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GUIDELINES ON USE OF FIBRE-REINFORCED POLYMER BARS IN ROAD PROJECTS

(PART 1: GLASS FIBRE-REINFORCED POLYMER BARS)

INDIAN ROADS CONGRESS
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PREFACE

It gives me great immense pleasure to present the first edition of the Guideines on Use of Fibre Reinforced Polymer Bars in Road Projects (Part 1: Glass Fibre-Reinforced Polymer Bars).

The highway sector in India is poised for rapid growth and mechnization plays an important tole in achieving economy, speed and quality in highway construction and maintenance. Currently, their exists no single guidelines on Use of Fibre Reinforced Polymer Bars. Therefore, an initiative has been taken to come out with this Guidelines.

During the last few decades, fibre-reinforced polymer (FRP) bars have emerged as an alternative to carbon steel bars in reinforced concrete structures. The FRP bars are non-corrosive. They also exhibit other beneficial properties such as high tensile strength, making them suitable for use in concrete structures. In addition to their durability advantage, recent life-cycle assessment studies also show that concrete structures reinforced with FRP bars can have a significantly lower environmental impact than the traditional reinforced concrete structures

Many countries have developed standards and guidelines on various aspects of the material, their testing, design and construction. Indian Roads Congress (IRC) has now come up with the State-of-the-Art Report and Guidelines on Use of FRP on National Highways work by taking inputs from all stakeholders incluidng IITs, Government Department, Industry, etc.

However, the highway structures where FRP bars are used should be closely monitored to assess its performance. The monitoring of both long term and short term use should include visual assessment as well as instrumented measurement of various parameters of interest. As there is currently limited manufacturing capacity in the country and only FRP bars manufactured using vinyl ester resin systems and glass fibres classified as E-CR or R fulfils the criteria for acceptance parameters so, the concrete structural components may need to simultaneously use both carbon steel and GFRP bars.

I wish to express my appreciation for the efforts put in by Shri R.K. Pandey, Prof. Ravi Sinha, Dr (Mrs) Lakshmy Parmeswaran and other Members of Exeprt Group and Drafting Group in preparing this document and GSS Committee & IRC Council for approving the Guidelines.

I hope this Guideline, in its present form, will prove to be very useful for all the engineers. However, the compilation of this Guideline will need to be updated periodically with changes in technology, environment, experienced gained etc. The Indian Roads Congress would, therefore, welcome suggestions and feedback from users so that any further amplification/modification/updating may be attempted in due course.

New Delhi
October, 2022

(S.K. Nirmal)
DG (RD) & SS, MoRTH &
Secretary General, IRC

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GUIDELINES ON USE OF FIBRE-REINFORCED POLYMER BARS IN ROAD PROJECTS (PART 1: GLASS FIBRE-REINFORCED POLYMER BARS)

1. INTRODUCTION

1.1. Background

1.1.1. Reinforced concrete structures are designed to take advantage of the compressive strength of concrete and tensile strength of steel to meet the required performance criteria. Sometimes, plain concrete is also used for structural applications in road projects. Reinforcement is generally provided in plain concrete structures to control the effect of creep and shrinkage. While concrete is generally chemically inert to the structure's surrounding environment, the reinforcement steel can deteriorate over time due to corrosion. The steel in both plain concrete and reinforced concrete structures is initially protected from corrosion by the alkalinity of the embedding concrete. Sufficiently thick cover concrete is provided to reduce the exposure of the surrounding atmosphere to the reinforcement bars and provide protection. Over time, the protection from the surrounding atmosphere gets reduced due to chemical reactions in the concrete, leading to corrosion. The life of a reinforced concrete structure is typically governed by the time required for its reinforcement steel to corrode and compromise the structure's strength.

1.1.2. India has vast coastal lines both on the eastern and western sides and many of the road infrastructures are exposed to the marine environment that can hasten corrosion. Also, with rapid industrialization and infrastructure development in our country, the emission of carbon dioxide into the atmosphere is also increasing. All these contribute to the corrosion of reinforcement steel and may reduce the design life of the structure. Early deterioration of the structures also enhances maintenance requirements and increases their life cycle cost.

1.1.3. The steel industry has a very high impact on the environment. Each tonne of steel production results in over 1.8 tonnes of carbon dioxide emissions. A 2020 report by International Energy Agency shows that the steel industry contributed around 7% of the global carbon dioxide emissions. Considering the vast requirements of the construction industry, there is a need to identify additional reinforcement options that can be used in reinforced concrete constructions so as to reduce its carbon footprint.

1.1.4. During the last few decades, Fibre-Reinforced Polymer (FRP) bars have emerged as an alternative to carbon steel bars in reinforced concrete structures. The FRP bars are non-corrosive. They also exhibit other beneficial properties such as high tensile strength, making them suitable for use in concrete structures. In addition to their durability advantage, recent life-cycle assessment studies also show that concrete structures reinforced with FRP bars can have a significantly lower environmental impact than the traditional reinforced concrete structures. Although it is not a new material and widely used in aerospace applications, the extent of use of FRP bars for civil engineering applications is much lower. One of the reasons is that the mechanical properties and behaviour of FRP and carbon steel bars are different. Therefore, a change in the traditional design philosophy of concrete structures is needed for use of FRP reinforcement bars.

1.1.5. The Ministry of Road Transport and Highways (MoRTH) requested IRC to constitute the Expert Committee for framing Guidelines for "Use of Fibre-Reinforced Polymer Bars in Highway Works". Accordingly, Indian Roads Congress (IRC), constituted an Expert Committee under Shri R.K. Pandey, Member, NHAI in March 2021 comprising members from Technical Committees, academicians, research organizations etc.

The Composition of the Expert Committee is as under:

Pandey, R.K.	……..	Chairman

Members

Alex, Dr. T.C.	Puri, S.K.
Banerjee, A.K.	Rao, P. Ravinder
Bhasin, Col. A.K. (Expired on October, 2021)	Reddy, Prof. M.A.
Blah, W.	Ransinchung, Prof. G.D.
Ghoshal, A.	Sharan, G.
Joshi, C.P.	Shahu, Prof. J.T.
Heggade, V.N.	Sharma, R.S.
Kumar, Ashok	Sinha, N.K.
Kumar, Dr. Rakesh	Sinha, Prof. Ravi
Parameswaran, (Mrs.) Dr. Lakshmy	Tandon, Prof. Mahesh
	Wanjari, Prof. Swapnil

The Expert Committee in its 1st Meeting held on 1st May, 2021 deliberated in detail and chalked out action plan for this task and also recommended to form Sub-Group headed by Prof. Ravi Sinha, IIT Bombay to prepare the outline & document. The other members of Sub-group are viz. Banerjee, Prof. Sauvik; Dinesh Ganvir; Dr. Alex, T.C.; Goel, Dr. Rajeev; Heggade, V.N.; Kumar, S. Arun; Kumar, Dr. Rakesh; Laskar, Prof. Arghadeep; Madhav, Madhumira; Ojha, P N; Pant, Sanjay; Parameswaran, (Mrs.) Dr. Lakshmy; Ransinchung, Prof. G.D.; Reddy, Prof. M.A.; Shahu, Prof. J.T.; Tandon, Prof. Mahesh and Wanjari, Prof. Swapnil.

1.1.6. The Expert Committee deliberated on the international practices regarding the use of FRP reinforcement in concrete structures as an alternate to carbon steel in countries such as Japan, USA, Canada and Australia and in European countries. The Committee noted that FRP bars are manufactured with several different combinations of fibres and matrix materials. Glass, Carbon, Basalt and Aramid are most commonly used fibres, while vinyl ester, epoxy and polyester resins are often used as binding material.

1.1.7. The Committee also noted that, internationally, there are limited uses of FRP bars as compared to carbon steel bars in concrete constructions, and most engineers are unfamiliar with their characteristics. Some countries have developed standards and guidelines on various aspects of the materials, their testing, design and construction. However, additional Guidelines are typically issued by the user agencies in addition to the Codes and Guidelines. The Committee also noted that a large number of important developments are contained in scientific literature that are yet to be incorporated in the Codes and Guidelines. The Committee therefore decided that a State-of-the-Art Report (SOAR) on FRP reinforcement bars and their use in reinforced concrete constructions shall be prepared. The SOAR shall form the base status document to facilitate further deliberations of the Committee, and shall also constitute as the reference document for the Guidelines being prepared by the Committee.

1.1.8. The Committee noted that Glass Fibre-Reinforced Polymer (GFRP) bars have the longest history of use in civil engineering applications. The GFRP bars are also the most frequently used type of FRP bars in reinforced concrete constructions. The Committee also took note of the manufacturing base of FRP bars in India, which is predominated by GFRP bars. The Committee, therefore, decided that initially, Guidelines for the use of GFRP bars in road projects in India shall be developed for the consideration of the Ministry. The Committee also decided that based on the experience gained after its adoption, the Guideline may be updated in due course. The Committee further decided that the Guidelines for the use of FRP bars with other types of fibres may be taken up infuture.

1.1.9. The FRP bars have been used in concrete structure applications in several countries. The applications are for both new constructions, where the carbon steel bars are either partially or fully replaced by FRP bars or for rehabilitation of deteriorated structures. The Committee noted that while considerable experience regarding the use of FRP bars exist in several countries, the formal standardisation of the use of FRP bars is most comprehensively developed in the USA. The Committee therefore decided to adopt the relevant Codes, Guidelines and Specifications of the USA for the use of FRP bars in India.

