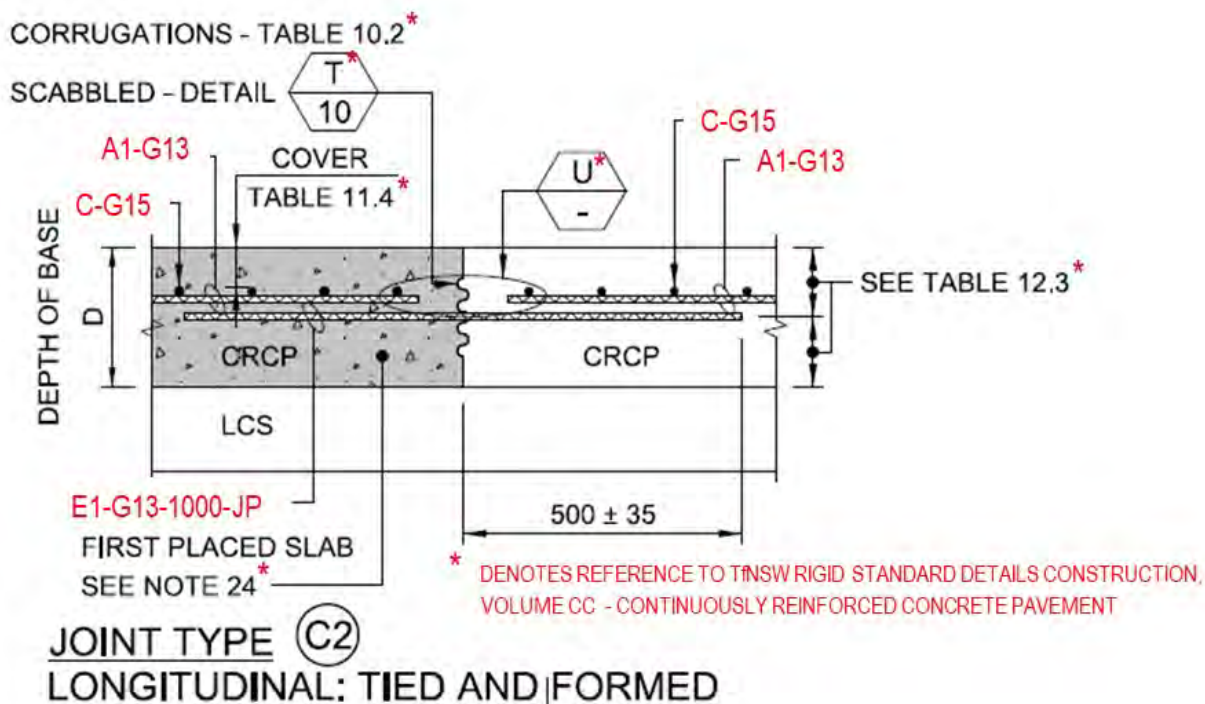
Figure 3-5 - Proposed Joint Type C2 using GFRP Bars

