



An ACI / NEx Manual

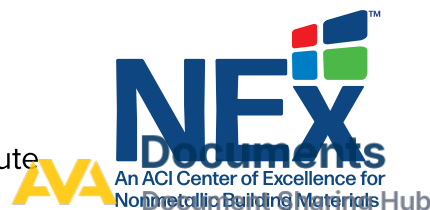
GFRP-Reinforced Concrete Design Handbook

MNL-7(23)

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GFRP-Reinforced Concrete Design Handbook

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GFRP-Reinforced Concrete Design Handbook

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CONTENTS

PREFACE	6
CHAPTER 1—INTRODUCTION	7
1.1—ACI CODE-440.11 format and scope	8
1.2—Format and scope of this manual	10
1.3—Example building floor plan and section	10
1.4—Example building loads	13
1.5—Example building material properties	13
CHAPTER 2—FRP MATERIALS	15
2.1—Constituent materials	15
2.2—Mechanical properties	16
2.3—Thermal properties	18
2.4—Long-term properties	19
CHAPTER 3—BENEFITS AND USE	21
3.1—Introduction	21
3.2—Noncorrosive	21
3.3—Lightweight	22
3.4—Easily cut	23
3.5—Nonmagnetic	24
3.6—Nonconductive	25
3.7—Low thermal conductivity	25
CHAPTER 4—CODES AND STANDARDS	27
4.1—Material tests and standards	27
4.2—Construction standards	29
4.3—Scope of ACI CODE-440.11	29
4.4—ACI CODE-440.11 and the International Building Code	30
CHAPTER 5—APPLICATIONS	33
CHAPTER 6—FIRE	37
6.1—Fire resistance in ACI CODE-440.11	37
6.2—Other fire protection strategies	40
CHAPTER 7—ONE-WAY SLABS	41
ONE-WAY SLAB EXAMPLE—FIVE SPAN CONTINUOUS SLAB	42
STEP 1—MATERIAL REQUIREMENTS	42
STEP 2—SLAB GEOMETRY	43
STEP 3—LOADS AND LOAD PATTERNS	44
STEP 4—ANALYSIS	44
STEP 5—FLEXURAL DESIGN FOR CRACK CONTROL	45
STEP 6—CHECK DEFLECTIONS	48
STEP 7—CHECK SUSTAINED STRESS LIMIT	53
STEP 8—CHECK MOMENT CAPACITY	53
STEP 9—CHECK SHEAR CAPACITY	55
STEP 10—CHECK GFRP REINFORCEMENT LIMITS	57
STEP 11—DEVELOPMENT LENGTH AND SPLICES	57
STEP 12—FINAL DESIGN AND DETAILING	58

CHAPTER 8—TWO-WAY SLABS	59
TWO-WAY SLAB EXAMPLE—DIRECT DESIGN METHOD	60
STEP 1—MATERIAL REQUIREMENTS	60
STEP 2—SLAB GEOMETRY	61
STEP 3—LOADS AND LOAD PATTERNS	61
STEP 4—ANALYSIS	62
STEP 5—FLEXURAL DESIGN FOR SERVICEABILITY	66
STEP 6—CHECK DEFLECTIONS	69
STEP 7—CHECK SUSTAINED STRESS LIMIT	72
STEP 8—CHECK MOMENT CAPACITY	72
STEP 9—ONE-WAY SHEAR STRENGTH	73
STEP 10—TWO-WAY SHEAR STRENGTH	74
STEP 11—DEVELOPMENT LENGTH AND SPLICES	75
STEP 12—FINAL DESIGN AND DETAILING	76
CHAPTER 9—BEAMS	77
BEAM EXAMPLE 1—CONTINUOUS INTERIOR T-BEAM	80
STEP 1—MATERIAL PROPERTIES	80
STEP 2—BEAM GEOMETRY	81
STEP 3—LOADS AND PATTERNS	82
STEP 4—ANALYSIS	83
STEP 5—FLEXURAL DESIGN FOR SERVICEABILITY	83
STEP 6—CHECK SPACING REQUIREMENTS	88
STEP 7—CHECK CREEP RUPTURE STRESS LIMIT	92
STEP 8—CHECK FLEXURAL STRENGTH	93
STEP 9—DEVELOPMENT LENGTHS, HOOKS, AND SPLICES	95
STEP 10—DETAIL THE BOTTOM REINFORCEMENT	96
STEP 11—SKIN REINFORCEMENT	101
BEAM EXAMPLE 2—CONTINUOUS INTERIOR T-BEAM AT FIRST INTERIOR SUPPORT	104
STEP 1—MATERIAL REQUIREMENTS	104
STEP 2—BEAM GEOMETRY	105
STEP 3—FLEXURAL DESIGN FOR SERVICEABILITY	105
STEP 4—CHECK CREEP RUPTURE STRESS LIMIT	111
STEP 5—CHECK FLEXURAL STRENGTH	111
STEP 6—CONSIDER IMPACT ON MIDSPAN DEFLECTION	114
STEP 7—DEVELOPMENT LENGTH AND SPLICES	114
STEP 8—DETAIL THE TOP REINFORCEMENT	115
STEP 9—SKIN REINFORCEMENT	116
BEAM EXAMPLE 3—CONTINUOUS INTERIOR T-BEAM AT EXTERIOR SUPPORT	118
STEP 1—MATERIAL REQUIREMENTS	118
STEP 2—BEAM GEOMETRY	119
STEP 3—FLEXURAL DESIGN FOR SERVICEABILITY	119
STEP 4—CHECK CREEP RUPTURE STRESS LIMIT	122
STEP 5—CHECK FLEXURAL STRENGTH	122
STEP 6—DEVELOPMENT LENGTH AND HOOKS	124
STEP 7—DETAIL THE TOP REINFORCEMENT	126
STEP 9—SKIN REINFORCEMENT	127

BEAM EXAMPLE 4—SHEAR DESIGN OF FIRST INTERIOR BEAM 130

STEP 1—MATERIAL PROPERTIES	130
STEP 2—BEAM GEOMETRY AND LOADS	131
STEP 3—BEAM SHEAR CONTRIBUTION	132
STEP 4—DETERMINE SPACING OF GFRP STIRRUPS	134
STEP 5—CHECK SHEAR AT BAR CUTOFF LOCATIONS	136
STEP 6—FINAL STIRRUP PLACEMENT	137
STEP 7—FINAL STIRRUP DETAILING	138

BEAM EXAMPLE 5—CONTINUOUS EXTERIOR L-BEAM 139

STEP 1—MATERIAL PROPERTIES	139
STEP 2—BEAM GEOMETRY	141
STEP 3—LOADS AND PATTERNS	141
STEP 4—ANALYSIS	142
STEP 5—FLEXURAL DESIGN AT MIDSPAN	143
STEP 6—DETAIL THE BOTTOM REINFORCEMENT	151
STEP 7—NEGATIVE MOMENT REINFORCEMENT	154
STEP 8—SKIN REINFORCEMENT	158
STEP 9—SHEAR REINFORCEMENT REQUIREMENTS	159
STEP 9—TORSION REINFORCEMENT REQUIREMENTS	161
STEP 10—CHECK FLEXURAL STRENGTH IN THE NEGATIVE MOMENT REGION	168
STEP 11—DETAILING LONGITUDINAL REINFORCEMENT	169

CHAPTER 10—COLUMNS 176**COLUMN EXAMPLE 1—INTERIOR COLUMN ANALYSIS 179**

STEP 1—DETERMINE COLUMN SIZE	180
STEP 2—EVALUATE SLENDERNESS	182
STEP 3—SWAY OR NONSWAY MOMENT FRAME	184
STEP 4—DETERMINE SECOND-ORDER ($P\Delta$) EFFECTS FOR SWAY	185
STEP 5—SUMMARY	186

COLUMN EXAMPLE 2—INTERIOR COLUMN DESIGN 187

STEP 1—LONGITUDINAL REINFORCEMENT MATERIAL PROPERTIES	187
STEP 2—INITIAL DESIGN OF LONGITUDINAL REINFORCEMENT	187
STEP 3—AXIAL LOAD-MOMENT INTERACTION DIAGRAM	188
STEP 4—TRANSVERSE REINFORCEMENT MATERIAL PROPERTIES	193
STEP 5—DETAILING TRANSVERSE REINFORCEMENT	194
STEP 6—REINFORCEMENT THROUGH THE JOINT AT LEVEL 2	196
STEP 7—DETAIL THE COLUMN SPLICE AT JOINT AT LEVEL 2	196
STEP 8—SUMMARY	198

REFERENCES 199

Authored documents	200
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APPENDIX 203

PREFACE

The *GFRP Reinforced Concrete Design Handbook* is a vital reference for professionals interested in the use of non-metallic GFRP reinforcement for concrete structures. It is meant to provide valuable insight to structural engineers on understanding and utilizing the provisions of “Building Code Requirements for Structural Concrete Reinforced with Glass Fiber Reinforced Polymer (GFRP) Bars” (ACI CODE 440.11).

The *GFRP Reinforced Concrete Design Handbook* provides several engineering design examples for various concrete members reinforced with GFRP bars including beams, one-way slabs, two-way slabs, and slender columns. The examples help illustrate the provisions of ACI CODE 440.11 as they pertain to serviceability, flexural strength, shear strength, torsional strength, axial strength, stability, and structural analysis. Many of the examples are based on a fictitious four-story GFRP reinforced concrete building to illustrate how the design provisions work together in a full building design. These examples are also closely related to the example problems presented in the *ACI Reinforced Concrete Design Handbook* (ACI MNL-17) to allow for comparison to the steel reinforced concrete members presented in MNL-17. Each example starts with a brief problem statement and then presents a full set of design calculations that reference the appropriate provisions in ACI CODE 440.11 (red highlighted text next to equations) to arrive at a solution. Detailed explanations of the design calculations are provided throughout. In addition to the example problems, this handbook provides general information and guidance about the appropriate use of GFRP reinforcement, its material and durability characteristics, typical applications, and considerations for fire resistance. It also highlights key differences between designing GFRP reinforced concrete versus traditional steel reinforced concrete.

The appendix to this handbook provides additional detailed information from FRP bar manufactures on commercially available products and solutions.

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CHAPTER 1—INTRODUCTION

The use of fiber-reinforced polymer (FRP) composite materials in structural applications has transformed many industries over the past several decades. The aerospace industry has used these materials due to their very high strength-to-weight ratio and excellent fatigue resistance; the naval and ship building industry has used these materials for their durability because these materials do not corrode, rot, or decay; and the sporting goods industry has used these materials for their stiffness, which can be tailored in various directions, and for their ability to be molded into a variety of structural shapes. Their use in the construction industry has not been as widespread as other industries, but it has had a significant impact. Structures such as the carbon fiber-reinforced polymer (CFRP) roof of the auditorium on Apple Computer's campus have reimagined what is possible in architecture; and concrete bridges that use no steel reinforcement, such as the 28-span Harker Island bridge in North Carolina, have reimagined how civil structures can resist deterioration due to corrosion.