1.1.10. The initial draft prepared by the sub-group was considered by Expert Committee in its various meetings and finally approved in its 4th meeting held on 12.03.2022 for placing before the GSS. The draft Guidelines placed before the General Specifications and Standards Committee (GSS) in its meeting held on 11.06.2022. The GSS Committee approved this Guideline and recommended it for placing before EC/Council. The EC in its meeting held on 16.06.2022 approved the draft Guideline placing before the Council. The 222nd Mid-Term Council in its meeting held on 17^{th}-18^{th} June, 2022 at Shillong (Meghalaya) considered and approved the draft “Guidelines on Use of Fibre-Reinforced Polymer Bars in Road Projects” for printing.

1.2. Characteristics of FRP Bars

1.2.1. The FRP reinforcing bars are made from filaments or fibres held in a polymeric resin matrix binder. FRP reinforcing can be made from various types of fibres such as Glass (GFRP), Aramid (AFRP), Basalt (BFRP) or Carbon (CFRP) (shown in Fig. 1.1). The matrix binders typically used include vinyl ester, epoxy and polyester resins. The manufacturing process most commonly uses pultrusion, wherein the fibres are pulled through a resin-impregnated bath followed by shaping bath where the resin is cured. This makes the bars very strong along the orientation of the fibres. A surface treatment is typically provided that enhances the bond between the reinforcing bar and the surrounding concrete (shown in Fig. 1.2).

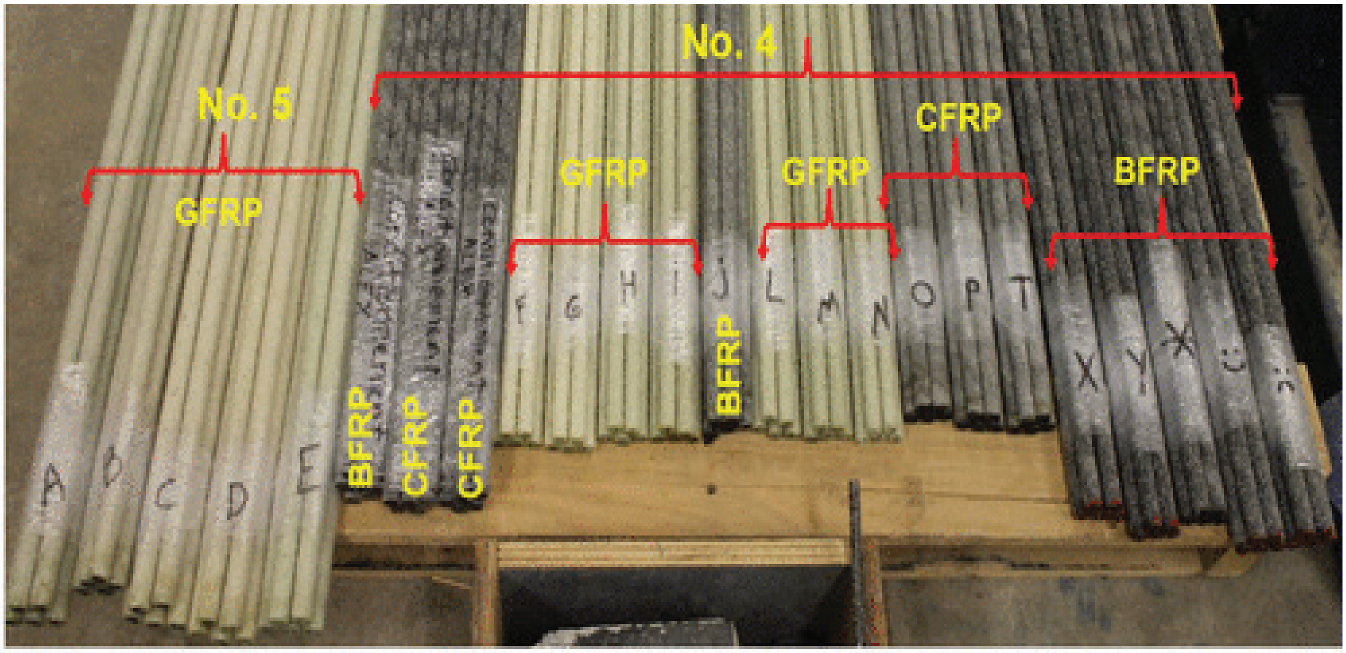


Fig. 1.1 Various Types of FRP bars (Benmokrane et al., 2020)

Fig. 1.2 Different Surface Characteristics of FRP bars (Abedini et al., 2017)

1.2.2. The FRP bars possess several favourable properties for use as reinforcement in reinforced concrete constructions. The main beneficial characteristics of FRP bars include:

a) FRP bars are highly resistant to chloride ion and chemical attack,

b) Their tensile strength is greater than that of carbon steel,

c) FRP bars are light weight, with mass density only one quarter as of carbon steel,

d) GFRP bars are transparent to magnetic fields and radar frequencies,

e) GFRP and BFRP bars have low electrical and thermal conductivity,

f) Smaller cover concrete can be provided when reinforced with FRP bars,

g) Admixtures to reduce corrosion are not required in the concrete, and

h) FRP bars have high fatigue endurance.

1.2.3. The FRP bars cannot be used as a one-to-one replacement of carbon steel. The properties of FRP bars need to be taken into account during design and construction. Some important differences that necessitate a different approach when using FRP bars include the following:

a) FRP bars exhibit linear elastic behaviour to failure, while carbon steel yields,

b) FRP bars are anisotropic while carbon steel is isotropic material,

c) The modulus of elasticity of FRP bars is different in tension and compression. The modulus of elasticity in tension is significantly lower than that of steel bars. Due to low tensile modulus of elasticity, the structural design using FRP bars is often based on serviceability consideration instead of strength,

d) The creep rupture threshold of FRP bars are generally much lower than that of carbon steel bars,

e) The coefficient of thermal expansion of FRP bars is different in longitudinal and radial directions, and

f) FRP bars have lower endurance to elevated temperature than carbon steel bars.

1.2.4. There are several situations where the beneficial characteristics of FRP bars provide unique advantages for the concrete members, in addition to the construction having lower carbon footprint, when compared to traditional option of carbon steel reinforcement. These include:

a) Concrete members located in highly corrosive environment,

b) Concrete members requiring non-ferrous reinforcement due to electromagnetic considerations,

c) As an alternative in concrete members where use of stainless steel, galvanised or epoxy-coated steel reinforcement bars is otherwise required from corrosion consideration,

d) Temporary concrete members that will get consumed during construction by machinery, such as in tunnelling and mining applications, and

e) Concrete members requiring enhanced thermal insulation.

1.3. Environmental & Sustainability Considerations

1.3.1. Use of carbon steel in reinforced concrete structures is a major source of carbon dioxide emissions. According to the World Steel Association, each tonne of steel production in the world in 2019 resulted in 1.83 tonnes of carbon dioxide emissions. Another report by International Energy Agency in 2020 shows that the steel industry contributed around 7% of the global carbon dioxide emissions. The International Energy Agency report also states that Asia-Pacific countries contribute nearly 80% of the emissions. The use of steel in construction adds further to the carbon dioxide emissions.

1.3.2. The production of FRP bars have significantly less impact on the environment. The high strength and longer durability enable efficient use in new constructions. Recent studies based on Life Cycle Assessment framework has shown that, in both developed and emerging economies, the use of FRP bars in concrete constructions has much lower carbon dioxide emissions when compared to using carbon steel bars.

1.3.3. The use of FRP bars as an alternative to carbon steel bars provides the opportunity to reduce carbon footprint of the road construction projects. A typical construction project using carbon steel has high carbon footprint due to the steel manufacturing process and the construction practices associated with use of carbon steel in the structure. The manufacturing process for FRP bars have lower carbon footprint. The construction practices can also achieve lower carbon footprint due to the lighter weight.

1.4. Durability Considerations

1.4.1. The changes in properties of FRP bars over time are described under its durability characteristics. The strength and stiffness of FRP bars change when exposed to certain environmental factors. The environmental factors inducing changes includes moisture and water, ultraviolet radiation, temperature, alkaline solution, and saline solution.The most important properties of reinforced concrete members that can change over time due to environmental factors are the tensile strength and stiffness of the FRP bars and the bond between FRP bars and surrounding concrete.

1.4.2. Highly alkaline solutions, such as those present in pores in concrete, degrade the tensile strength and stiffness of GFRP bars. Higher temperature and longer exposure time to alkaline environments can further enhance the rate of degradation. The tensile strength of GFRP bars is significantly reduced due to exposure to highly alkali or acidic environments.

1.4.3. It is widely believed that vinyl ester resin and ECR (E Corrosion Resistant) glass, which consist of boron-free modified E-Glass compositions for improved resistance to corrosion by most acids, provide superior protection against the effects of alkali or acidic environments on tensile strength and stiffness and are suitable for reinforced concrete applications.

1.4.4. The bond between GFRP bars and concrete is very important to ensure monolithic behaviour of the reinforced concrete members. The bond of FRP bars is a resin-dominated mechanism and relies on the transfer of shear and transverse forces at the interface between bar and concrete, and between individual fibres within the bar. The bond properties can be conservatively specified for design of concrete structures with FRP bars based on the environmental exposure and considering the durability requirement of the concrete structure.