4 References

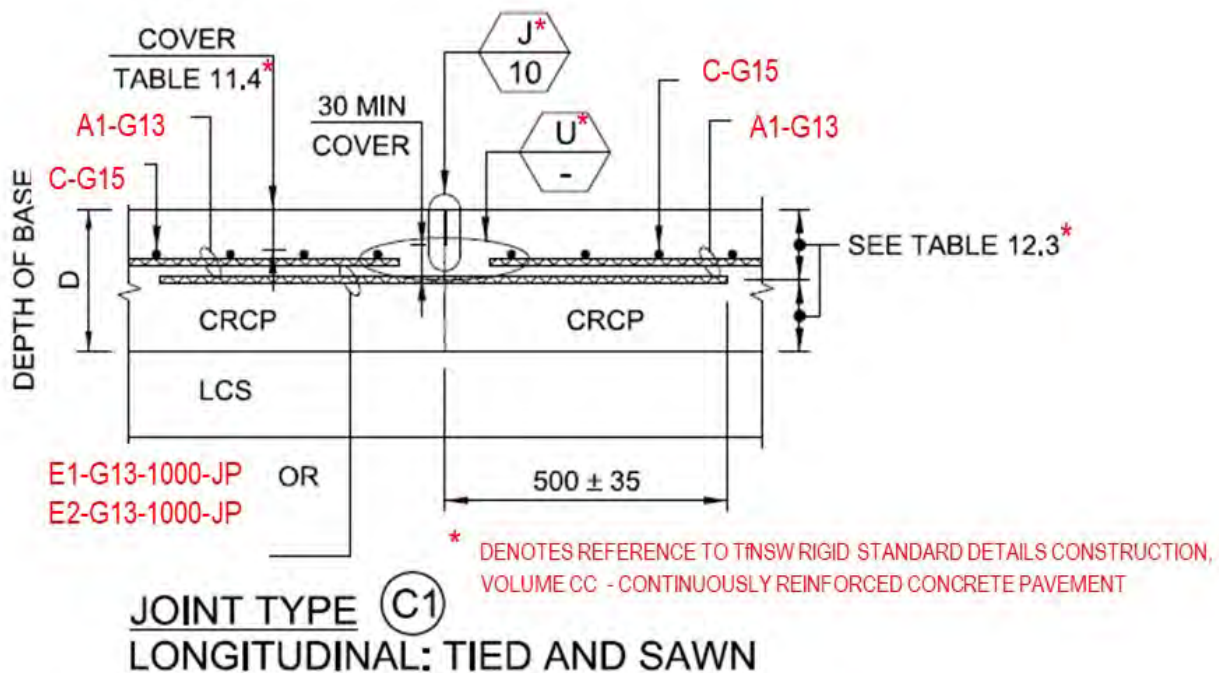1. A. C. Manalo; P. Mendis; Y. Bai; B. Jachmann; and C. D. Sorbello (2020) *Fiber-Reinforced Polymer Bars for Concrete Structures: State-of-the-Practice in Australia*. ASCE Journal of Composites for Construction 2021-02 | journal-article. DOI: 10.1061/(ASCE)CC.1943-5614.0001105

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Appendix A – Material and Testing Requirements

Table A-1- Properties and specified limits

Property to be Tested	Method No.	Specified limit
Actual cross-sectional area	CSA S806-12, Annex A. The submerged section of bar shall retain all surface bonding mechanisms such as sand coating undulations, etc.	Refer to Table 2-1 Conformance Test: 24 tests from 3 production lots for all bar sizes or only bars manufactured by the supplier Project Assessment: 5 tests for each bar size per lot used on project
Fibre content by weight	ASTM D2584	≥70% Conformance Test: 9 tests from 3 production lots for all bar sizes or only the sizes manufactured by the supplier Project Assessment: 3 tests for each bar size per lot used on project
Water absorption (24h immersion)	ASTM D570	≤0.35% Conformance Test: 15 tests from 3 production lots for all bar sizes or only the sizes manufactured by the supplier Project Assessment: 5 tests for each bar size per lot used on project
Water absorption at full saturation (Long-term immersion)	ASTM D570	≤1% Conformance Test: 15 tests from 3 production lots for all bar sizes or only the sizes manufactured by the supplier Project Assessment: 5 tests for each bar size per lot used on project
Cure ratio (not applicable for thermoplastic resins)	CSA S807:19, Annex A Tested sample shall be taken from the centre of the cross-section. The following two values are required to compute cure ratio using the differential scanning calorimetry (DSC). The neat resin content (by mass) shall be reported by the manufacturer or supplier. The value of enthalpy of polymerization of the neat resin Used in the GFRP shall be reported by the manufacturer.	≥95% Conformance Test: 15 tests from 3 production lots for all bar sizes or only sizes manufactured by the supplier Project Assessment: 5 tests for each bar size per lot used on project
Glass transition temperature	ASTM D3418	Dynamic Mechanical Analysis (DMA) ≥90°C DSC ≥80°C Conformance Test: 15 tests from 3 production lots for all bar sizes or only the sizes manufactured by the supplier Project Assessment: 5 tests for each bar size per lot used on project
Transverse coefficient of thermal expansion	ASTM E831	$\leq 40 \times 10^{-6}/^{o}C$ Conformance Test: 9 tests from 3 production lots for all bar sizes or only the sizes manufactured by the supplier Project Assessment: N/A
Guaranteed tensile strength	CSA S806-12, Annex C	Refer to Table 2 1 Conformance Test: 24 tests from 3 production lots for all bar sizes or only bars manufactured by the supplier Project Assessment: 5 tests for each bar size per lot used on project