The use of non-metallic, FRP reinforcement for concrete structures has, in fact, started to gain widespread use. Not only is this reinforcement non-corrosive, it is also lightweight and easy to handle, allowing increases in productivity as well as the health and safety of workers. These and other advantages, as discussed in more detail in Chapter 3 of this manual, are resulting in increased use of FRP reinforcement for concrete structures.

However, as the use of this type of reinforcement increases, it is important to implement its use in a safe and effective manner. FRP reinforcement behaves differently than steel. (These differences and the unique properties of FRP reinforcement are discussed in Chapter 2 of this manual.) As such, the engineering design of FRP-reinforced concrete structures must take into account the way in which the material behaves and how that is different than steel reinforcement. Some of the most important design differences are due to the lack of ductility of FRP reinforcement, which results in the need for higher reserves of strength, and the lower modulus of elasticity of some FRP reinforcements, which results in most FRP-reinforced concrete structures being controlled by serviceability (deflection, crack width, or sustained stress limits). Most importantly, it is not appropriate to simply replace steel reinforcement with an equal amount of FRP reinforcement. The design of FRP reinforcement must be carried out with specific engineering principals that take into account its material characteristics.

The American Concrete Institute (ACI) and other institutions globally have recognized the need for specific engineering guidance on the use of FRP reinforcement for concrete. ACI published the first state-of-the-art report on FRP reinforcement of concrete in 1996 (ACI 440R-96, which has been subsequently updated to ACI PRC-440-07) and has since published numerous guidelines and specifications for the design, construction, testing, and material requirements for FRP reinforcement. This includes ACI PRC-440.1-15, "Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars," which was first published in 2001. These documents all establish methods for properly using FRP reinforcement and have been used to design and construct FRP-reinforced concrete elements for decades. As this industry and technology has matured, building officials, designers, contractors, and manufacturers have all seen an increased need to codify requirements for FRP-reinforced concrete. As such, in 2022, ACI published the first building code requirements for FRP-reinforced concrete: ACI CODE-440.11-22, "Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary." This manual serves as a companion to ACI CODE-440.11, which provides additional insights on the background of the code, engineering design approaches using the code, and detailed example problems that illustrate how to apply the code.

1.1—ACI CODE-440.11 format and scope

Relative to the type of FRP reinforcement, ACI CODE-440.11-22 limits the scope of the code to solid, round glass fiber-reinforced polymer (GFRP) reinforcing bars constructed using vinyl ester resins and that conform to ASTM D7957/7957M-22. Although there are other shapes of FRP reinforcing bars (square and rectangular cross sections and hollow bars or tube sections), other resin types that may be used (vinyl esters, polyesters, epoxies, and other polymers have all been used to produce FRP bars), and other types of fiber comprising the FRP material (basalt and carbon fiber being the most notable), the scope of ACI CODE-440.11 is limited to solid, round, GFRP bars made with vinyl ester polymers. This scope limitation is based on the preponderance of research data and field experience using this type of FRP reinforcement as well as the acceptance and availability of the ASTM D7957/7957M material standard for this type of reinforcement. As of the publication of this manual, there is now an ASTM standard that includes basalt fiber-reinforced polymer bars (BFRP): ASTM D8505/D8505M. This may allow for inclusion of BFRP bars in future editions of ACI CODE-440.11; however, the current code limits the use to bars conforming to ASTM D7957/7957M. (Indications are that future editions of the code will include reference to both material standards to allow bars conformance to either standard. Additional discussion of these standards is in Chapter 4 of this manual.) The ACI PRC-440.1 design guide also serves as a resource for using FRP reinforcing bars of many various types.

ACI CODE-440.11-22 follows the same structure and format as ACI CODE-318-19(22), “Building Code Requirements for Structural Concrete—Code and Commentary.” The intent of ACI CODE-440.11 is to maintain all the requirements of ACI CODE-318 and only replace requirements that would change when using GFRP reinforcement instead of steel reinforcement. Some chapters of ACI CODE-318 are omitted in ACI CODE-440.11 where there is not sufficient research into the use of GFRP reinforcement (such as Chapter 12 on Diaphragms); these chapters are marked “Not Addressed”. Other chapters where GFRP reinforcement would not be used (such as Chapter 14 on Plain Concrete) are marked “Not Applicable”. However, most topics pertaining to regularly reinforced concrete structures are covered in ACI CODE-440.11. Table 1.1 provides a comparison of the chapters that ACI CODE-440.11 covers versus the chapters that ACI CODE-318-19(22) covers.

In addition to the chapters indicated in Table 1.1 that ACI CODE-440.11 excludes, there are other topics that the code does not cover. These include provisions for the use of lightweight concrete, the use of shotcrete, and the design of deep beams. Additionally, the code does not cover prestressed concrete; however, FRP prestressing systems (using prestressed FRP bars or tendons) do exist and there is a guideline available from ACI on this topic: ACI PRC 440.4-04(11), “Prestressing Concrete Structures with FRP Tendons.” Neither ACI CODE-318 or ACI CODE-440.11 cover topics such as slabs-on-ground, residential construction, or environmental structures. FRP bars are, however, common in many of these applications. ACI PRC-440.1-15 and the *ACI Recommended Practice Guidelines for FRP Bars in Pre-Engineered Projects* (MNL-6) provide recommendations on slabs-on-ground, and MNL-6 provides recommendations on residential foundation walls.

All the chapter and section numbers in ACI CODE-440.11 mirror the chapter and section numbers in ACI CODE-318-19(22). This has been done to allow the user familiar with ACI CODE-318 to easily navigate the requirements in ACI CODE-440.11 and to allow for direct comparisons between the requirements of each code. Code provisions in ACI CODE 440.11 that are direct copies of code provisions in ACI CODE-318 are marked with a superscript equal sign (⁼) before the provision to further assist the user in comparing requirements in the two codes (refer to Fig. 1.1 for an example). Some provisions of ACI CODE-440.11 are marked “Not Applicable” where the corresponding code requirement in ACI CODE-318 would not apply to GFRP reinforcement (such as provisions for plain concrete or epoxy-coated steel reinforcement). Other provisions of ACI CODE-440.11 are marked “Out of Scope” where there is not sufficient data, research, or experience to include provisions for the corresponding requirement in ACI CODE-318 (such

Table 1.1—Comparison of chapters in ACI CODE-318 versus ACI CODE-440.11

ACI CODE 318-19(22) Chapters	ACI CODE 440.11 Chapters
Chapter 1: General	Chapter 1: General
Chapter 2: Notation and Terminology	Chapter 2: Notation and Terminology
Chapter 3: Referenced Standards	Chapter 3: Referenced Standards
Chapter 4: Structural System Requirements	Chapter 4: Structural System Requirements
Chapter 5: Loads	Chapter 5: Loads
Chapter 6: Structural Analysis	Chapter 6: Structural Analysis
Chapter 7: One-Way Slabs	Chapter 7: One-Way Slabs
Chapter 8: Two-Way Slabs	Chapter 8: Two-Way Slabs
Chapter 9: Beams	Chapter 9: Beams
Chapter 10: Columns	Chapter 10: Columns
Chapter 11: Walls	Chapter 11: Walls
Chapter 12: Diaphragms	Chapter 12: Not Addressed
Chapter 13: Foundations	Chapter 13: Foundations
Chapter 14: Plain Concrete	Chapter 14: Not Applicable
Chapter 15: Beam-Column and Slab-Column Joints	Chapter 15: Beam-Column and Slab-Column Joints.
Chapter 16: Connections between Members	Chapter 16: Connections between Members
Chapter 17: Anchoring to Concrete	Chapter 17: Not Addressed
Chapter 18: Earthquake-Resistant Structures	Chapter 18: Not Addressed
Chapter 19: Concrete: Design and Durability Requirements	Chapter 19: Concrete: Design and Durability Requirements
Chapter 20: Reinforcement Properties, Durability and Embedments	Chapter 20: GFRP Reinforcement Properties, Durability, and Embedments
Chapter 21: Strength Reduction Factors	Chapter 21: Strength Reduction Factors
Chapter 22: Sectional Strength	Chapter 22: Sectional Strength
Chapter 23: Strut-and-Tie Method	Chapter 23: Not Addressed
Chapter 24: Serviceability Requirements	Chapter 24: Serviceability Requirements
Chapter 25: Reinforcement Details	Chapter 25: GFRP Reinforcement Details
Chapter 26: Construction Documents and Inspection	Chapter 26: Construction Documents and Inspection
Chapter 27: Strength Evaluation of Existing Concrete Structures	Chapter 27: Strength Evaluation of Existing Concrete Structures

 **2.1.1** Design properties for concrete shall be selected to be in accordance with **Chapter 19**.

Fig. 1.1—Example provision from ACI CODE-440.11 highlighting the superscript equal sign, (̑) that is used to designate provisions in ACI CODE-440.11 that are identical to the corresponding provision in ACI CODE-318.

as flexural reinforcement in prestressed slabs). Provisions marked “Out of Scope” generally are provisions that could apply to GFRP-reinforced concrete and may become part of future editions to the code, but are currently beyond the state of current knowledge and research.

There are two other important topics that are specifically limited in terms of the scope of ACI CODE-440.11 and where GFRP reinforcement is allowed for use. Those are fire resistance and seismic resistance. The code limits the use of GFRP reinforcement to structures that do not require a fire rating due to the lack of detailed fire testing of these elements. However, the code does allow for building officials and designers to implement rational fire methods for achieving fire ratings when necessary, and there is commentary language to support this type of approach.

Further information on fire resistance is provided in Chapter 12 of this manual and Section 4.11 of the code (and Commentary Section R4.11).

Similarly, the code limits the use of GFRP reinforcement to buildings depending on their assigned Seismic Design Category (SDC) due to the lack of knowledge on the seismic performance of FRP-reinforced concrete structures. The code allows GFRP reinforcement to be used in all structural elements of buildings assigned to SDC A; GFRP reinforcement can only be used in elements that are not part of the seismic-force-resisting system in SDC B and C (that is, they can only be used in gravity-load-resisting structural members); and they are not permitted to be used in any structural element in buildings assigned to SDC D, E, or F. Additional information is provided in Chapter 4 of this manual and in Section 4.4.6 of the code (and Commentary Section R4.4.6).

1.2—Format and scope of this manual

This manual provides basic information about FRP materials and how they behave (Chapter 2) as well as the benefits and typical applications of FRP reinforcement (Chapters 3 and 4). Much of the basic information is pertinent to all types of FRP reinforcing bars, including CFRP and BFRP bars. The manual also provides a discussion on current codes and standards related to FRP bars (Chapter 5), including material specifications, construction specifications, and how ACI CODE-440.11 relates to other codes such as the *International Building Code*.

The remaining chapters provide detailed design examples and discussion of key aspects of engineering design of concrete elements using GFRP reinforcement. The example problems all follow ACI CODE-440.11 requirements and illustrate the provisions of the code. As such, example problems only consider GFRP bars conforming to ASTM D7957/7957M (consistent with the scope of ACI CODE-440.11).