1.5. Combined Use with Carbon Steel Bars

1.5.1. The concrete structural components may need to simultaneously use both carbon steel and GFRP bars. The transfer of stress between the bar and the surrounding concrete are not the same for carbon steel and GFRP bars. The properties of each bar type may be taken into account when use of both carbon steel and GFRP bars is envisaged.

1.6. GFRP Bar Production in India

1.6.1. GFRP reinforcing bars are not unknown materials in the country. There are a few manufacturers of GFRP bars in different parts of the country. Their products are most commonly between 6 mm diameter to 16 mm diameter. Some of them also produce larger diameters of GFRP bars. The largest diameter of GFRP bars that are currently produced in India is 40 mm. The use of this material in road projects therefore may not require it to be imported from another country.

1.6.2. The GFRP bars manufactured in India typically have their tensile strength in the range of 1000 MPa and maximum elongation of 3% - 5%.

1.6.3. There is currently limited manufacturing capacity in the country. This is expected to be augmented by the existing manufacturers once the demand improves if the product is permitted to be used for road projects. New manufacturers may also set up manufacturing facilities in the future if the demand improves.

2. USES AND RESTRICTIONS

2.1. Permitted Structural & Non-structural Components

2.1.1. Only GFRP bars manufactured using vinyl ester resin systems and glass fibres classified as E-CR or R that meet the requirements of ASTM D578 shall be used in road projects. The bars shall be manufactured using pultrusion, variations of pultrusion, or other suitable processes, subject to the approval of the project authorities.

2.1.2. GFRP reinforcing bars may be used in the following concrete components in road projects (also see Fig. 2.1 and 2.2) subject to complying with the provisions of this Guideline:

(i) Approach Slabs

(ii) Bridge Decks and Bridge Deck overlays, Walkways of Foot Over Bridge, Slab Culverts

(iii) Bridge cum Bandhara, including Deck Slabs and Barriers between Piers

(iv) Concrete Roads including Jointed Plain Concrete Pavement, Continuously-Reinforced Concrete Pavements (CRCP) and Short-Panel Concrete Pavements (both cast-in-situ and precast)

(v) Retaining Walls

(vi) Noise barriers

(vii) Box Culverts

(viii) Crash Barriers & Bridge Parapets

(ix) Pedestrian Parapets and Railings

(x) Bulkheads and Bulkhead Copings

(xi) Mechanically Stabilised Earth Wall Panels and Copings

(xii) Drainage Structures

(xiii) Plain Concrete Components

Fig. 2.1 Bridge Panel Construction Using GFRP Bars (www.tuf-bar.com)

Fig. 2.2 Application of GFRP Bars in Bridge Deck Slab (Ahmed et al. 2014)

2.2. Restrictions

2.2.1. The use of GFRP reinforcing bars will be limited to the concrete components listed in

Section 2.1. GFRP reinforcing bars shall not be used for any other concrete component of road projects.

Table 3.1. List of permitted concrete components with their applicable standards.

Sr. No.	Components	Applicable Standards
1	Approach Slabs	AASHTO (2018), Section 2.10, FDOT (2021), Section 400-20
2	Bridge Decks and Bridge Deck overlays, Walkways of Foot Over Bridge, Slab Culverts	AASHTO (2018), Section 2.10.1, CSA (2006), S6:19, Section 16.7, Section 16.8
3	Bridge cum Bandhara, including Deck Slabs and Barriers between Piers	AASHTO (2018), Section 2.10.1,CSA (2006), S6:19, Section 16.7, Section 16.8
4	Concrete Roads including Jointed Plain Concrete Pavement, Continuously-Reinforced Concrete Pavements (CRCP) and Short-Panel Concrete Pavements (both cast-in-situ and precast)	Transport for NSW (2020)
5	Retaining Walls	FDOT (2021), Sections 548 & 544
6	Noise Barriers	FDOT (2021), Section 534
7	Box Culverts	FDOT (2021), Section 410
8	Crash Barrier & Bridge Parapets	AASHTO (2018), Section 5
9	Pedestrian Parapets and Railings	FDOT (2021), Section 521
10	Bulkheads and Bulkhead Copings	CSA (2006), S6:19, Section 16.9.4
11	Mechanically Stabilised Earth Wall Panels and Copings	FDOT (2021), Section 548
12	Drainage Structures	FDOT (2021), Sections 436, 440, 443 & 446
13	Plain Concrete Components	ACI 440.1R-15 (2015), Section 9.1

3. DESIGN CRITERIA

3.1. Applicable Design Standards

3.1.1. The load calculations shall be based on the relevant IRC Specifications & Guidelines and MoRTH Specifications. The load combinations shall also be based on the IRC Codes & Guidelines and MoRTH Specifications.

3.1.2. The modelling of structure, analysis method and determination of design forces shall also be based on the relevant IRC Specifications & Guidelines and MoRTH Specifications.

3.1.3. The design of concrete components with GFRP reinforcing bars shall be based on the relevant AASHTO and ACI Specifications as given in **Table 3.1**. For flexural members, either compression-controlled or tension-controlled mode of flexure failure may be adopted during design.

3.1.4. The latest edition of the following Standards and Guidelines shall be adopted for the use of GFRP bars in permitted concrete components. The applicable Standards and Guidelines for the design of permitted concrete components is given in **Table 3.1**.

(i) ACI 440R-07 (2007). Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures.

(ii) ACI 440.1 (2015). Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars.

(iii) ACI 440.5 (2018). Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars.

(iv) ACI 440.6M-08 (2017). Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement.

(v) AASHTO (2018). LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete.

(vi) CSA CAN/CSA-S6-06 (2006). Canadian Highway Bridge Design Code.

(vii) FDOT (2021). Florida Department of Transportation Standard Specifications for Road and Bridge Construction.

(viii) FHWA (2005). Design of Continuously Reinforced Concrete Pavements using Glass Fiber Reinforced Polymer Rebars. Rep. No. FHWA-HRT-05-081.

(ix) Transport for NSW (2020). Technical Guide Design of Continuously Reinforced Concrete Pavement using Glass Fibre Reinforced Polymer (GFRP) Bars at Traffic Loop Locations.

3.2. Other Design Standards

3.2.1. Design standards other than those specified in 3.1 shall not be adopted for the design of structures using GFRP bars without prior approval of the project authorities.

4. GFRP BAR MANUFACTURER QA/QC REQUIREMENT

4.1. Standards for Materials and Products

4.1.1. The sizes and loads of GFRP reinforcing bars shall meet the requirements in **Table 4.1**. The measured cross-sectional area, including any bond enhancing surface treatments, shall be determined according to **Table 4.2**.

4.1.2. The minimum guaranteed ultimate tensile strength shall be specified by the manufacturer. The minimum guaranteed ultimate tensile strength shall be less than or equal to the mean minus three standard deviations of the samples tested according to the specified method.

Table 4.1 Geometric and Mechanical Property Requirements (ASTM D7957)

Bar Designation* (mm)	Nominal Dimensions		Limits on Measured Cross-Sectional Area		Minimum Guaranteed Ultimate Tensile Strength (kN)
	Diameter (mm)	Cross-Sectional Area (mm)	Minimum (mm^2)	Maximum (mm^2)	
M6	6.3	32	30	55	27
M10	9.5	71	67	104	59
M13	12.7	129	119	169	96
M16	15.9	199	186	251	130
M19	19.1	284	268	347	182
M22	22.2	387	365	460	241
M25	25.4	510	476	589	297
M29	28.7	645	603	733	365
M32	32.3	819	744	894	437

* M in front of nominal bar diameter in **Table 4.1** refers to Metric unit of diameter adopted by ASTM and is not related to the grade of concrete.

4.1.3. The guaranteed transverse shear strength shall be specified by the manufacturer. The guaranteed transverse shear strength shall be less than or equal to the mean minus three standard deviations of the samples tested according to the specified method.

4.1.4. The guaranteed bond strength shall be specified by the manufacturer. The guaranteed bond strength shall be less than or equal to the mean minus three standard deviations of the samples tested according to the specified method.

4.1.5. Product qualification certification of GFRP reinforcing bars shall be based on tests given in **Table 4.2**. For the determination of the mean and guaranteed properties, at least 24 samples shall be obtained in groups of eight or more from three or more different production lots.