Property to be Tested	Method No.	Specified limit
Longitudinal tensile modulus and ultimate elongation	CSA S806-12, Annex C	≥60GPa Ultimate elongation ≥1.2% Conformance Test: 24 tests from 3 production lots for all bar sizes or only bars manufactured by the supplier Project Assessment: 5 tests for each bar size per lot used on project
Apparent horizontal shear strength by the short beam method	ASTM D4475	≥45 MPa Conformance Test: 24 tests from 3 production lots for all bar sizes or only bars manufactured by the supplier Project Assessment: 5 tests for each bar size per lot used on project
Apparent horizontal shear strength in high pH solution at 60 °C (alkali resistance)*	ASTM D4475 Test duration: 3 months	The average from testing shall not be less than 85% of the average from room temperature testing for qualification (Refer to Table 7 of CSA S807)
Bond-dependent coefficient (k_b)	CSA S806-12, Annex S	≤ 1.0 Conformance Test: One concrete beam test for each bar size manufactured by the supplier. Project Assessment: N/A
Bond strength	ASTM D7913/ D7913M	≥ 10 MPa Slip at loaded end is limited to 0.5 mm at 10MPa Conformance Test: 24 tests from 3 production lots for all bar sizes or only bars manufactured by the supplier Project Assessment: 5 tests for each bar size per lot used on project
Alkali resistance in high pH solution (without load)*	ASTM D7705/ D7705M; or CSA S806-12, Annex M. Test duration: 3 months	The average from testing shall not be less than 70% of UTS for D2 bars and grids, where UTS is from Conformance Testing. Conformance Test: 24 tests from 3 production lots for all bar sizes or only the sizes manufactured by the supplier Project Assessment: N/A
Alkali resistance in high pH solution (with load)*	ASTM D7705/ D7705M; or CSA S806-12, Annex M. The sustained tensile stress should be set to induce a tensile strain equal to 3,000 microstrain. Test duration: 3 months	The average from testing shall not be less than 75% of UTS for D2 bars and grids, where UTS is from Conformance Testing. Conformance Test: 24 tests from 3 production lots for all bar sizes or only the sizes manufactured by the supplier Project Assessment: N/A
Creep rupture strength	ASTM D7337/ D7337M; or CSA S806-12, Annex H	≥35% of UTS Conformance Test: 24 tests from 3 production lots; tests on 15mm bars or other bars required by the owner Project Assessment: N/A
Creep	ASTM D7337/ D7337M; or CSA S806-12, Annex H. Two sustained tensile stress levels to be used: 20% and 40% of UTS for GFRP Test duration: 10,000 h.	Report creep strain values at 1000h; 3000h; and 10,000 h Tests on one size bar

Property to be Tested	Method No.	Specified limit
Fatigue strength	ACI 440.3R, Test Method B.7; or CSA S806-12, Annex J	Fatigue strength at 1 million cycles $\geq$ 35% UTS Tests on one size bar