The example problems are all based on the design of various elements in a fictitious, four-story, GFRP-reinforced concrete building. These examples are intended to mirror the examples in the MNL-17, *ACI Reinforced Concrete Design Handbook*. MNL-17 is based on designing a seven-story, steel-reinforced concrete building according to ACI CODE-318. The building design for this manual is a more modest four-story building that would be more realistic for columns, walls, and foundations designed using GFRP reinforcement. However, the basic floor plan and structural system for the building presented in this manual is the same as the building in MNL-17. The intent is to allow for comparison between elements that are designed using GFRP in this manual to elements designed using steel reinforcement in MNL-17.

All example problems are formatted with shaded regions, indicating the calculations that are required to be performed and text outside of the shaded regions to provide additional commentary on the design steps involved or alternate calculation procedures.

1.3—Example building floor plan and section

The overall floor plans for the building that will be considered in this manual are shown in Fig. 1.3a and 1.3b, and the typical building section is illustrated in Fig. 1.3c. Design loads for the example building and other structural considerations are given in Section 1.4; material properties for the example building are given in Section 1.5.

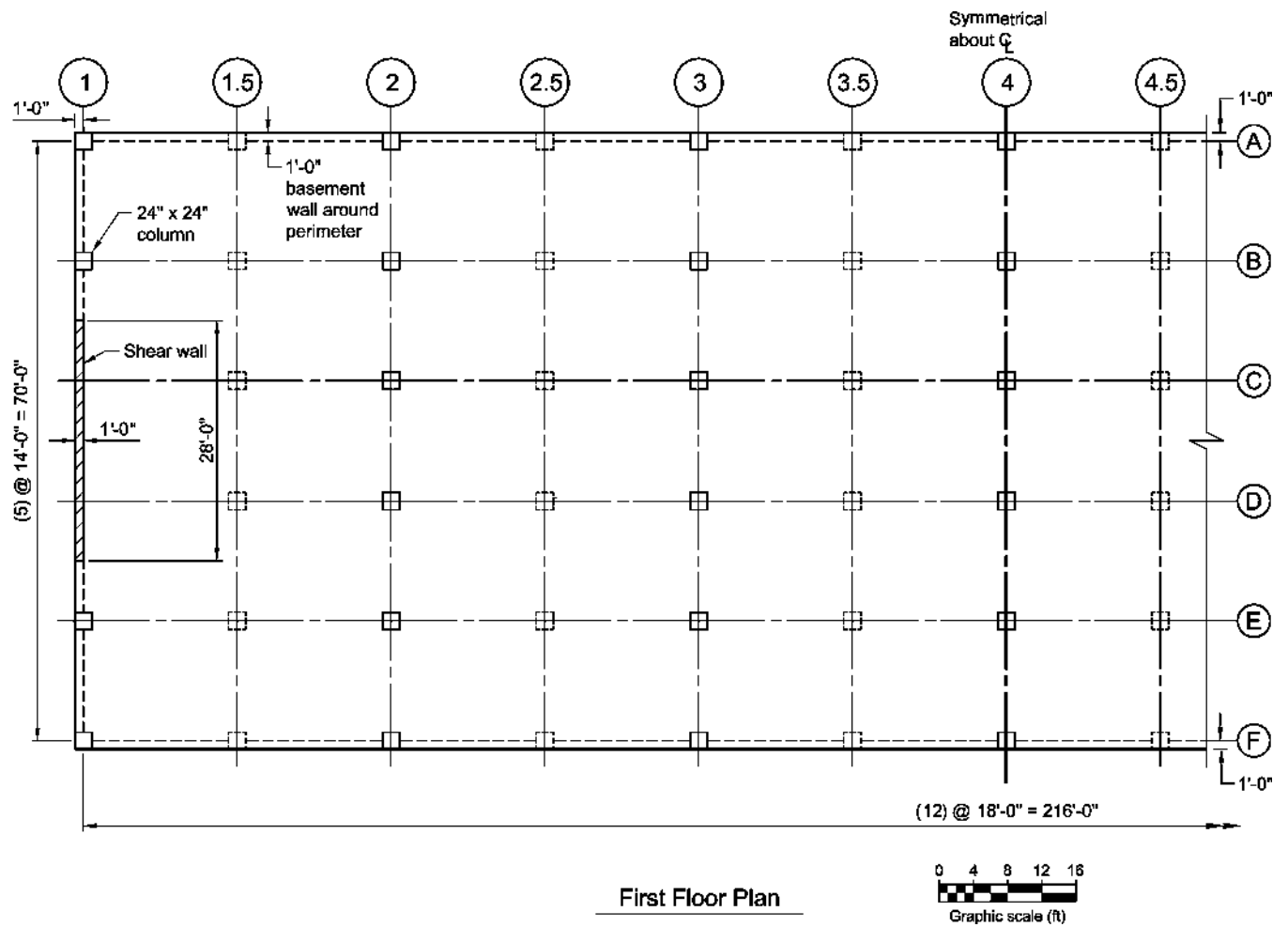


Fig. 1.3a—Example building first-floor plan.

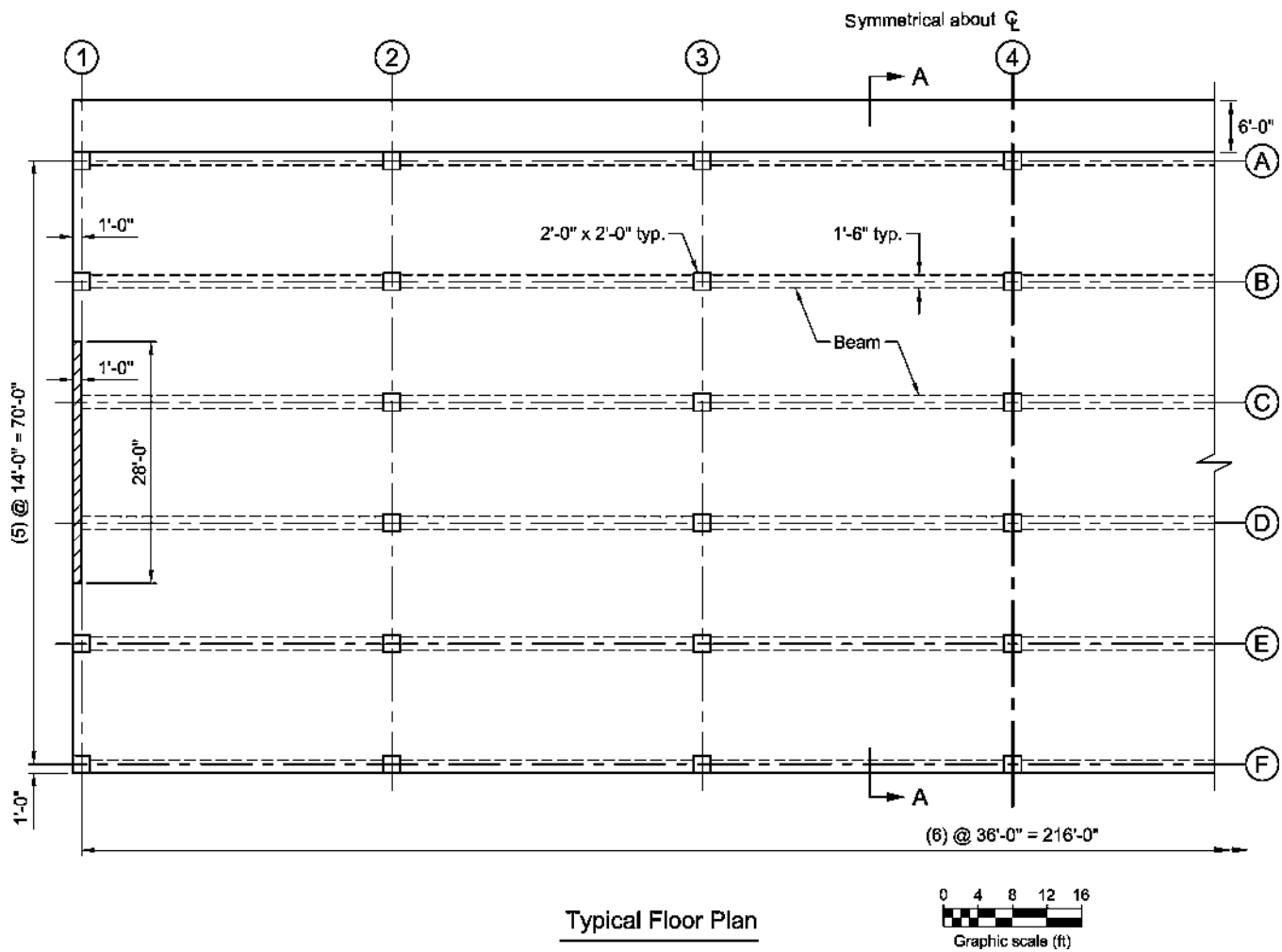


Fig. 1.3b—Example building typical floor plan for third and fourth floors.

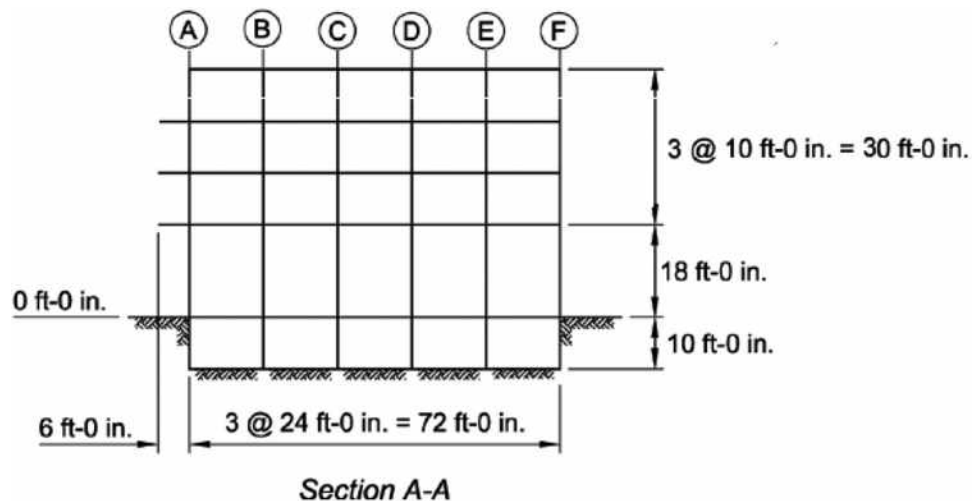


Fig. 1.3c—Typical building section.

1.4—Example building loads

The loads are generated in accordance with ASCE/SEI 7. The Risk Category is II.