Table 4.2 Property Limits and Test Methods for Product Qualification (ASTM D7957)

Property	Limit	Test Method
Mean Glass Transition Temperature	Mid-point temperature $\geq$ 100 ^{O}C	ASTM E1356
Mean Degree of Cure	$\geq$ 95%	ASTM E2160
Mean Measured Cross-Sectional Area	Table 4.1	ASTM D7205, Subsection 11.2.5.1
Guaranteed Ultimate Tensile Strength	Table 4.1	ASTM D7205
Mean Tensile Modulus of Elasticity	$\geq$ 44,800 MPa	ASTM D7205
Mean Ultimate Tensile Strain	$\geq$ 1.1%	ASTM D7205

Guaranteed Transverse Shear Strength	≥ 131 MPa	ASTM D7617
Guaranteed Bond Strength	≥ 7.6 MPa	ASTM D7913
Mean Moisture Absorption to Saturation	≤ 1.0% to saturation at 50^{O}C	ASTM D570
Mean Alkaline Resistance	≥ 80% of initial mean ultimate tensile force following 90 days at 60 ^{O}C	ASTM D7705

Table 4.3 Property Limits and Test Methods for Quality Control and Certification (ASTM D7957)

Property	Limit	Test Method
Fibre Mass Content	≥ 70%	ASTM D2584
Glass Transition Temperature	Mid-point temperature ≥ 100 ^{O}C	ASTM E1356
Degree of Cure	≥ 95%	ASTM E2160
Measured Cross-Sectional Area	Table 4.1	ASTM D7205, Subsection 11.2.5.1
Ultimate Tensile Strength	Table 4.1	ASTM D7205
Tensile Modulus of Elasticity	≥ 44.800 GPa	ASTM D7205
Ultimate Tensile Strain	≥ 1.1%	ASTM D7205
Moisture Absorption – Short Term	≤ 0.25% in 24 hours at 50^{O}C	ASTM D570
Moisture Absorption – Long Term	≤ 1.0% to full saturation at 50^{O}C	ASTM D570

4.1.6. Product quality control certification shall be based on random tests of properties. For the determination of each of the property limits, five random samples shall be obtained from each production lot. Each individual sample shall satisfy the property limits given in **Table 4.3**.

4.2. Standards for Test Methods

The latest revision of the test methods mentioned in **Annexure-1** shall be used to determine the properties of GFRP bars.

4.3. Format of Product Specification Sheet

4.3.1. The standard technical data sheets for GFRP bars shall be provided by the manufacturer.

4.3.2. The standard technical data sheet shall include the information given in **Table 4.4**. Separate data sheets shall be provided for each diameter of GFRP bar supplied by the manufacturer. Additional information to this may be provided by the manufacturer.

Table 4.4 Format for Technical Data Sheet

Bar Designation Mxx				
A. Property	**Specification Test Method**		**Value**	
Type of Fibre				
Type of Resin				
Production Process				
Bar Geometry				
Surface Treatment				
Coefficient of Longitudinal Thermal Expansion				
Coefficient of Transverse Thermal Expansion				
Colour				
B. Property	**Test Method**	**Unit**	**Value**	
Mean Ultimate Tensile Strength	ASTM D7205	MPa		
Standard Deviation of Ultimate Tensile Strength		MPa		
Number of Samples for Standard Deviation		Count		
Mean Transverse Shear Strength		MPa		
Standard Deviation of Transverse Shear Strength		MPa		
Number of Samples for Standard Deviation		Count		
Mean Bond Strength		MPa		
Standard Deviation of Bond Strength		MPa		
Number of Samples for Standard Deviation		Count		
C. Property	**Test Method**	**Unit**	**Value**	**Acceptable (Y/N)**
Nominal Cross Section Area	ASTM D792	mm^2		
Unit Weight/Length	ASTM D792	kg/m		
Nominal Ultimate Tensile Force	ASTM D7205	kN		
Nominal Ultimate Tensile Strength	ASTM D7205	MPa		
Nominal Ultimate Tensile Strain	ASTM D7205	%		
Nominal Ultimate Transverse Shear Strength	ASTM D7617	MPa		
Nominal Tensile Modulus of Elasticity	ASTM D7205	MPa		
Nominal Bond Strength	ASTM D7913	MPa		
D. Property	**Test Method**	**Unit**	**Value**	**Acceptable (Y/N)**
Fibre Mass Content	ASTM D2584	%		
Mean Glass Transition Temperature	ASTM E1356	^{O}C		
Degree of Cure	ASTM E2160	%		
Moisture Absorption in 24 hours at 50^{O}C	ASTM D570	%		
Moisture Absorption to Saturation at 50^{O}C	ASTM D570	%		
Total Enthalpy of Polymerisation	ASTM E2160	J/g		
Alkaline Resistance: Tensile Load Retention	ASTM D7705-A	%		

5. MORTH SPECIFICATIONS FOR USE

5.1. Permitted Constituent Materials

5.1.1. Only GFRP bars manufactured using vinyl ester resin systems and glass fibres classified as E-CR or R that meet the requirements of ASTM D578 shall be used. The bars shall be manufactured using pultrusion, variations of pultrusion, or other suitable processes, subject to the approval of the project authorities.

5.2. Properties of Straight GFRP Bars

5.2.1. The physical and mechanical properties of straight GFRP bars shall meet the requirements given in **Table 5.1**.

Table 5.1 Physical and Mechanical Property Requirements for Straight GFRP Bars

Property	Test Method	Requirement	Specimens per Lot
Fibre Mass Fraction	ASTM D2584 or ASTM D3171	≥ 70%	5
Short-Term Moisture Absorption	ASTM D570	≤ 0.25%	5
Long-Term Moisture Absorption	ASTM D570	≤ 1.0%	5
Glass Transition Temperature (Tg)	ASTM E1356 (DSC, T_m), ASTM D3418 (DSC, T_{mg})	≥ 100 °C	3
Total Enthalpy of Polymerisation	ASTM E2160	Average value of three replicates for each resin system	--
Degree of Cure	ASTM D2160	≥ 95% Total polymerisation enthalpy	3
Measured Cross Section Area	ASTM D7205	Within specified range as per diameter	10
Guaranteed Tensile Strength	ASTM D7205	Within specified range as per diameter	10
Tensile Modulus	ASTM D7205	≥ 44.8 GPa	10
Alkali Resistance with Load	ASTM D7705; Procedure B, set sustained load to 30% of Minimum Guaranteed Strength, 3 months test duration, followed by tensile strength as per ASTM D7205	≥ 70% Tensile strength retention	5
Transverse Shear Strength	ASTM D7617	≥ 152 MPa	5
Bond Strength to Concrete, Block Pull-Out	ACI 440.3R, Method B.3 or ASTM D7913	≥ 7.6 MPa	5

5.3. Properties of Bent GFRP Bars

5.3.1. For all bars produced by bending straight solid GFRP bars before fully curing the resin, the minimum inside bend radius shall be at least three times the nominal diameters for bar sizes M6 through M25; and four times the nominal diameters for sizes M29 and M32.

5.3.2. The straight portion of a bent GFRP reinforcing bar shall be extracted with sufficient length for tensile testing according to **Table 5.2**. When the bent shape does not allow for the tensile testing of one of its straight portions, test specimens produced at the same time during the same production lot shall be used.

Table 5.2 Physical and Mechanical Property Requirements for Bent GFRP Bars

Property	Test Method	Requirement	Specimens per Lot
Fibre Mass Fraction	ASTM D2584 or ASTM D3171	≥ 70%	5
Short-Term Moisture Absorption – Bent Portion	ASTM D570	≤ 0.25%	5
Long-Term Moisture Absorption	ASTM D570	≤ 1.0%	5
Glass Transition Temperature (T_g)	ASTM E1356 (DSC, T_m), ASTM D3418 (DSC, T_{mg})	≥ 100 ^{O}C	3
Degree of Cure – Bent Portion	ASTM D2160	≥ 95% Total polymerisation enthalpy	3
Measured Cross Section Area – Straight Portion	ASTM D7205	Within specified range as per diameter	5
Guaranteed Tensile Strength – Straight Portion	ASTM D7205	Within specified range as per diameter	5
Tensile Modulus – Straight Portion	ASTM D7205	≥ 44.8 GPa	5
Alkali Resistance with Load – Straight Portion	ASTM D7705; Procedure B, set sustained load to 30% of Minimum Guaranteed Strength, 3 months test duration, followed by tensile strength as per ASTM D7205	≥ 80% Tensile strength retention	5
Strength of 90^{O} Bends	ACI 440.3, Method B.5 or ASTM D7914	> 60% Guaranteed tensile strength	5
Transverse Shear Strength – Straight Portion	ASTM D7617	≥ 152 MPa	5

6. CONSTRUCTION PRACTICE & QUALITY CONTROL

6.1. On-Site Practices : Protection of Materials

6.1.1. GFRP reinforcement bars shall be stored above the surface of the ground/floor, in boxes or upon platforms, skids, or other supports, and protected from any kind of damage. The GFRP bars stored at locations which may experience ambient temperature of more than 45ºC, or direct exposure to sunlight at any temperature, should be protected with opaque sheet covers ensuring that their damage due to such conditions is avoided.

6.1.2. No special protective measures are required in cold weather, other than those given in 6.1.1.

6.1.3. It shall be ensured that the GFRP reinforcement is free from dirt, paint, oil, and other foreign material prior to incorporation into the work. GFRP bars shall be protected from exposure to incidental cement paste contamination by suitable means such as wrapping the bars with approved materials when they are not part of the member being concreted.

6.1.4. After placing the GFRP reinforcing bars on shuttering/formwork, the concreting shall be carried out expeditiously. In case of delay in concreting, care shall be taken to avoid exposing the GFRP bars to high temperature and/or direct exposure to sunlight. Protection measures as specified in 6.1.1 shall be adopted in such cases.