Table A-2 - Referenced Standards and Test Methods

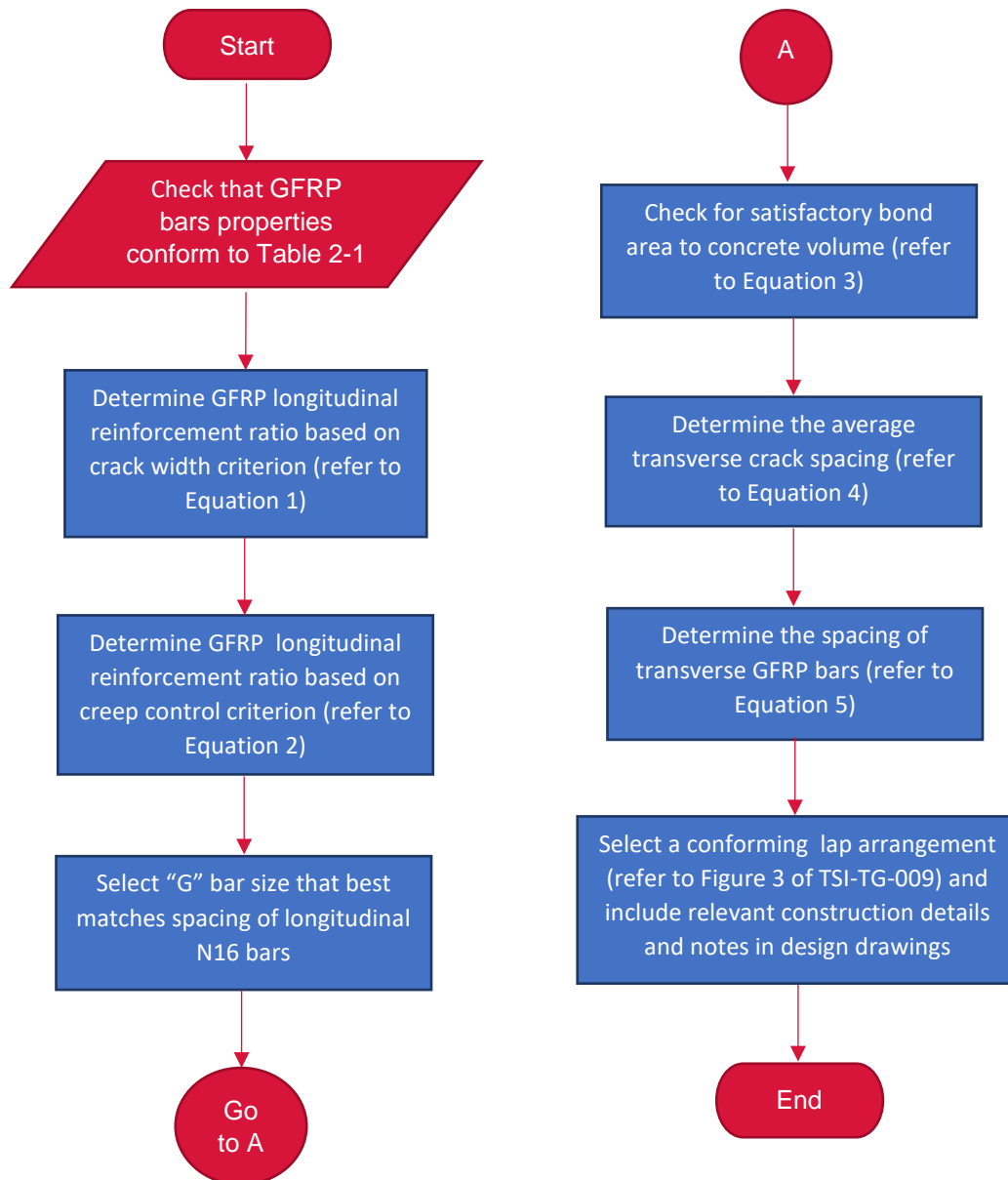| Reference	Title
ACI 440.1R	Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars
ACI 440.3R	Guide Test Methods for Fiber-Reinforced Polymer (FRP) Composites for Reinforcing or Strengthening Concrete and Masonry Structures
CSA S806-12	Design and construction of building structures with fibre-reinforced polymers
CSA S807:19	Specification for fibre-reinforced polymer
ASTM D570	Standard test method for water absorption of plastics
ASTM D3171	Standard test method for constituent content of composite materials
ASTM D3418	Test method for transition temperatures of polymers by thermal analysis
ASTM D4475	Standard Test Method for Apparent Horizontal Shear Strength of Pultruded Reinforced Plastic Rods by the Short-Beam Method
ASTM D5117	Standard test method for dye penetration of solid fibreglass reinforced pultruded stock
ASTM D7205	Standard Test Method for Tensile Properties of Fibre-Reinforced Polymer Matrix Composite Bars
ASTM D7705 / D7705M	Standard Test Method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction
ASTM D7913/ D7913M	Standard Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing
ASTM D7337/ D7337M	Standard Test Method for Tensile Creep Rupture of Fiber Reinforced Polymer Matrix Composite Bars
ASTM D7957	Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement
ASTM E831	Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis
ASTM E2160	Standard Test Method for Heat of Reaction of Thermally Reactive Materials by Differential Scanning Calorimetry
ISO 104061-1	Fibre-reinforced polymer (FRP) reinforcement of concrete – Test methods, Part 1: FRP bars and grids