Gravity loads	Lateral loads
Dead load D : • Self weight • Additional $D = 15 \text{ lb/ft}^2$ • Perimeter walls = 15 lb/ft^2	Wind load: • Basic (ultimate) wind speed = 115 mph • Exposure category = C • Wind directionality factor $K_d = 0.85$ • Topographic factor $K_{zt} = 1.0$ • Gust-effect factor $G_f = 0.85$ (rigid) • Internal pressure coefficient $GC_{pi} = \pm 0.18$ • Directional procedure
Live load: • First and second floors: Lobbies, public rooms, and corridors serving them = 100 lb/ft^2 • Typical floor: Private rooms and corridors serving them = 40 lb/ft^2	
Roof live load: • Unoccupied = 20 lb/ft^2	Seismic load: • Importance $I_e = 1.0$ • Site class = D • $S_S = 0.15$, $S_{DS} = 0.16$ • $S_I = 0.08$, $S_{DI} = 0.13$ • Seismic design category = A • Equivalent lateral force procedure • Building frame system; ordinary reinforced concrete shear walls in the east-west direction ◦ $R = 5$ ◦ $C_s = 0.046$ • Moment-resisting frame system; ordinary reinforced concrete moment frame in the north-south direction ◦ $R = 3$ ◦ $C_s = 0.032$
Snow load: • Ground load $P_g = 20 \text{ lb/ft}^2$ • Thermal $C_t = 1.0$ • Exposure $C_e = 1.0$ • Importance $I_s = 1.0$ • Flat roof load $P_f = 20 \text{ lb/ft}^2$	

1.5—Example building material properties

The material properties for the concrete used in the example problems are given below and are the same as those provided in the MNL-17 building example. MNL-17 gives some additional discussion on selection of the concrete and its properties. As discussed in MNL-17, the designer should investigate local availability of concrete and reasonable material properties.

Also note that ACI CODE-440.11 does not cover the use of lightweight aggregate concrete. Normalweight concrete is used exclusively in the elements of this example. Due to the lighter weight of GFRP reinforcement versus steel reinforcement, it is generally acceptable to use a lower unit weight of 145 lb/ft^3 for GFRP-reinforced concrete versus 150 lb/ft^3 often assumed for steel-reinforced concrete. There may be some efficiencies gained by using the lower unit weight, however these examples all use 150 lb/ft^3 to provide some consistency with the loads used in MNL-17 and to be conservative.

- $f'_c = 5000 \text{ psi}$
- Normalweight $w_c = 150 \text{ lb/ft}^3$
- $E_c = 4,030,000 \text{ psi}$ (ACI CODE-440.11 Eq. (19.2.2.1b))
- $\nu = 0.20$

The properties of GFRP bars can vary based on the bar manufacturer. A list of select manufacturers and their associated bar properties is provided in the Appendix to this manual. However, the designer should specify that GFRP bars conform to the minimum requirements in ASTM D7957/7957M. Thus, for design, it is acceptable to use the minimum properties indicated in ASTM D7957/7957M. This also does not require the designer to pre-select one specific GFRP bar manufacturer. Do note, however, that ACI CODE-440.11 does allow the use of a specific manufacturer's properties instead of ASTM D7957/7957M minimums in the design of GFRP-reinforced elements.

Although the use of ASTM D7957/7957M minimums does not require the designer to pre-select a specific manufacturer, it is recommended that designers become familiar with the GFRP bar manufacturers that supply bars in their geographic area. The availability of specific bar sizes and bar details (hooks and bends) may vary. It is important to understand what is available and feasible for any GFRP-reinforced concrete project.

GFRP bar tensile strength does vary with bar size. This is discussed in more detail in Chapter 2. The bar modulus generally remains constant. For this manual, the example problems use the minimum modulus from ASTM D7957/7957M of:

- $E_f = 6,500,000$ psi

As discussed in Chapter 2, higher modulus bars are available and may provide for more efficient designs.

CHAPTER 2—FRP MATERIALS

As with any reinforcing material, the mechanical and durability properties of fiber-reinforced polymer (FRP) are key to understanding its performance as reinforcement for concrete. At a fundamental level, FRP reinforcement behaves in a much different way than steel reinforcement. It is important to understand that simply replacing steel reinforcement with the same size and spacing of FRP reinforcement is not appropriate. FRP reinforcement must be specifically designed based on the unique properties of FRP. This chapter is meant to provide a synopsis of the key properties of FRP as it relates to its use in reinforcing concrete structures.

2.1—Constituent materials

FRP materials are a composite material consisting of a network of high-strength fibers that are bound together by a polymer matrix. The fibers provide the strength and stiffness properties to the composite and the polymer binds the fibers together, allows stresses to be transferred between fibers, and give the material its form. FRP reinforcing bars are typically constructed of glass fiber (GFRP), basalt fiber (BFRP), or carbon fiber (CFRP). Aramid fibers (AFRP) may also be used but are less common. The polymers used to construct FRP bars are typically vinyl ester thermosetting polymers. Other thermoset polymers such as epoxies and phenolics may also be found but are not as common.

The proportion of the volume of fibers in a composite to the overall volume of the composite material is a property referred to as volume fraction. Typical FRP materials will have a volume fraction of 50% to 70% with higher volume fractions generally yielding better tensile properties. FRP reinforcing bars will typically have volume fractions exceeding 55%.

It is important to recognize that FRP materials are anisotropic; their properties vary in different directions. FRP materials are strongest and stiffest in the direction of the fibers, but significantly weaker in directions off axis to the fiber direction. The FRP material shown in Fig. 2.1, for example, would have high strength only in the direction along the fibers. In the directions perpendicular to the fibers, the strength of the material would be the significantly lower strength of the polymer alone. In addition to mechanical properties, other properties such as the coefficient of thermal expansion, electrical conductivity, and thermal conductivity also vary depending on direction.

In many cases, FRP materials can be designed with fibers running in a variety of directions to suit the structural requirements of the application. Fiber orientations can be aligned with principal stress directions to accommodate the applied loads on

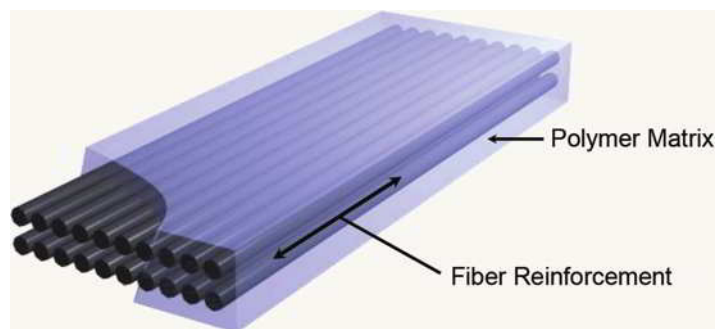


Fig. 2.1—Fiber-reinforced polymer (FRP) material showing the two constituent materials. The fibers used in high-strength FRP composites are essentially continuous (they are not chopped fibers or discrete fibers such as that which might be found in fiber-reinforced concrete). The fibers themselves have a very small diameter (less than the diameter of a human hair). A dense network of these small-diameter, continuous fibers reinforce the FRP material. An FRP material will generally have several million fibers per square inch of cross section.

the material and optimize the performance of the material. FRP reinforcing bars, however, typically have fibers running only along the length of the bar. This allows the bars to have high strength and stiffness along the length of the bar, but the bars have relatively lower strength and stiffness perpendicular to the bar. As such, FRP bars have lower shear strength, provide lower levels of dowel action, and may have lower bond strength than comparable steel bars.

2.2—Mechanical properties

2.2.1 Tensile properties—The tensile behavior of FRP is essentially linearly-elastic until failure, and ACI CODE-440.11 Section 20.2.1.2 considers FRP bars linearly-elastic until failure. The lack of ductility in FRP materials is one of the most significant differences between FRP reinforcement and steel reinforcement from a structural design standpoint. It results in designing structures with higher reserves of strength to compensate for the brittle failure mechanisms. The other significant difference between tensile behavior of FRP and steel reinforcement is the initial elastic modulus. GFRP and BFRP bars in particular have a lower initial elastic modulus than steel reinforcement. In many instances, this results in serviceability considerations governing the design of concrete structures reinforced with these bars as opposed to strength considerations. The differences in design that result from the differences in tensile behavior are discussed in more detail throughout this manual. A comparison of the behavior of FRP bars versus steel bars is shown in Fig. 2.2.1.

It is also important to note that the tensile strength of FRP bars does vary with the bar size. Larger bar diameters generally have lower net tensile strength because the outer fibers of the bar are more highly stressed than the inner fibers of the bar when loaded in tension (and bonded to concrete). ASTM D7957/D7957M provides a table of the minimum tensile force for GFRP bars with a range of values depending on the bar size. For example, the minimum tensile force for a 1/4 in. diameter (No. 2) bar is 6.1 kip, which translates to 125 ksi, whereas the minimum strength of a 1-1/4 in. diameter (No. 10) bar is 98.2 kip, which translates to 77 ksi.

ASTM D7957/D7957M does require that the tensile capacity of FRP bars be based on a statistical population of bar tests. It requires 24 samples of each bar be tested in groups of eight or more from three or more production lots. Manufacturers conforming to ASTM D7957/D7957M requirements will report a property called “guaranteed ultimate tensile force” that is based on testing this population of bars and taking the mean tensile force at rupture minus at least three times the standard



Fig. 2.2.1—Idealized tensile stress-strain curves for various FRP reinforcing bars versus Grade 60 steel reinforcing bars. FRP is, in general, a brittle material that is linearly elastic until failure. GFRP and BFRP bars have high strength but lower initial elastic modulus than steel. CFRP bars have very high strength and similar, but slightly less, initial elastic modulus to steel reinforcement.

deviation of this value. ACI CODE-440.11 uses a property referred to as the “guaranteed ultimate tensile strength”. This strength value is the “guaranteed ultimate tensile force” divided by the “nominal cross-sectional area” from ASTM D7957/D7957M.

2.2.2 Compressive properties—Compressive strength and stiffness of FRP materials can be as high as its tensile strength and stiffness when they are manufactured with methods that have significant controls in place to limit any voids in the polymer. Minor imperfections in the polymer may result in lower compressive properties, however. FRP bars are typically manufactured with high quality, but not to the extent that all voids in the polymer are necessarily eliminated. It is assumed that the compressive properties of FRP bars are lower than their tensile properties. ACI CODE-440.11 design criteria assumes the FRP bars that are in compression to be at the same compressive stress as the surrounding concrete (that is, they are assumed to have the same compressive modulus as concrete and provide equivalent compressive resistance).

2.2.3 Shear strength—The shear strength of FRP bars is generally lower than comparably sized steel bars due to the anisotropic nature of FRP bars. The reduction in the shear strength conceptually would affect aspects such as dowel action of longitudinal bars or bars meant to transfer shear across an interface (such as a composite topping placed over a precast element). The effects of this are currently not well known. ACI CODE-440.11 does provide for a lower shear contribution of the concrete (V_c) that is based on testing of FRP-reinforced concrete beams and may be in part due to lower dowel action of the steel bars. ACI CODE 440.11 does not cover the use of FRP bars or dowels across an interface to transfer shear.

ASTM D7957/D7957M does require a minimum “guaranteed transverse shear strength” of 19,000-psi when tested per ASTM D7617/D7617M. This is meant to ensure that the shear strength of bars is generally in conformance with bars that have been used in current research on FRP-reinforced concrete. The “guaranteed transverse shear strength” is determined from a similar population of production samples as are used in determining tensile force and taking the mean minus three standard deviations of the resulting shear strength values.