6.1.5. Electrical grounding of GFRP bars is prohibited.

6.2. On-Site Practices : Bending and Cutting

6.2.1. No field fabrication of GFRP reinforcing bars is permitted except tying and field cutting as per ACI 440.5.

6.2.2. Bending or straightening, coupling, thermal cut, or shear cut of GFRP reinforcing bars shall not be permitted.

Fig. 6.1 Bending of GFRP bars (http://www.pulwellpultrusions.com)

6.3. On-Site Practices :Tying

6.3.1. GFRP reinforcing bars shall be tied using self-locking plastic straps; or plastic coated pliable steel wire that readily bends and twists without breaking and that provides a tie of sufficient strength to hold the GFRP reinforcing in its proper position.

6.3.2. No other method of tying of GFRP bars shall be permitted.

6.4. On-Site Practices : Splicing

6.4.1. Splicing shall only be permitted with the approval of the Engineer-in-Charge.

6.4.2. Where splices are permitted, the bars shall be rigidly clamped or tied in a manner meeting the Engineer’s approval. Only lap splices shall be used and lap splice length shall be shown on the drawing.

6.4.3. Use of mechanical couplers is not permitted for GFRP reinforcing bars.

6.5. On-Site Practices : Metal Bar Supports

6.5.1. The use of metal bar supports or metal chairs to support GFRP reinforcing bars is prohibited. Only GFRP chairs shall be permitted.

6.5.2. In case of use of mixed reinforcement type (both GFRP bars and carbon steel bars) in the same member, each type of bar, if requiring support, shall be separately provided with suitable chairs.

6.6. On-Site Practices : Substitution of Reinforcement Bars

6.6.1. Substitution of GFRP bars of specified diameter with bars of other diameters shall not be permitted.

7. RESEARCH & DEVELOPMENT NEEDS

7.1. Life Cycle Assessment

7.1.1. The initial cost of the GFRP bars is comparatively higher than carbon steel reinforcement bars. However, this higher initial cost may be partially offset by a reduction in the concrete cover and the elimination of corrosion inhibiting admixtures typically used for steel reinforced concrete construction in extremely aggressive environments. A longer service life of the concrete component may also be expected if GFRP reinforcing bars is used by reducing the need for repairs. In concrete structures that require cathodic protection or sacrificial anodes, the same may be eliminated by using GFRP reinforcing bars thereby reducing the protection cost.

7.1.2. Due to the very limited inelastic capacity of GFRP reinforcing bars, and considering the limited experience with the use of this material in structures at present, the international design codes recommend to significantly reduce the allowable stress capacity that can be considered when designing with GFRP reinforcing bars. The inclusion of stringent stress reduction factors often makes the design uneconomical from initial cost considerations. Therefore, the damage tolerant and economical design of GFRP reinforced concrete structures will require further research to evaluate life-cycle performance of GFRP reinforced concrete members when subject to various static and dynamic loads.

7.1.3. The GFRP bars may be used as the only reinforcement, or may be combined with carbon steel bars. There is a need to take up pilot projects with only GFRP bars and used in combination with carbon steel bars to evaluate the structural durability and long-term performance of such structures.

7.2. Indian Standards and Test Data for GFRP Bars

7.2.1. While GFRP bars are being used as a replacement of carbon steel bars in many applications spread across several countries, in India the application of GFRP is largely limited for external strengthening and retrofitting purpose. The Bureau of Indian Standards (BIS) has published IS 15988 : 2013 'Seismic evaluation and strengthening of existing reinforced concrete buildings — Guidelines' to provide guidelines for shear strengthening of RCC beam using FRP sheets.

7.2.2. Indian Standards for test methods and specification for GFRP reinforcing bars are under preparation. Indian Standard for new construction with GFRP reinforcing bars also need to be prepared. The BIS should be also requested to expeditiously issue standards for usage of GFRP reinforcing bars in concrete structures.

7.2.3. There is absence of reliable information regarding the characteristics of GFRP bars that are supplied in India from local or international manufacturers. Therefore, it is of utmost importance that the manufactures seek expertise of research Institutions and laboratories in India so that sufficient test data on the properties of available GFRP bars are generated. This information would be also useful to assess the quality of the product, and if required, provide the opportunity to further improve manufacturing process.

7.3. Performance Monitoring

7.3.1. Extensive laboratory tests on columns/beams/slabs/girders cast with various grades of concrete reinforced with GFRP bars as replacement of steel bars need to be conducted under static, dynamic and fatigue loads for targeted design strength and serviceability criteria. The performance of the specimens reinforced with GFRP bars needs to be critically compared with the performance of specimens with carbon steel bars for the same design mixes to assess the effectiveness of replacement of carbon steel bars with GFRP bars.

7.3.2. The road structures where GFRP bars are used should be closely monitored to assess its performance. The monitoring should include visual assessment as well as instrumented measurement of various parameters of interest. Both short-term and long-term monitoring of performance should be carried out. The involvement of academic or research institutions should be encouraged. Load tests should be also carried out to validate the performance specifications. The R&D studies should also review international practices and develop indigenous acceptance criteria relevant to Indian specifications.

7.4. Standard Design Examples and Drawings

7.4.1. Since GFRP reinforcing bars are a new class of construction material, it is important to develop a large number of design examples. This activity can be carried out by academic or research institutions in partnership with MoRTH or NHAI. Where required, the private sector can also contribute to this activity.

7.4.2. Design examples and drawings should also be developed for the use of GFRP bars for non-structural applications in road projects, such as Earth Wall Panels, Bulkheads and drainage structures.

7.4.3. **Annexure-2** presents the example calculations from AASHTO Guidelines for design of reinforced concrete structures using GFRP bars. The examples illustrate the detailed steps required during the design of structures using GFRP bars.

7.5. Other Usesof GFRP Bars in NH Projects

It is not recommended to use GFRP reinforcing bars for road project work applications other than those permitted herein.

7.6. Comprehensive R&D through Institutionalized Approach

7.6.1. Widespread use of GFRP bars in projects in India can accrue several advantages as mentioned in the Guidelines. Greater use in future will be greatly facilitated if India possesses expertise in all aspects of the development and utilisation of this material. This requires that funding for research and development on all aspects of GFRP bar technology should be taken up by the Ministry of Roads Transport and Highways (MoRTH) through an institutionalised approach. The MoRTH may develop a suitable institutional mechanism for managing these research and development activities.

7.6.2. Particular attention should be paid to encourage the relatively more fundamental research and development on the GFRP bars. Research projects with Technology Readiness Level (TRL) up to 5 should be strongly encouraged in academic and research institutions in the country through appropriate funding. It is expected that such research and development projects will help to develop a strong base of intellectual property in this technology in the country. This will be essential for continuous improvements in the technology and materials with time after it has been introduced in projects in India.

7.6.3. Research and development should also be taken up on development of innovative technologies, equipment and products to use GFRP bars in the road sector. Adoption of trial stretches where new technologies can be taken up. Other forms of field-testing are also encouraged. These projects may be solely funded by MoRTH and other Indian funding agencies, or may be jointly taken up in partnership with the industry.

7.6.4. There is also a need to take up research and development to evaluate the applicability of international standards in the Indian context and for harmonisation of their specifications with the Indian standards.These projects may be solely funded by MoRTH and other Indian funding agencies, or may be jointly taken up in partnership with the industry.

ANNEXURE-1

STANDARDS ON GFRP REINFORCING BARS

1. AASHTO (2018), "LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete," American Association of State Highway and Transportation Officials.
2. ACI 440R-07 (2007), "Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures," ACI Committee 440.
3. ACI 440.1-15 (2015), "Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars," ACI Committee 440.
4. ACI 440.3R-12 (2012), "Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures," ACI Committee 440.
5. ACI 440.5-18 (2018), "Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars,"ACI Committee 440.
6. ACI 440.6M-08 (2017), "Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement", ACI Committee 440.
7. ASTM D570-98 (2018), "Standard Test Method for Water Absorption of Plastics," ASTM International.
8. ASTM D578/D578M-18 (2018), "Standard Specification for Glass Fiber Strands," ASTM International.
9. ASTM D792-20 (2020), "Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement," ASTM International.
10. ASTM D2584-18 (2018), "Standard Test Method for Ignition Loss of Cured Reinforced Resins," ASTM International.
11. ASTM D3171-15 (2015), "Standard Test Methods for Constituent Content of Composite Materials," ASTM International.
12. ASTM D7205/D7205M-21 (2021), "Standard Test Methods for Tensile Properties of Fiber-Reinforced Polymer Matrix Composite Bars," ASTM International.
13. ASTM D7617/D7617M-11 (2017), "Standard Test Method for Transverse Shear Strength of Fiber-reinforced Polymer Matrix Composite Bars," ASTM International.
14. ASTM D7705/D7705M-12 (2019), "Standard Test Method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction," ASTM International.

15. ASTM D7913/D7913M-14 (2020), "Standard Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing" ASTM International.

16. ASTM D7957/D7957M-17 (2017), "Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement" ASTM International.

17. ASTM E1356-08 (2014), "Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry." ASTM International.

18. ASTM E2160–04 (2018), "Standard Test Method for Heat of Reaction of Thermally Reactive Materials by Differential Scanning Calorimetry." ASTM International.

19. CSA CAN/CSA-S6-06 (2006), "Canadian Highway Bridge Design Code." Standards Council of Canada.

20. FHWA-HRT-05-081 (2005), "Design of Continuously Reinforced Concrete Pavements using Glass Fiber Reinforced Polymer Rebars." Federal Highway Administration, US Department of Transportation.

21. FDOT (2021), "Florida Department of Transportation Standard Specifications for Road and Bridge Construction." Florida Department of Transportation.