Appendix B – Design Process Flowchart

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                    ┌─────────┐                                    ┌─────────┐
                    │  Start  │                                    │    A    │
                    └─────────┘                                    └─────────┘
                         │                                              │
                         ▼                                              ▼
              ╱───────────────────╲                         ┌─────────────────────┐
             ╱   Check that GFRP    ╲                        │ Check for satisfactory│
            ╱    bars properties     ╲                       │ bond area to concrete │
            ╲   conform to Table 2-1 ╱                        │ volume (refer to      │
             ╲─────────────────────╱                         │ Equation 3)           │
                         │                                    └─────────────────────┘
                         ▼                                              │
              ┌───────────────────┐                                    ▼
              │ Determine GFRP     │                         ┌─────────────────────┐
              │ longitudinal       │                         │ Determine the average│
              │ reinforcement ratio│                         │ transverse crack     │
              │ based on crack     │                         │ spacing (refer to    │
              │ width criterion    │                         │ Equation 4)          │
              │ (refer to          │                         └─────────────────────┘
              │ Equation 1)        │                                    │
              └───────────────────┘                                    ▼
                         │                               ┌─────────────────────┐
                         ▼                               │ Determine the spacing │
              ┌───────────────────┐                      │ of transverse GFRP    │
              │ Determine GFRP     │                      │ bars (refer to        │