2.2.4 Bond strength—FRP bars intended to be used for concrete reinforcement generally have surface treatments that allow for bond to concrete. These can be sand coatings, deformations such as helically wound fibers that indent the surface of the bar, or protrusions or lugs machined into the surface of the bar. (There are other FRP bars used with concrete that do not use surface treatments such as FRP dowel bars and FRP bars embedded in epoxy used for strengthening existing structures. Those types of reinforcements are outside the scope of ACI CODE-440.11 and this manual.) GFRP bars conforming to ASTM D7957/D7957M are required to have an appropriate surface treatment and to have a “guaranteed bond strength” of at least 1100 psi to concrete when tested per ASTM D7913/D7913M. ASTM D7913/D7913M is a bond pull-out test similar to what is used to characterize the bond strength of steel bars.

2.2.5 Strength at bends—FRP bars cannot be field bent due to their linearly elastic behavior. However, it is common for bars to be produced with 90-degree bends by bar manufacturers. Bends larger than 90 degrees are not generally available, and because FRP bars do not plastically bend in use, larger bend angles do not improve performance. The bend radius that the fibers must follow to allow such bends do result in a lower tensile strength at bend locations. ASTM D7957/D7957M requires the tensile strength of the bent portion of a bar to be at least 60% of the strength of the straight bar.

Similar to the tensile capacity of straight bars, ASTM D7957/D7957M does require that the tensile capacity of bends bars be based on a statistical population of tests. Manufactures conforming to ASTM D7957/D7957M requirements will report a property called “guaranteed ultimate tensile force of bent portion of bar” that is based on these statistical requirements. ACI CODE-440.11 uses a property referred to as the “guaranteed ultimate tensile strength of bent portion of GFRP bars”. This strength value is the “guaranteed ultimate tensile force of bent portion of bar” divided by the “nominal cross-sectional area” from ASTM D7957/D7957M.

2.3—Thermal properties

2.3.1 Coefficient of thermal expansion—The coefficient of thermal expansion (CTE) of FRP materials can vary directionally depending on the fiber orientation. Typically, the polymers in FRP materials have a relatively high CTE and the fibers have a relatively low CTE (aramid and carbon fibers can, in fact, have negative CTE values). In the direction of the fibers, the lower CTE of the fibers restrains the overall composite CTE. In directions perpendicular to fibers, the CTE remains rather large with no restraint provided by the fibers. For FRP reinforcing bars, the CTE does typically vary in the longitudinal direction versus the transverse direction. Table 2.3.1 shows typical ranges of CTE for various FRP reinforcing bars in the longitudinal and transverse directions.

The CTE of GFRP and BFRP bars in the longitudinal direction are similar to the CTE of concrete and steel reinforcement. For CFRP and AFRP bars, the CTE can be significantly different than concrete. For extreme temperature differentials, the differences in the CTE may need to be investigated. Similarly, for all FRP bars, the transverse CTE is significantly different than the surrounding concrete. There is the potential for this difference to cause splitting cracking under large temperature changes, especially for larger bar sizes. However, these effects have not been observed in any field installations.

2.3.2 Glass transition temperature—The polymer component of FRP materials will soften under moderately high heat. At elevated temperatures, the polymer rapidly transitions from a glassy material to a rubbery material and the FRP material rapidly loses strength and stiffness. The glass transition temperature T_g of FRP materials is the average temperature over which it transitions from a rigid, glassy material to a rubbery material. The transition occurs rapidly over a small temperature change, as shown in Fig. 2.3.2. It is important to note that the transition to a

Table 2.3.1—Coefficient of thermal expansion of FRP reinforcing bars

Bar type	Longitudinal CTE ($10^{-6}/^{\circ}\text{F}$)	Transverse CTE ($10^{-6}/^{\circ}\text{F}$)
AFRP	−3.3 to −1.1	33 to 45
CFRP	−4.0 to 0.0	41 to 58
GFRP/BFRP	3.3 to 5.6	11 to 13

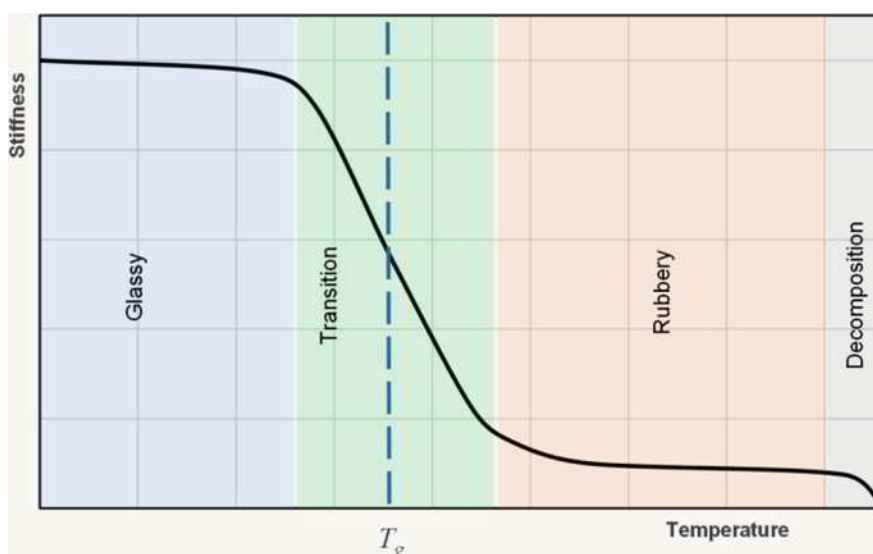


Fig. 2.3.2—Idealized stiffness versus temperature curve for FRP materials showing the transition from a glassy, rigid material to a rubbery, flexible material. The temperature at the mid-point of this rapid transition is the glass transition temperature T_g .

rubbery material is an irreversible change for thermosetting polymers that are typically used in FRP reinforcing bars.

Most commercially available FRP bars constructed using vinyl ester polymers have a glass transition temperature near 250°F. ASTM D7957/D7957M requires a minimum glass transition temperature of 212°F tested per ASTM E1356. In the commentary, ACI CODE-440.11 Section R20.2.2.3 recommends that GFRP reinforcement should not be used in structures that are in environments with service temperatures that rise to within 27°F of the glass transition temperature (that is, service temperature should not exceed $T_g - 27^\circ\text{F}$) to avoid softening of the FRP and loss of properties. Under more severe elevated temperature conditions, such as fire, the strength of the FRP bars may be compromised. Suitable protection of the FRP reinforcement is needed in for these conditions and is a significant design consideration. Additional discussion of fire considerations is given in Chapter 6 of this manual.

2.4—Long-term properties

2.4.1 Corrosion—FRP materials are inherently non-corrosive. In corrosive environments it is not necessary to use specific concrete properties that may be required with steel-reinforced concrete. For this reason, ACI CODE-440.11 Table 19.3.1 does not use Exposure Category C (Corrosion Protection of Reinforcement) that appears in ACI CODE-318 Table 19.3.1. It is anticipated that the service life of FRP reinforcing bars is much greater than steel in certain corrosive environments.

2.4.2 Accelerated aging—Accelerated aging studies of FRP bars have shown reductions in tensile strength (but not modulus) under exposure to certain environments. Alkaline environments, high humidity environments, high heat environments, and combinations of these three conditions are known to be deleterious to the properties of FRP bars. Generally, CFRP performs better than BFRP, which performs better than GFRP, but this can vary depending on the exact construction of the bar.

ASTM D7957/D7957M provides requirements on moisture absorption and retention of properties after exposure to elevated temperatures and alkalinity to ensure durability performance that is expected with GFRP bars. ACI CODE-440.11 uses an environmental reduction factor C_E to account for the loss of strength over time. The C_E value is applied to the guaranteed tensile strength and the guaranteed strength of bends in order to arrive at the design values for these properties. C_E is defined as 0.85 in accordance with ACI CODE-440.11 Section 20.2.2.3.

2.4.3 Creep rupture—FRP materials in general are susceptible to a phenomenon known as creep rupture or static fatigue. When the material is loaded in sustained tension, creep of the material results in higher induced strain. If the strain levels from creep become large enough, the material can suddenly experience tensile failure/rupture. The resistance of the material to creep rupture is dependent on many factors; however, the fiber type is one of the main influences. Generally, CFRP materials can resist stresses relatively close to their ultimate strength indefinitely, whereas GFRP can only resist stresses less than half of their ultimate strength indefinitely. To avoid this mode of failure, ACI CODE-440.11 Section 24.6.2 limits the sustained stress in the GFRP reinforcing bars to 30% of their design ultimate tensile strength.

CHAPTER 3—BENEFITS AND USE

3.1—Introduction

FRP reinforcing bars have many unique properties compared to traditional steel reinforcement. They are non-corrosive, non-magnetic, lighter weight, and easier to cut than steel reinforcement. All these properties make them an attractive alternative to steel reinforcement in certain applications. Many of the applications where GFRP reinforcement (Fig. 3.1) has specific benefits are described in this chapter.

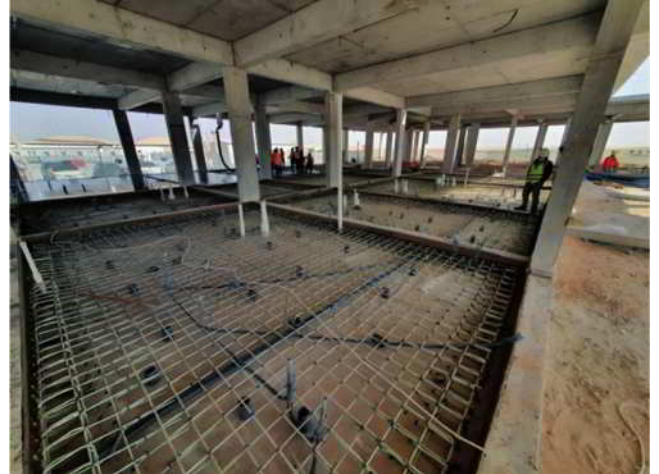


Fig. 3.1—GFRP reinforcement being used in slabs-on-ground for corrosion resistance and ease of installation (photo courtesy of Dextra).

3.2—Noncorrosive

One of the main benefits of FRP reinforcing bars is that they do not corrode. This has led to the use of FRP reinforcing bars as an alternative to steel reinforcing bars in several applications where corrosion of reinforcing steel is a significant concern.

Corrosion of reinforcing steel in concrete and its effects are well known. In new steel-reinforced concrete construction, the high alkalinity of the fresh concrete generates a passivating layer around internal steel reinforcement that protects it from corrosion. However, over time the alkalinity of concrete can be reduced by carbonation and/or the introduction of chlorides into the concrete can provide an environment suitable for corrosion of the steel to occur. As internal steel reinforcement corrodes, expansive forces from the oxidation of the steel lead to cracks and spalls of the concrete surrounding the reinforcing steel. Such cracks and spalls of concrete can be unsightly and hazardous. Ultimately, the corrosion of the reinforcing steel leads to a reduction in structural capacity since corrosion reduces both the cross-sectional area of steel able to carry tensile stresses and the bond between the steel and concrete.