22. Transport for NSW (2020), "Technical Guide Design of Continuously Reinforced Concrete Pavement using Glass Fibre Reinforced Polymer (GFRP) Bars at Traffic Loop Locations,"Document Number P-G-008, New South Wales Government, Australia.

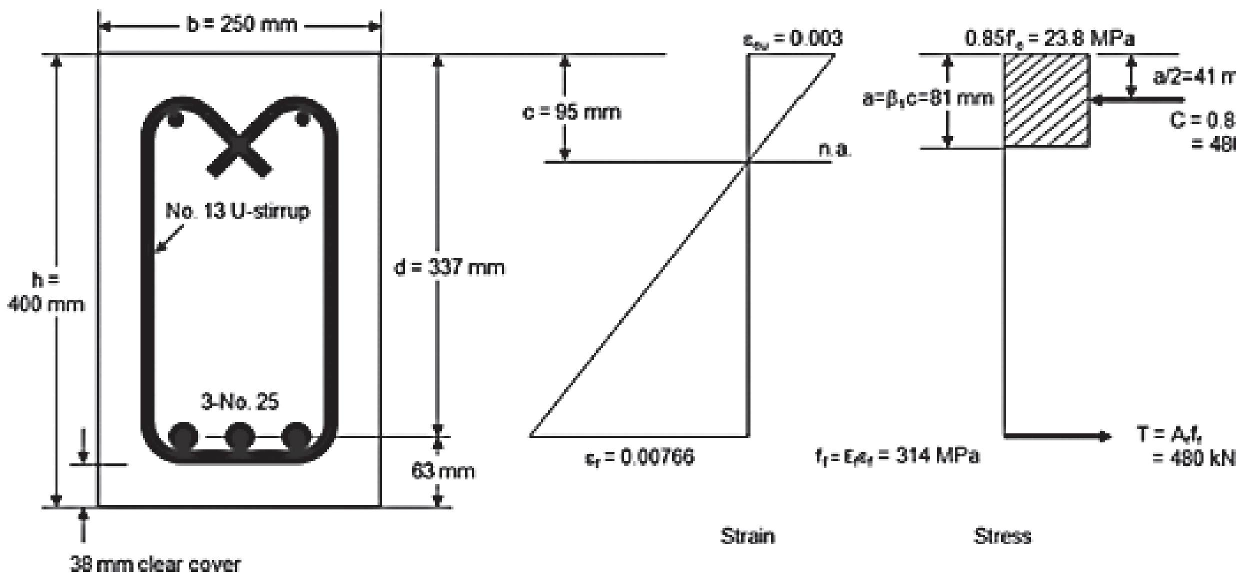
ANNEXURE-2

STANDARD DESIGN EXAMPLES AND DRAWINGS (FROM ACI440.1R-15)

(Symbols and Notations used are same as that in ACI 440.1R-15)

Example 1: Flexural (moment) strength using equivalent rectangular concrete stress distribution (compression-controlled section)

For the beam section shown, calculate moment strength based on static equilibrium using the equivalent rectangular concrete stress distribution as shown in Fig. 7.2 of ACI 440.1R-15. Assume f_c' = 28 MPa, f_{fu}* = 550 MPa, and E_f = 41,000 MPa. Assume interior exposure conditions and neglect compression reinforcement.



Calculations and Discussions	Reference
No. 25 bar properties:	440.06, Table 7.1
d_b = 25.4 mm	
$A_{f,bar}$ = 510 mm^2	
Design material properties:	
C_E = 0.8	440.1R, Table 6.2
$f_{fu} = C_E f_{fu}$* = (0.8)(550) = 440 MPa	440.1R, Eq. 6.2a

1. Determine the strength reduction factor

d = 400 – 38 – 12.7 – (25.4/2) = 337 mm

A_f = (3) (510) =1530 mm^2

$$\rho_f = \frac{A_f}{bd} = \frac{1530}{(250)(337)} = 0.01816$$ 440.1R, Eq. (7.2.1a)

$$\rho_{fb} = 0.85\beta_1 \frac{f_c'}{f_{fu}} \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}}$$ 440.1R, Eq. (7.2.1b)

$E_f \varepsilon_{cu}$ = (41,000) (0.003) =123 MPa

$$\rho_{fb} = 0.85(0.85)\frac{(28)}{(440)}\frac{(123)}{(123+440)} = 0.01004$$

$$\frac{\rho_f}{\rho_{fb}} = \frac{0.01816}{0.01004} = 1.81$$

Because $\rho_f \geq 1.4\rho_{fb}$, the section is compression -controlled. 440.1R, Eq. (7.2.3)

ϕ=0.65

2. Determine stress in tensile reinforcement at ultimate conditions

$$f_f = \sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85\beta_1 f_c'}{\rho_f} E_f \varepsilon_{cu}} - 0.5 E_f \varepsilon_{cu} \leq f_{fu}$$ 440.1R, Eq. (7.2.2d)

$$f_f = \sqrt{\frac{(123)^2}{4} + \frac{0.85(0.85)(28)}{(0.01814)}(123)} - 0.5(123) \leq 440$$

f_f= 314 MP$_a$

3. Determine nominal flexural strength M_n and design flexural strength ϕM_n

$$a = \frac{A_f f_f}{0.85 f_c' b} = \frac{(1530)(314)}{0.85(28)(250)} = 81 \text{ mm}$$ 440.1R, Eq.(7.2.2b)

$$M_n = A_f f_f \left(d - \frac{a}{2}\right) = (1530)(314)\left(337 - \frac{81}{2}\right)$$ 440.1R, Eq. (7.2.2a)

= 142.4×10^6 N$_{mm}$ = 142.4 kN$_m$

Alternatively, compute M_n directly:

$$M_n = \rho_f f_f \left(1 - 0.59\frac{\rho_f f_f}{f_c'}\right) bd^2$$ 440.1R, Eq. (7.2.2e)

$$= (0.01814)(314)\left(1 - 0.59\frac{(0.01814)(314)}{28}\right)(250)(337)^2$$

$=142.3\times10^6$ N_{mm} = 142.3 kN_m

ϕM_n =(0.65)(142.3) = 92.5 kN_m

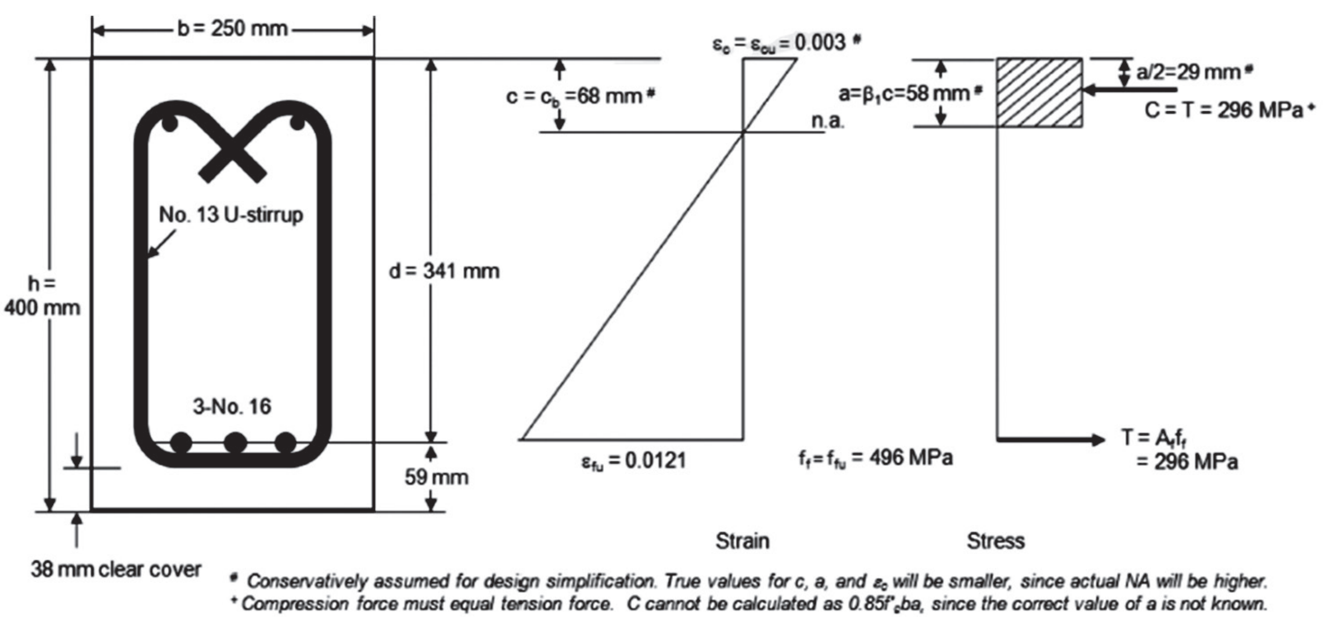
4. Minimum reinforcement

The minimum reinforcement provisions do not apply because the section is not tension-controlled. 440.1R, Sec. 7.2.4

Note: While the general procedure and principles used in this example are applicable for an FRP-reinforced beam of any cross-sectional shape, the specific equations used in this example are restricted to singly-reinforced rectangular cross sections (or flanged sections that exhibit rectangular section behaviour) with reinforcement in a single layer.