              │ longitudinal       │                      │ Equation 5)           │
              │ reinforcement ratio│                      └─────────────────────┘
              │ based on creep     │                                  │
              │ control criterion  │                                  ▼
              │ (refer to          │                      ┌─────────────────────┐
              │ Equation 2)        │                      │ Select a conforming   │
              └───────────────────┘                      │ lap arrangement       │
                         │                                │ (refer to Figure 3 of │
                         ▼                                │ TSI-TG-009) and       │
              ┌───────────────────┐                       │ include relevant      │
              │ Select "G" bar size│                      │ construction details  │
              │ that best matches  │                      │ and notes in design   │
              │ spacing of         │                      │ drawings              │
              │ longitudinal N16   │                      └─────────────────────┘
              │ bars               │                                  │
              └───────────────────┘                                  ▼
                         │                                    ┌─────────┐
                         ▼                                    │   End   │
                    ┌─────────┐                               └─────────┘
                    │  Go     │
                    │  to A   │
                    └─────────┘
```

Figure B-1 - Design Process Flowchart for GFRP Reinforcement in CRCP

Appendix C – Example of Lap Arrangement in Reinforcing Steel-Free Window

GFRP BAR	G15	G20
MINIMUM BAR LENGTH	6100	6700
LAP	525	660
A	3150	3960
B	8000	8120
C	14300	16040

N16 BARS   G BARS

DIMMENSIONS IN MILLIMITRES - TRANSVERSE REINFORCEMENT NOT SHOWN
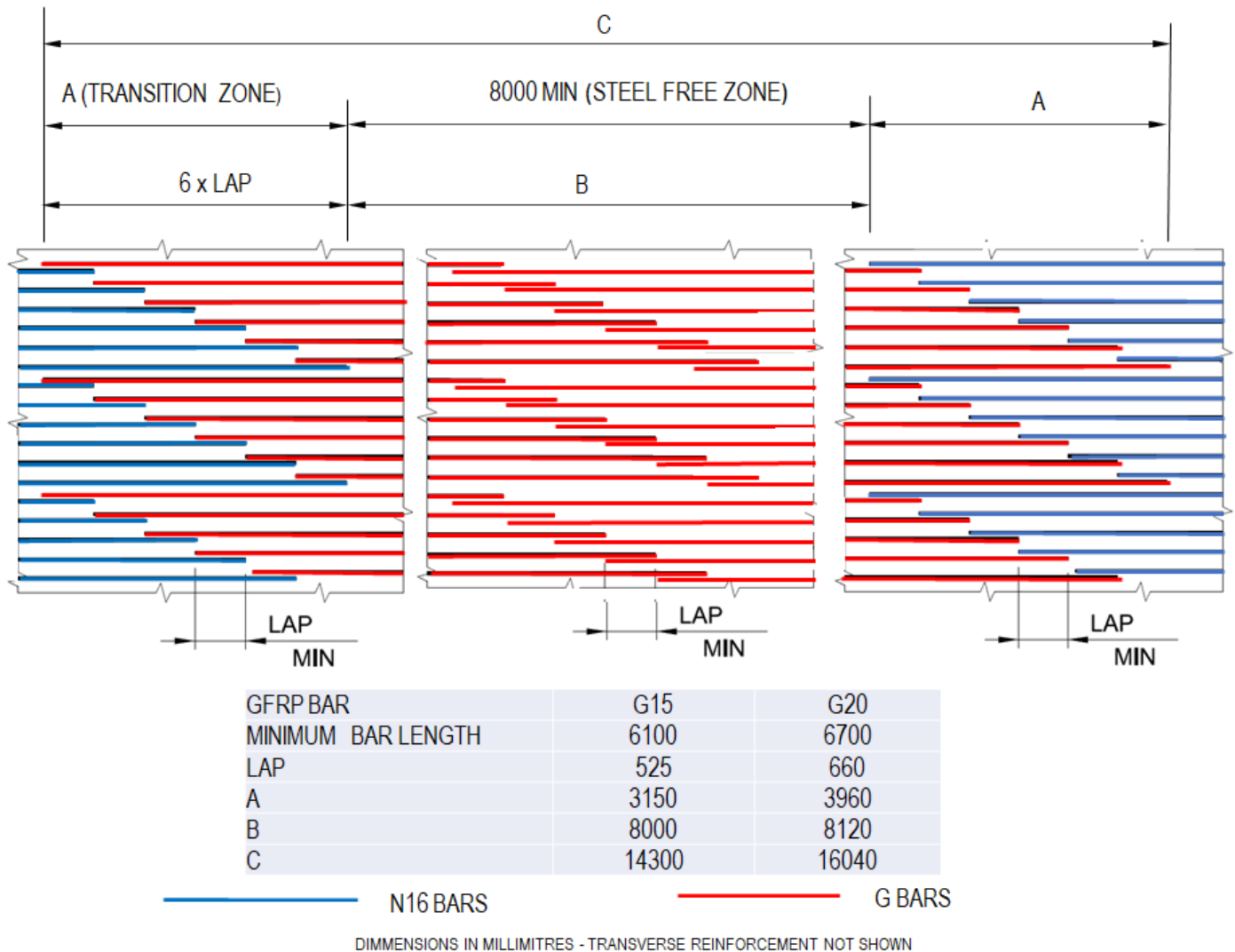
Figure C-1 - 6-Bar Lap Arrangement in Reinforcing Steel-Free Window

Contact Us:

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