Through our understanding of the steel-reinforced concrete corrosion process, design and construction practices have improved to mitigate corrosion of the reinforcing steel. These are well discussed in ACI PRC-222.3, “Guide to Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures”. However, many highly corrosive environments still present long-term durability challenges for steel-reinforced concrete. These might include:

- Marine structures that are directly exposed to chloride-laden seawater
- Coastal buildings and infrastructure which is exposed to airborne chlorides from nearby seawater bodies
- Bridge decks and pavements exposed to high levels of aggressive deicing salts
- Parking garages exposed to vehicles carrying deicing salts
- Highly corrosive industrial applications



Fig. 3.2—A seawall reinforced with GFRP bars (photo courtesy of Owens Corning Infrastructure Solutions).

In these applications, corrosion can be the limiting factor in the service life of a steel-reinforced concrete structure. If the expected service life cannot be met using steel-reinforced concrete, FRP reinforcement offers an attractive solution. In fact, there have been many examples of structures reinforced with GFRP in these applications such as the one shown in Fig. 3.2. Many examples of FRP-reinforced concrete structures that benefit from the non-corrosive nature of FRP reinforcement exist. These include seawalls, bridge decks, parking decks, and balconies on coastal high-rises.

In addition to environmental exposure to chlorides, chloride-induced corrosion of steel-reinforced concrete structures can also be caused by chlorides cast into the original concrete. This may occur with the use of calcium chloride admixtures for accelerating cure or from mixing water or aggregates that contain chlorides. In the case of steel-reinforced concrete, the amount of chlorides that are contained in a concrete mixture are strictly limited to avoid potential corrosion issues. However, there is the potential to ease these restrictions for FRP-reinforced concrete structures. This may allow for the use of non-compliant materials (such as seawater or beach sand) or higher doses of calcium chloride admixtures in concrete structures constructed with FRP reinforcement. Although most FRP-reinforced concrete construction still follows basic guidelines for material requirements for steel-reinforced concrete, there is potential for other approaches in the future that take advantage of the unique characteristics of FRP.

3.3—Lightweight

FRP is a high-strength, lightweight material. Its unit density is 1/3 to 1/4 that of mild steel. As an example, a No. 5 GFRP bar weighs approximately 0.30 lb/linear foot, whereas a No. 5 steel reinforcing bar weighs 1.04 lb/linear foot. The lighter weight of FRP reinforcement does allow for a slight reduction in the self-weight of reinforced concrete structure (GFRP reinforcement can reduce overall dead loads by around 5 lb/ft² compared to a steel-reinforced structure).

Most notably, the lighter weight of GFRP reinforcing bars can improve jobsite productivity, reduce transportation costs, and reduce complexities in areas that are difficult (Empananza et al. 2021; Steputat et al. 2022). In some cases, FRP reinforcement may be able to be located and placed without heavy lifting equipment that may be needed for similar steel reinforcement, as shown in Fig. 3.3. The lighter weight of FRP reinforcement also has benefits to worker health and safety. Repetitive lifting and placing of reinforcement produce less physical strain on workers handling FRP reinforcing bars versus steel reinforcement.



Fig. 3.3—A worker carrying a bundle of 12 No. 4 bars, 20 ft long. This bundle weighs less than 50 lb (photo courtesy MST Rebar, Inc.).

3.4—Easily cut

GFRP reinforcing bars are relatively easy to cut using a circular saw with a carborundum blade. Reciprocating saws with metal cutting blades can also be used. (Torches or shearing-type tools such as bolt cutters should never be used to cut FRP bars.) These bars are cut quicker and with far less effort than steel bars, which can speed and ease the installation process. Bundles of bars can be cut through easily in a single pass, as shown in Fig. 3.4a.

This is also a vital property for some applications of temporary reinforced concrete structures. Where reinforced concrete structures need to be constructed and subsequently removed, GFRP reinforcement is easily demolished or cut as concrete is removed. For example, in tunneling applications, FRP reinforcement is often used in diaphragm walls or piles that are constructed in the path of the tunnel boring machine (TBM). These structures are often needed to temporarily support elements of the tunnel, but need to be easily removed as the TBM advances through them. FRP reinforcement is easily consumed by TBMs making it an ideal method of reinforcing these temporary structures. The photo in Fig. 3.4b shows a “soft-eye” through an end wall as a TBM is advancing through it. Soft eyes reinforced with FRP bars that do not interfere with the TBM cutting mechanism have become a vital element of this type of construction.



Fig. 3.4a—A bundle of GFRP bars being cut through on a job site (photo courtesy GatorBar).



Fig 3.4b—A tunnel boring machine (TBM) exiting a “soft eye” reinforced with GFRP bars (photo courtesy of Owens Corning Infrastructure Solutions).

3.5—Nonmagnetic

FRP reinforcing bars are a non-metallic, non-ferrous reinforcement that is non-magnetic. This property is a benefit in certain applications involving exposure to electromagnetic fields. The use of steel reinforcement around equipment that generates magnetic fields can cause disruption to the operation of the equipment. Similarly, equipment that generates high current may induce high heat in adjacent steel reinforcement that would reduce its structural capacity. In these applications, non-metallic reinforcement becomes a necessary component of the safe and effective operation of the equipment. These applications may include areas around magnetic resonance imaging (MRI) units in hospitals, magnetic levitating (maglev) trains as shown in Fig. 3.5, and reactors in powerplants.

Magnetic resonance imaging (MRI) units used in medical facilities produce a very strong magnetic field (six times as strong as the earth’s magnetic field or more). Ferrous metal components, such as reinforcing steel, in the vicinity of the magnet used in these units can distort the magnetic field and disrupt the proper operation of these large devices. For this reason, the manufacturers of MRI units typically specify a maximum amount of ferrous metal that can be used within a certain radius of the magnet in these units. When these units are able to be placed on a concrete slab-on-ground, steel reinforcement or fiber-reinforced concrete may be able to satisfy temperature/shrinkage and structural reinforcement requirements without exceeding the ferrous metal limits prescribed by the MRI unit manufacturer. However, in many cases, especially where the units are placed on elevated slabs (a practice becoming more common), the steel reinforcement requirements far exceed the amount of ferrous metal that is recommended around these units. The structural demand can be quite high due to the substantial weight of an MRI unit (15 to 80 kip) and the vibrations it can induce. In these cases, FRP reinforcement is an ideal choice, as it can be designed to provide the required structural capacity and to limit floor vibration while not disrupting the magnetic field induced.



Fig. 3.5—GFRP reinforcement of a structure built to support a magnetic levitating (maglev) train (photo courtesy of Owens Corning Infrastructure Solutions).

3.6—Nonconductive

With the exception of carbon fiber-reinforced polymer (CFRP) bars, FRP bars generally are electrically non-conductive. They can be readily embedded with steel reinforcement without concern for galvanic corrosion cells being formed by mixing dissimilar electrically conductive metals (such as aluminum and mild steel or stainless steel and mild steel). CFRP bars are conductive and the potential for accelerating the corrosion of steel reinforcement embedded with CFRP bars does need to be considered.

3.7—Low thermal conductivity

Glass fiber-reinforced polymer (GFRP) and basalt fiber-reinforced polymer (BFRP) bars also have low thermal conductivity. They have been used in applications where thermal bridging needs to be avoided such as tying concrete faces of internally insulated precast concrete panels together.

The low thermal conductivity also has advantages in handling the reinforcement. Bars do not become excessively hot to the touch in hot, sunny conditions, nor do they become excessively cold to the touch in freezing conditions. Figure 3.7 is a photo of workers handling bars in cold conditions.



Fig. 3.7—Working with GFRP bars in cold conditions (photo courtesy of Galen-Panamerica/Binevir).

CHAPTER 4—CODES AND STANDARDS

Industry consensus design guidelines for fiber-reinforced polymer (FRP) reinforced concrete have been around for decades. ACI published the first design guidelines for FRP reinforced concrete in 2001: ACI PRC-440.1, “Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars.” ACI PRC-440.1 is a non-mandatory guideline that describes many of the unique aspects and design considerations for FRP-reinforced concrete. These guidelines have been used within the industry to use FRP reinforcement safely and effectively in a wide variety of structures. As this technology has grown, researchers and practitioners have advanced this technology to a point where more strict guidance on its use is now needed and possible. For this reason, in 2022, ACI published its first design code for FRP-reinforced concrete: ACI CODE-440.11. As stated earlier, this manual is a companion to ACI CODE-440.11. ACI CODE-440.11 is an ACI standard and an ANSI standard that is intended to be directly referenced and adopted by other building codes. The basic scope of ACI CODE-440.11 and the other related standards are discussed in this chapter.

4.1—Material tests and standards

ASTM D7957/D7957M is the current material standard for GFRP reinforcing bars. ACI CODE-440.11 code requirements cover only bars that conform to this ASTM D7957/D7957M specification. Additionally, the design examples in this manual are all based on bars with minimum properties conforming to ASTM D7957/D7957M. ASTM D7957/D7957M requires that GFRP bars be tested in accordance with a variety of test standards and meet minimum requirements. A list of the test methods of interest are shown in Table 4.1a. A list of the minimum properties of GFRP bars per ASTM D7957/D7957M requirements are shown in Table 4.1b.

Bar surface treatments are not standardized under ASTM D7957/D7957M. The bond characteristics of GFRP bars to concrete is important, and ASTM D7957/D7957M does prescribe minimum bond properties. However, it does not prescribe the method of surface treatment to achieve adequate bond. As such, GFRP bars from various manufacturers may look quite a bit different. Some manufacturers use sand-coated bars (Fig. 4.1(d)), some helically wound glass fiber along the bar to create a surface indentation (Fig. 4.1(b)), some etch a surface indentation in the bar (Fig. 4.1(e)), and others mold ribs on the surface of the bar (Fig. 4.1(c)). All these treatments or combinations of these (Fig. 4.1(a) and 4.1(f) use a combi-

Table 4.1a—Material properties and associated test methods

Property	ASTM test method	ASTM D7957/D7957M limit
Cross-sectional area	D7205/D7205M	Refer to Table 4.1b
Longitudinal tensile strength and modulus	D7205/D7205M	Refer to Table 4.1b
Shear strength	D7617/D7617M	19,000 psi guaranteed minimum
Bond strength to concrete	D7913/D7913M	1100 psi guaranteed minimum
Strength at bends in FRP bars	D7914/D7914M	60% of the strength of the straight portion of the bar minimum
Creep properties	D7337/D7337M	Not specified
Flexural properties	D790 and D4476/D4476M	Not specified
Coefficient of Thermal Expansion	E831 and D696	Not specified
Glass transition temperature	E1356	212°F minimum
Volume fraction	D3171 or D2584	Not specified
Moisture absorption	D570	1.0% to saturation at 122°F
Alkaline resistance	D7705/D7705M	Retain at least 80% of initial mean ultimate tensile force following 90 days submersion at 140°F
Longitudinal wicking	D5117	Not specified
Degree of cure	E2160	Mean greater than 95%

Table 4.1b—ASTM D7957/D7957M minimum properties for GFRP bars

Bar no.	Diameter, in.	Area, in. ²	Guaranteed ultimate tensile force, kip	Guaranteed ultimate tensile strength*, psi	Guaranteed tensile strength at bends, psi	Mean tensile elastic modulus, psi	Guaranteed transverse shear strength, psi	Guaranteed bond strength, psi
2	0.25	0.049	6.1	124,000	74,400	6,500,000	19,000	1100
3	0.375	0.11	13.2	120,000	72,000			
4	0.5	0.2	21.6	108,000	64,800			
5	0.625	0.31	29.1	93,900	56,400			
6	0.75	0.44	40.9	93,000	55,800			
7	0.875	0.6	54.1	90,200	54,000			
8	1.0	0.79	66.8	84,600	51,000			
9	1.125	1.0	82.0	82,000	49,200			
10	1.25	1.27	98.2	77,300	46,200			

*Guaranteed ultimate tensile strength is not specifically listed in ASTM D7957/D7957M. However, for convenience, in this table, it is calculated based on dividing the minimum guaranteed ultimate tensile force by the cross-sectional area.