Example 2: Flexural (moment) strength using equivalent rectangular concrete stress distribution (tension-controlled section)

For the beam section shown, calculate moment strength based on static equilibrium using the equivalent rectangular concrete stress distribution as shown in Fig. 7.2 of ACI 440.1R-15. Assume f_c = 28 MPa, f_{fu}* = 620 MPa, and E_f= 41,000 MPa. Assume interior exposure conditions and neglect compression reinforcement.



Calculations and Discussions **Reference**

No. 16 bar properties: 440.06, Table 7.1

d_b = 15.9 mm

$A_{f\ bar}$ =199 mm^2

Design material properties:

C_E = 0.8 440.1R, Table 6.2

$f_{fu} = C_E f_{fu}$ * = (0.8)(620) = 496 MPa 440.1R, Eq. 6.2a

1. Determine the strength reduction factor

d = 400-38-12.7-(15.9/2) = 341 mm

A_f= (3)(199 mm^2) = 597 mm^2

$$\rho_f = \frac{A_f}{bd} = \frac{597}{(250)(341)} = 0.00700$$

440.1R, Eq. (7.2.1a)

$$\rho_{fb} = 0.85\beta_1 \frac{f'_c}{f_{fu}} \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}}$$

440.1R, Eq. (7.2.1b)

$$E_f \varepsilon_{cu} = (41{,}000)(0.003) = 123 \text{ MPa}$$

$$\rho_{fb} = 0.85(0.85) \frac{(28)}{(496)} \frac{(123)}{(123 + 496)} = 0.00810$$

$$E_f \varepsilon_{cu} = (41{,}000)(0.003) = 123 \text{ MPa}$$

$$\rho_{fb} = 0.85(0.85) \frac{(28)}{(496)} \frac{(123)}{(123 + 496)} = 0.00810$$

$$\frac{\rho_f}{\rho_{fb}} = \frac{0.00700}{0.00810} = 0.86$$

Because $\rho_f \leq \rho_{fb}$, the section is tension-controlled and ϕ = 0.55. 440.1R, Eq. (7.2.3)

2. Determine stress in tensile reinforcement at ultimate conditions

Because section is tension-controlled, $f_f = f_{fu}$=496 MPa

3. Determine nominal flexural strength M_n and design flexural strength ϕ M_n

$$c_b = \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fu}}\right) d = \left(\frac{0.003}{0.003 + \frac{496}{41{,}000}}\right)(341) = 68 \text{ mm}$$

440.1R, Eq. (7.2.2h)

$$M_n = A_f f_{fu}\left(d - \frac{\beta_1 c_b}{2}\right)$$

$$= (597)(496)\left(341 - \frac{(0.85)(68)}{2}\right)$$

$$= 92.4 \times 10^6 \text{ Nmm} = 92.4 \text{ kNm}$$

440.1R, Eq. (7.2.2g)

$$\phi\, M_n = (0.55)(92.4) = 50.8 \text{ kNm}$$

4. Minimum reinforcement

The minimum reinforcement provisions apply since the section is tension-controlled

$$A_{f,\min} = \frac{0.41\sqrt{f_c'}}{f_{fu}} b_w d \geq \frac{2.3}{f_{fu}} b_w d$$ 440.1R, Sec. 7.2.4

$$A_{f,\min} = \frac{0.41\sqrt{f_c'}}{f_{fu}} b_w d \geq \frac{2.3}{f_{fu}} b_w d$$ 440.1R, Eq. (7.2.4)

$$A_{f,\min} = \frac{0.41\sqrt{28}}{496}(250)(341) \geq \frac{2.3}{496}(250)(341)$$

$$A_{f,\min} = 395 \text{ mm}^2$$

$$A_f \text{ (provided)} = 597 \text{ mm}^2 > A_{f,\min} = 395 \text{ mm}^2 \text{ (OK)}$$

Note: While the general procedure and principles used in this example are applicable for an FRP-reinforced beam of any cross-sectional shape, the specific equations used in this example are restricted to singly-reinforced rectangular cross sections (or flanged sections that exhibit rectangular section behaviour) with reinforcement in a single layer.

Example 3: Design of one-way solid slab

Determine the required thickness and reinforcement for a one-way slab continuous over three or more equal spans. Center-to-center span ℓ = 5.8 m and clear span ℓ_n = 5.5 m. Assume interior exposure conditions. Assume f_c' = 28 MPa, f_{fu}^* = 650 MPa, and E_f = 41,000 MPa. Service loads: w_D= slab self-weight (no superimposed dead load), w_L = 24 kN/m².

Calculations and Discussions | **Reference**

Design material properties:

C_E = 0.8 — 440.1R, Table 6.2

$f_{fu} = C_E f_{fu}^* = (0.8)(650) = 520$ MPa — 440.1R, Eq. 6.2a

1. Determine required slab thickness

Based on minimum thickness table, consider estimated depth.

End span will control thickness:

$$h \approx \frac{\ell}{17} = \frac{(5.8)(1000)}{17} = 341 \text{ mm}$$ 440.1R, Table 7.3.2.1

Table 7.3.2.1 is only intended to provide guidance for initial design, therefore, assume h = 300 mm.

2. Compute the design moments using approximate moment analysis permitted by ACI 318-11

Sec. 8.3.3. Design will be based on the end span because it will yield the highest moments. Assume the end of the end span is integral with the support.

300 mm slab weighs [(300)/(1000)](24)=7.2 kN/m^2 318-11, Eq. (9-2)

Factored load q_u=1.2 (7.2)+1.6 (2.4)=12.5 kN/m^2 318-11, Sec. 8.3.3

Positive moment at discontinuous end integral with support:

$$+M_u = \frac{q_u \ell_n^2}{14} = \frac{(12.5)(5.5)^2}{14} = 27.0\ \text{kN}-\text{m/m}$$

Negative moment at exterior face of first interior support:

$$-M_u = \frac{q_u \ell_n^2}{10} = \frac{(12.5)(5.5)^2}{10} = 37.8\ \text{kN}-\text{m/m}$$ 318-11, Sec. 8.3.3

3. Determine required reinforcement and select bars

Assume section is tension-controlled. For this case, 440.5 -08, Table 3.1

$f_f = f_{fu}$ = 520 MPa and ϕ = 0.55.

For interior exposure, clear cover is 19 mm.

Assume No. 16 bars for flexural reinforcement. No. 16 bar Diameter: d_b = 15.9 mm

$$d = 300 - \left[(19) + \frac{(15.9)}{2}\right] = 273\ \text{mm}$$ 440.6-08, Table 7.1

$$c_b = \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fu}}\right) d = \left(\frac{0.003}{0.003 + \frac{520}{41,000}}\right)(273) = 52\ \text{mm}$$ 440.1R, Eq. (7.2.2h)

Use moment strength equation to solve for area of reinforcement.

Consider –M because it governs.

$$M_u = \phi M_{n,\text{ reqd}} = \phi A_{f,\text{ reqd}}\, f_{fu}\left(d - \frac{\beta_1 c_b}{2}\right)$$ 440.1R, Eq. (7.2.2g)

$$A_{f,\text{ reqd}} = \frac{M_u}{\phi f_u\left(d - \frac{\beta_1 c_b}{2}\right)}$$

$$= \frac{(37.8)(10^6)}{(0.55)(520)\left(273 - \frac{(0.85)(52)}{2}\right)}$$

$$= 527\ \text{mm}^2/\text{m}$$

Note that this requirement is well less than the minimum reinforcement, as computed in the following.

$$\rho_{f,ts} = 0.0014 \leq 0.0018 \times \frac{414}{f_u}\frac{E_s}{E_f} \leq 0.0036$$ 440.1R, Eq. (9.1)

$$\rho_{f.ts} = 0.0014 \leq 0.0018 \times \frac{414}{520}\frac{200{,}000}{41{,}000} \leq 0.0036$$

$$\rho_{f'ts} = 0.0014 \leq 0.0070 \leq 0.0036, \text{ so } \rho_{fts} = 0.0036$$

$$A_{f,\min} = \rho_{f,\min}\, bh = (0.0036)(1000)(300) = \frac{1080 \text{ mm}^2}{\text{m}}$$

Select No. 16 at 180 mm spacing (A_f= 1106 mm^2/m)

Verify assumption of tension-controlled behavior:

$$\rho_{fb} = 0.85\beta_1 \frac{f_c'}{f_{\text{fu}}}\frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{\text{fu}}}$$ 440.1R, Eq. (7.2.1b)

$$E_f \epsilon_{cu} = (41{,}000)(0.003) = 123 \text{ MPa}$$

$$\rho_{fb} = 0.85(0.85)\frac{(28)}{(520)}\frac{(123)}{(123 + 520)} = 0.00744$$

$$\rho_f = \frac{A_f}{bd} = \frac{1106}{(1000)(273)} = 0.00405$$ 440.1R, Eq. (7.2.1a)

$$\frac{\rho_f}{\rho_{fb}} = \frac{0.00405}{0.00744} = 0.54 \quad \text{(OK)}$$

The slab may be designed to be 300 mm thick with No. 16 at 180 mm for –M.

By observation, the same minimum reinforcement will be required for +M.

In addition to flexural strength, the slab should be examined for shear and serviceability criteria of crack control, deflection and creep rupture stress limits.

Further calculations show that this slab will be uncracked at service by a significant margin, and is even uncracked at ultimate conditions. The slab will work, but will be highly inefficient. Therefore, consider a more efficient slab design that is selected to be cracked at service.

4. Redesign slab to be cracked at service loads

When cracked, FRP-reinforced concrete slabs are seldom governed by flexural strength. Whereas a slab designed for flexural strength alone would have a ratio of service level moment to nominal moment strength(M_{serv}/M_n) of approximately 0.40 to 0.45, depending on the ratio of dead-to-live load, most FRP-reinforced slabs are governed by serviceability requirements and will exhibit ratios closer to 0.20 to 0.25. As a design approximation, design for a flexural strength corresponding to approximately twice the actual factored moment (2.0 M_u).

Select a reinforcement ratio corresponding to a compression-controlled section, as this will promote the use of enough reinforcement to control cracking and reduce deflections.

Design for 2.0 M_u and as a starting point, assume $\rho_f = 1.5\rho_{fb}$

$\rho_f = 1.5\rho_{fb} = 1.5(0.00744) = 0.01116$

Calculate the stress in the tensile reinforcement (f_f) at ultimate conditions for the assumed value of ρ_f.

$$f_f = \sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85\beta_1 f_c'}{\rho_f} E_f \varepsilon_{cu}} - 0.5 E_f \varepsilon_{cu} \leq f_{fu}$$ 440.1R, Eq. (7.2.2d)

$$f_f = \sqrt{\frac{(123)^2}{4} + \frac{0.85(0.85)(28)}{(0.01116)}(123)} - 0.5(123) \leq 520$$

$f_f = 415$ MPa

Estimate dead load based on an assumed 200 mm slab thickness:

200 mm slab weighs [(200)/(1000)](24) = 4.8 kN/m^2

Factored load $q_u = 1.2\ (4.8)+1.6(2.4) = 9.6$ kN/m^2 318-11, Eq. (9-2)

Negative moment at exterior face of first interior support (governs):

$$-M_u = \frac{q_u \ell_n^2}{10} = \frac{(9.6)(5.5)^2}{10} = 29.0 \text{ kN} - \text{m/m}$$ 318-11, Sec. 8.3.3

Use the moment capacity equation to determine a depth for the slab.

$$M_u = \phi M_n = \phi \rho_f f_f \left(1 - 0.59 \frac{\rho_f f_f}{f_c'}\right) b d^2$$ 440.1R, Eq. (7.2.2e)

$$2(29.0)(10^6) = (0.65)(0.01116)(415)\left(1 - 0.59 \frac{(0.01116)(415)}{(28)}\right)(1000) d^2$$

d =146 mm

Assume No. 19 bars for flexural reinforcement.

$$h = (146) + (19) + \frac{(19.1)}{2} = 175 \text{ mm}$$

Round up to be conservative (180 mm thick slab [h=180mm]).

Correct dead load for 180 mm thickness:

180 mm slab weighs [(180)/(1000)](24) = 4.3 kN/m^2

Factored load q_u = 1.2(4.3)+1.6(2.4) = 9.0 kN/m^2 318-11, Eq. (9-2)

Select reinforcement for the slab. Assume the same reinforcement for -M and +M.

$A_f = \rho_f bd$=(0.01116)(1000)(146)=1629 mm^2/m 440.1R, Eq. (7.2.1a)

Select No. 19 bars at 150 mm spacing (A_f= 1890 mm^2/m).

5. Select temperature and shrinkage reinforcement for transverse direction

$$\rho_{f,ts} = 0.0014 \leq 0.0018 \times \frac{414}{f_{fu}} \frac{E_s}{E_f} \leq 0.0036$$ 440.1R, Eq. (9.1)

$$\rho_{f,ts} = 0.0014 \leq 0.0018 \times \frac{414}{520} \frac{200{,}000}{41{,}000} \leq 0.0036$$

$$\rho_{f,ts} = 0.0014 \leq 0.0070 \leq 0.0036, \text{ so } \rho_{f,ts} = 0.0036$$

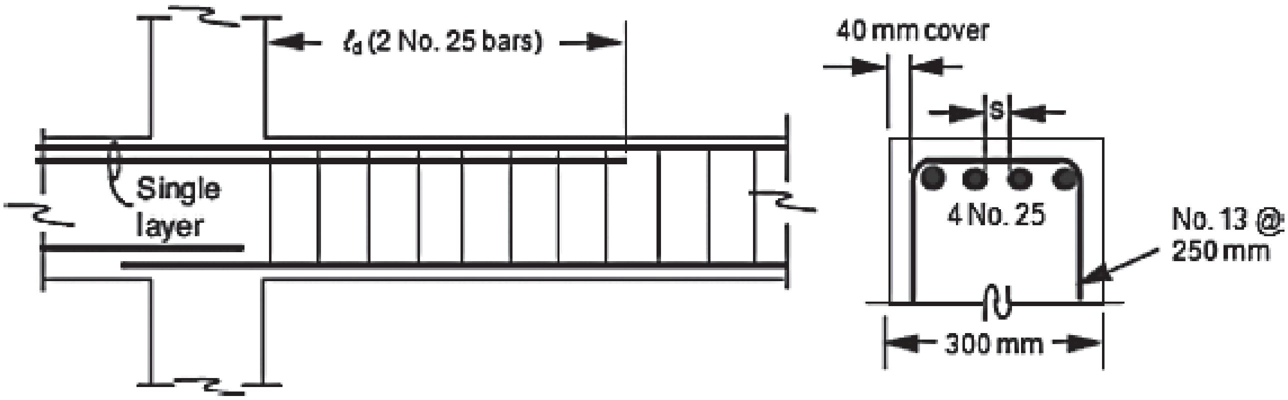
$$A_{f,ts} = \rho_{f,ts}\, bh = (0.0036)(1000)(180) = 648 \text{ mm}^2/\text{m}$$

Select No. 13 bars at 180 mm spacing (A_f= 717 mm^2/m).

Note: The slab should now be examined for shear, crack control, deflections, and creep rupture. Calculations related to these requirements are not shown: If these design criteria are not satisfied, then the slab thickness may be increased incrementally or additional reinforcement added.

Example 4: Development of bars in tension (Tension-controlled section)

Calculate the length required to develop the inner two No. 25 glass FRP (GFRP) bars at the column face in the following figure. The two No. 25 outer bars are to be made continuous along full length of beam. Use f_c'=28 MPa (normal weight concrete), f_{fu}^* = 550 MPa, and E_f= 41,000 MPa. Assume d = 700mm. Assume interior exposure conditions.



Calculations and Discussions	**Reference**
No. 25 bar properties	440.06, Table 7.1
d_b = 25.4 mm	
$A_{f,bar}$ = 510 mm^2	
Design material properties:	440.1R, Table 6.2
C_E = 0.8	
$f_{fil} = C_E f_{fu}{}^*$ = (0.8)(550) = 440 MPa	440.1R, Eq. 6.2a

1. Determine required slab thickness

A_f = (4) (510 mm^2) = 2040 mm^2

$$\rho_f = \frac{A_f}{bd} = \frac{2010}{(300)(700)} = 0.00957$$ 440.1R, Eq. (7.2.1a)

$$\rho_{fb} = 0.85\beta_1 \frac{f_c'}{f_{fu}} \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}}$$

$$E_f \varepsilon_{cu} = (41{,}000)(0.003) = 123 \text{ MPa}$$

$$\rho_{fb} = 0.85(0.85)\frac{(28)}{(440)}\frac{(123)}{(123+440)} = 0.01004$$ 440.1R, Eq. (7.2.1b)

$$\frac{\rho_f}{\rho_{fb}} = \frac{0.00957}{0.01004} = 0.95$$

Because $\rho_f \leq \rho_{fb}$, the section is tension-controlled — 440.1R, Eq. (7.2.3)

2. Determine stress in tensile reinforcement at ultimate condition

Because section is tension-controlled, $f_f = f_{fu}$=440 MPa

3. Determine development length

$$\ell_d = \frac{\alpha \frac{f_{fr}}{0.083\sqrt{f_c'}} - 340}{13.6 + \frac{c}{d_b}} d_b$$ 440.1R, Eq. (10.3a)

$$f_{fr} = f_f = 440 \text{ MPa}$$ 440.1R, Sec. 10.3

Bar location modification factor should be taken as α=1.5 because more than 300 mm of concrete is cast below the reinforcement.	ACI 440.1R, Sec. 10.1.1

Clear spacing of bars being developed =[300-2(40)-2(12.7)-4(25.4)]/3=31mm

$$C = \min\left(d_c, \frac{\text{ctr-to-ctr spacing}}{2}\right) \leq 3.5 d_b$$

ACI 440.1R, Sec.10.1

$$= \min\left(40 + 12.7 + \frac{25.4}{2}, \frac{12.7 + 31 + 12.7}{2}\right)$$

$$\leq 3.5(25.4) = \min(65,28) \leq 89$$

$$C = 28 \text{ mm}$$

$$\ell_d = \frac{\alpha \frac{f_{fr}}{0.083\sqrt{f_c'}} - 340}{13.6 + \frac{C}{d_b}} d_b = \frac{(1.5)\frac{(440)}{0.083\sqrt{28}} - 340}{13.6 + \frac{28}{25.4}}(25.4) = 2010 \text{ mm}$$

The required development length is 2010mm.

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