Fig. 4.1—Photo of different GFRP bars with various surface treatments including helically wound (b), sand-coated (d), sand-coated and helically wound [(a) and (f)], helically grooved or etched (e), and molded ribs (c).

nation of helically wound glass fiber and sand coating) are acceptable, provided that the bond strength to concrete exceeds ASTM D7957/D7957M minimums. More recently, GFRP bar manufacturers have used additional coatings over the bar to improve handling (less splintering and abrasion) and UV resistance. Again, these coatings are acceptable, provided ASTM D7957/D7957M minimum bond strengths are met.

It is important to note that GFRP bars conforming to ASTM D7957/D7957M are numbered similar to mild steel reinforcement and have the same diameters and cross-sectional areas as the corresponding mild steel bars (for example, a No. 4 GFRP bar has a diameter of 0.25 in. and a cross sectional area of 0.2 in.², similar to a No. 4 steel bar).

Also important to note is that, unlike steel bars, the minimum tensile properties of GFRP bars vary based on bar size. As discussed in Chapter 2, smaller-diameter GFRP bars have greater ultimate tensile strength than larger-diameter GFRP bars due to a higher amount of stress near the perimeter of the bar versus the center of

the bar. This is reflected in the ASTM D7957/D7957M minimum properties and is an important design consideration in that selection of a different bar size means adjusting the diameter and area of the bar as well as the strength of the bar in design calculations. The elastic modulus and other properties such as shear strength and bond strength are typically not affected by bar size. Minimums for these properties in ASTM D7957/D7957M are not dependent on bar diameter.

ASTM D7957/D7957M uses the term “guaranteed” for many of the minimum material properties. This term is for those properties that are determined by a set statistical method. This method involves testing a representative sample of at least 24 bars (eight or more from three or more different production lots) and determining the average property and the standard deviation. The “guaranteed” property is the average property minus three standard deviations. This is meant to insure consistency of these properties.

Important design consideration on ASTM minimums

ACI CODE-440.11 allows the designer to use the minimum properties in ASTM D7957/D7957M in design equations or to use the properties reported by the bar manufacturer. Using the minimum ASTM D7957/D7957M properties does not require the designer to pre-select a specific bar manufacturer and this is the approach taken in the design examples in this manual. However, specific manufacturers may have bar properties that are superior to ASTM D7957/D7957M minimums that allow for more cost-efficient designs. The tensile modulus in particular plays a significant role in the outcome of the design of GFRP-reinforced concrete members. Higher-modulus bars will typically result in lower amounts of required reinforcement. Thus, it is often useful for designers to consider specific bar manufacture properties to optimize designs and allow them to be more cost effective. Many commercially available bars currently far exceed the minimum modulus of 6,500,000 psi in ASTM D7957/D7957M. Newer ASTM standards under development may in fact increase this value to 8,700,000 psi to reflect the improvements in current bar properties.

Although there are a variety of FRP reinforcing bars available from various manufacturers, ASTM D7957/D7957M only covers solid, round GFRP bars. A new ASTM standard covering both GFRP and BFRP solid, round bars is currently in development, and ASTM standards for other types of bars (for example, CFRP) may be developed in the future. Prior to the development of ASTM D7957/D7957M, ACI published a material standard for both CFRP and GFRP bars: ACI SPEC-440.6. This standard is still available for CFRP bars; GFRP bars were removed from the standard upon publication of ASTM D7957/D7957M.

4.2—Construction standards

ACI SPEC-440.5 provides a construction specification for GFRP reinforcement for concrete, and it is recommended to reference this specification in construction documents when GFRP reinforcement is being used. ACI SPEC-440.5 covers all aspects of GFRP bar handling and installation (including tying, bar supports, cutting, and other installation aspects). ACI SPEC-440.5 covers only aspects of construction related to the GFRP bars, however. It is meant to replace Section 3 on Reinforcement in ACI SPEC-301 (which addresses steel reinforcement only). ACI SPEC-301 provides additional requirements for other aspects of concrete construction and should also be referenced by construction documents for general concrete requirements, formwork, mixtures, and other concrete construction considerations.

4.3—Scope of ACI CODE-440.11

The scope of ACI CODE-440.11 is limited to bars that conform to ASTM D7957/D7957M. This is intended to allow the code to only address GFRP bars which are currently and historically the most commonly used type of FRP bar. (Guidance, but not code requirements, for the use of other bar types is currently in ACI PRC-440.1.) The code is also limited to concrete members reinforced with

only GFRP reinforcing bars. “Hybrid” structures with both GFRP and steel reinforcement are not covered. In cases where some concrete elements of a building are GFRP reinforced and some are steel reinforced, the ACI CODE-440.11 would apply to the GFRP-reinforced elements and ACI CODE-318 would apply to the steel-reinforced elements.

4.3.1 Earthquake-resistant structures—The seismic performance of GFRP-reinforced concrete structures is not well known. The lack of ductility of FRP bars is certainly a concern with seismic applications. (However, the large total elastic deformations GFRP-reinforced concrete can experience may allow for high energy dissipation. Future design approaches may make these elements an appropriate part of a seismic-force-resisting system.) Until the topic is more thoroughly understood, ACI CODE-440.11 does not provide code language for GFRP-reinforced elements in any element of any structure assigned to Seismic Design Categories D, E, and F. For Seismic Design Categories B and C, the code can be used for GFRP-reinforced elements that are not part of the seismic-force-resisting system per the Code Section 4.4.6.5 (for example, beams and slabs that only support gravity loads). The code does apply to all GFRP-reinforced concrete elements of buildings in Seismic Design Category A.

4.3.2 Fire-rated structures—The resins used to produce FRP bars typically have low temperature thresholds to maintain mechanical properties. The glass transition temperature of GFRP bars as discussed in Chapter 2 is typically in the range of 212°F (which is the ASTM D7957/D7957M minimum) to 250°F. As GFRP bars experience temperatures above these levels, they lose bond to the surrounding concrete. Because GFRP bars may experience these temperatures in a fire scenario, the code requirements in ACI CODE-440.11 Section 4.11.1 stipulate that: “Structural concrete reinforced with GFRP bars shall not be permitted where fire-resistance ratings are required except where the fire resistance has been shown to be adequate by calculations or tests and approved by the building official.” However, in the commentary, ACI CODE-440.11 Section R4.11.1 does suggest some methods to attain fire ratings that protect bond regions of the FRP bar. These are discussed in more detail in Chapter 12 of this manual. The recommendations in the commentary still require experimental verification before they become part of the code requirements. Until that time, GFRP bars are restricted to structures not requiring fire resistance ratings in the code unless the building official approves its use based on specific validation through testing or calculation.

4.3.3 Prestressed concrete—ACI CODE-440.11 does not cover prestressed concrete (concrete prestressed with FRP tendons). FRP prestressed concrete is a technology that has been developed and has been used on several large-scale projects. ACI PRC-440.4 was developed several years ago as a guideline for the engineering design of these types of structures and remains a resource for this technology. However, this practice has not been developed to the extent that regular GFRP reinforced concrete has been. As the technology expands, it may become a future part of the ACI CODE-440.11.

4.3.4 Masonry—ACI CODE-440.11 only covers GFRP reinforcement of concrete elements; it does not apply to masonry elements. However, TMS 402/602 does now include an appendix for designing masonry with GFRP reinforcement.

4.3.5 Other topics not covered—Based on the current state of knowledge and practice, there are several other topics covered by ACI CODE-318 that are not part of the ACI CODE-440.11. These include applications involving lightweight concrete, shotcrete, connections of precast members, diaphragms, deep beams, drilled piers and caissons, brackets and corbels, methods for designing discontinuity regions using strut-and-tie theory (where section-based methods do not apply), shear friction, and anchoring to concrete. As the research and application in these areas increases, these may be incorporated into future versions of the code.

4.4—ACI CODE-440.11 and the International Building Code

ACI CODE-440.11 has been adopted by the International Building Code (IBC) and the 2024 edition of the IBC will reference ACI CODE-440.11 for require-

Table 4.4a—Limits permissible story height for sprinklered buildings with no fire resistance rating required by type

	IIB	IIIB (except exterior walls)	VB
Assembly	3	3	2
Business	4	4	3
Education	3	3	2
Mercantile	5	5	2
Residential R-1, R-2	5	5	3

Table 4.4b—Limits on permissible square footage of sprinklered buildings with no fire resistance rating required by type

	IIB	IIIB (except exterior walls)	VB
Assembly	34,000	34,000	22,000
Business	92,000	76,000	36,000
Education	58,000	58,000	38,000
Mercantile	50,000	50,000	36,000
Residential R-1, R-2	64,000	64,000	28,000

ments for GFRP-reinforced concrete. The IBC will place stricter limits on the use of GFRP reinforcement than ACI CODE-440.11 currently does. Specifically, the IBC will only allow the use of GFRP bars in buildings assigned to Seismic Design Category A. It will also only allow for the use of GFRP reinforcement in structures not requiring a fire rating.

Fire resistance ratings are generally required for reinforced concrete columns, elevated slabs, beams, and structural walls in building types that require structural fire ratings (such as high-rise buildings, schools, and hospitals). Elements such as slabs-on-ground and footings generally do not require fire ratings. Additionally, there are many common building types that do not require structural fire resistance ratings, especially when other fire protection methods (such as the use of sprinkler systems) are in place. Tables 4.4a and 4.4b give limitations on building story height and building area (square footage) where no fire resistance requirement is required provided sprinkler systems are in place. Type II-B, Type III-B, and Type-VB construction do not require structural fire ratings. Type II-B buildings are constructed from unprotected non-combustible materials but do not have fire resistance rating requirements. Concrete buildings with FRP reinforcement would fall into this category because the construction is non-combustible but does not possess/require a fire resistance rating. Type III-B buildings are typically a combination of masonry or concrete walls with a fire rating and roof and floor assemblies constructed of wood with no fire ratings required. Usually these comprise historic buildings. Type VB construction is unprotected wood construction common in residential construction. FRP reinforcement may be used in concrete components of such buildings. IBC Section 504 provides additional information.

4.5—ACI CODE-440.11 and other codes

ACI CODE-440.11 is a dependent code on ACI CODE-318. However, GFRP bars have utility in structures covered by other ACI codes such as ACI CODE-332, “Code Requirements for Residential Concrete” and ACI CODE-350, “Code Requirements for Environmental Engineering Concrete Structures”. Similarly, the International Building Code will reference ACI CODE-440.11, but the International Residential Code (IRC) is currently not planning reference to ACI CODE-440.11. As acceptance of GFRP reinforcement grows, it is anticipated that other codes such as those mentioned will adapt to include provisions for GFRP bars. Currently ACI publishes a separate manual, *ACI Recommended Practice Guidelines for FRP Bars in Pre-Engineered Projects (MNL-6)* to provide specific recommendations on the use of GFRP reinforcement in residential applications.

CHAPTER 5—APPLICATIONS

Use of GFRP reinforcement began in the late 1970s as a non-metallic alternative to steel reinforcement. Much of the initial interest in GFRP reinforcement was due to applications that demanded non-metallic reinforcement. These include reinforcement of structures around magnetic resonance imaging (MRI) units in hospitals as shown in Fig. 5a and in magnetic levitating (maglev) trains such as shown in Fig. 3.5. In both these applications, ferrous materials can interfere with the operation of the equipment and GFRP reinforcement as a non-metallic, non-ferrous alternative has become a standard construction practice for these applications. Some of the largest early applications of GFRP reinforcing bars were in the Gonda Building at the Mayo Clinic in Rochester, MN, built in 2001 and at the National Institute of Health in Bethesda, MD, built in 1984, both involving reinforcing concrete elements in close proximity to MRI units.



Fig. 5a—A GFRP reinforcement cage being transported to a concrete placement in a room that will eventually house an MRI unit (photo courtesy of Doug Gremel).

During this time, there was also interest in the non-corrosive nature of GFRP reinforcement and an increasing awareness of the deterioration of steel-reinforced concrete due to corrosion of the embedded steel. By the mid-1990s, several bridge structures were constructed using GFRP reinforcement as way of reducing maintenance costs associated with corrosion issues. There are several early examples of bridge decks exposed to deicing salts being reinforced with GFRP bars to reduce corrosion and spalling of the concrete surface. One example is shown in Fig. 5b.

Early applications of GFRP reinforcement were coupled with and supported by research into the structural capacity of GFRP-reinforced concrete members. Early studies of FRP-reinforced concrete focused on beams and slabs reinforced with GFRP (Faza and GangaRao 1993; Nanni 1993; Benmokrane 1996). These early studies verified that many of the same principles of steel-reinforced concrete also apply to GFRP-reinforced concrete.

Later studies focused on specific aspects of GFRP reinforcement such as durability (Benmokrane and Rahman 1998; Porter et al. 1997). Much of the durability research was concerned with the ability of GFRP bars to sustain loads in the alkaline environment of cast concrete. These studies indicated that proper resin systems in these bars would provide protection to the glass fiber reinforcement and allow for long-term performance. This has been further substantiated through

long-term studies of bars in service (Gooranorimi et al. 2019). More discussion of durability is in Chapter 2.

Research on bond characteristics of GFRP reinforcement to concrete (Bakis et al. 1998; Bank et al. 1998), the shear strength of concrete elements reinforced with FRP (Tureyen and Frosch 2003) and reinforcing other concrete elements such as square and circular columns (De Luca et al. 2010; Afif 2013) have all helped serve as the basis the development of ACI CODE-440.11. Additional information on the research and initial applications of GFRP reinforcement can be found in ACI PRC-440.1, “Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars”.

Today, GFRP reinforcing bars are used extensively in coastal construction, bridge construction, and general construction where lightweight, easy-to-place reinforcement is advantageous. A few recent examples are highlighted in Fig. 5c to 5g.



Fig. 5b—Bridge decks reinforced with GFRP bars as a way of mitigating corrosion issues when exposed to deicing salts. The photo on the left is of the Sierrita de la Cruz Creek Bridge in Amarillo, TX, which was constructed in 2000. The photo on the right is of the Floodway Bridge over the Red River in Winnipeg, MB, Canada, which consumed over 310,000 lb (140,000 kg) of GFRP reinforcing bars and was constructed in 2006.



Fig. 5c—The use of GFRP reinforcing bars on Bray’s Bayou Hike & Bike Trail in Houston, TX, allowed the contractor to work efficiently using lighter equipment. This was in areas where heavier equipment was not always possible to use. The contractor was able to pre-tie grids of reinforcement that were easily moved into position.

Project size: 10 ft wide x 9 miles long, or 475,000 ft²

· GFRP bar: GatorBar GFRP #3

· Construction timeframe: Summer/Fall 2022



Fig. 5d—The foundations and shear walls of this eight-story building were reinforced with GFRP reinforcing bars. Sizes ranging from No. 3 to No. 11 bars were used and required complicated bend geometries for anchorages and ties. This illustrates the utility of GFRP bars in complex and demanding structural applications.

- Project size: 1,400,000 linear feet of GFRP bar
- GFRP bar: MST-BAR Sizes No. 3, No. 5, No. 8, and No. 11
- Construction timeframe: 2020



Fig. 5e—The Low Battery Seawall and seaside promenade is a historic landmark in Charleston, SC. The seawall was raised 1.8 ft (0.5 m) to match the High Battery Wall. GFRP reinforcement was used due to its ability to resist corrosion in this severe coastal environment and for aesthetic concerns with steel corrosion product leaching onto the surface of the concrete (Steputat et al. 2022).

- Project size: 3.9 miles of seawall
- GFRP bar: Fiberglas™ Rebar by Owens Corning Infrastructure Solutions
- Construction timeframe: 2021-2022



Fig. 5f—Currently the largest single project to use GFRP reinforcement, the Jizan Flood Mitigation Channel is a megaproject to protect the refining facilities of Saudi Aramco on the banks of the Red Sea in Saudi Arabia. The GFRP bar provides corrosion resistance in this coastal region and its light weight allowed for faster installation than traditional methods. There was a reported 21% cost savings in initial construction using GFRP bars versus epoxy-coated steel bars (Villen Salan et al. 2021).

- Project size: Total length of 13 miles; the channel reaches a maximum width of 236 ft
- GFRP bar: Dextra ASTEC Glass Rebar, Galen-Panamerica/Binevir Fiberglass Rebar, and IKK Mateenbar™
- Construction timeframe: 2019-2020



Fig. 5g—The Harker Island Bridge in Carteret County, NC, is a 3.2 mile-long vehicular bridge near the Outer Banks that includes 28 spans. The bridge deck is reinforced with GFRP bars, and the bridge girders are both prestressed with carbon FRP (CFRP) tendons and reinforced with GFRP bars. The entire bridge structure uses almost no steel reinforcement. FRP solutions were used on this bridge to combat the corrosive, brackish coastal environment of the Outer Banks.

- Project Size: 1,575,000 linear feet of GFRP reinforcement
- GFRP bar: Fiberglas™ Rebar by Owens Corning Infrastructure Solutions No. 4, No. 5, No. 6, and No. 8
- Construction timeframe: 2022-2023

CHAPTER 6—FIRE

Fire resistance of GFRP-reinforced concrete members is a key design consideration for many applications.

Generally, steel-reinforced concrete structures designed according to ACI CODE-318 have good inherent fire endurance. The specified concrete cover over the reinforcing steel provides insulation and protection to the steel in a fire event, and the steel itself can withstand high temperatures while losing only a fraction of its strength. In the case of GFRP-reinforced concrete members, the concrete cover does still provide protection and insulation for the reinforcement. However, GFRP bars lose structural capacity at much lower temperatures than steel. At temperatures above the glass transition temperature (T_g) of FRP materials, described in more detail in Chapter 2, the polymer that binds the fibers together in an FRP material loses a considerable level of stiffness and bond. When bars reach this temperature in a GFRP-reinforced concrete member subject to fire, the strength of the member is significantly reduced. For most commercially available GFRP bars, this glass transition temperature is near 212°F. Compare this to steel reinforcement, which would only lose at most 10% of its tensile strength at 212°F and would maintain 50% of its tensile strength even at temperatures exceeding 1000°F (ACI CODE-216.1).

Although the glass transition temperature is a critical temperature for FRP materials, the behavior of GFRP-reinforced concrete in a fire is more complex than simply assuming that a concrete member will collapse once GFRP bars reach the glass transition temperature. The polymer in the material certainly does lose most of its structural properties once it reaches T_g . However, the glass fibers in the material can withstand much higher temperatures and maintain tensile strength. It has been observed that GFRP bars in concrete members subject to fire can provide and transfer some level of tensile reinforcement to maintain overall structural integrity of the member even when temperatures exceed T_g (Hajiloo and Green 2018). For example, when a GFRP-reinforced concrete simply-supported beam is subject to a fire from below, if the ends of the GFRP reinforcement can be kept cool (below the T_g) and maintain bond to the concrete over their development length, the beam can maintain substantial loads even though the GFRP reinforcement loses bond along the middle portion of the beam. These cool anchorage zones are often a key strategy for providing fire endurance of GFRP-reinforced concrete structures.

The fire resistance of GFRP-reinforced concrete is an area of much recent and ongoing research. ACI CODE-440.11 provides guidance in this area based on available research. It is expected that the code will continue to advance on this subject as more research becomes available.

Currently, when GFRP reinforced concrete is being considered in fire-rated construction, the unique properties of GFRP bars and performance of GFRP-reinforced concrete need to be carefully considered. This chapter aims to describe the current provisions of ACI CODE-440.11 related to fire resistance and offer other fire protection strategies that have been suggested. There are, however, no current code requirements for fire resistance ratings of GFRP-reinforced concrete. If GFRP-reinforced concrete elements are being considered for fire-rated construction, close coordination with local building officials or other authorities having jurisdiction are highly recommended.

6.1—Fire resistance in ACI CODE-440.11

Section 4.11 of the code addresses fire resistance of GFRP-reinforced concrete. The code provisions are direct, simply stating that GFRP-reinforced concrete shall not be permitted where fire-resistance ratings are required unless approved by the building official. Approval by the building official would necessitate additional calculations or tests to demonstrate fire endurance. The commentary to the code in Section R4.11, however, provides additional guidance on how fire ratings might be achieved. It is important to note that this guidance in the commentary is not mandatory under the code. The recommendations in the commentary require further vali-

Table 6.1—Fire resistance rating provided by minimum cover for non-bond-critical GFRP reinforcement from commentary to ACI CODE-440.11

Specified cover, in.	Fire resistance, hours		
	Slabs and non-load bearing walls	Beams	Columns and load-bearing walls
2	1.5	1	0.5
1-1/2	1	0.5	0.5
3/4	0.5	NA	Less than 0.5

dation before they become part of the code and before mandatory requirements for achieving fire ratings are available.

The commentary suggests that fire resistance be achieved through a combination of appropriate concrete cover and detailing. The commentary provides a table in Section R20.5.1.3.1 that suggests what fire resistance rating (hourly rating) can be achieved for various levels of concrete cover (this table is reproduced here as Table 6.1). This table is for non-bond-critical GFRP reinforcement. Non-bond-critical reinforcement requires that the bars also be detailed such that sufficient anchorage is maintained in a fire. Stated another way, this is detailing to ensure that cool anchorage zones are maintained in a fire event.

To achieve the fire resistance ratings in Table R20.5.1.3.1 in the commentary to the code (Table 6.1 in this manual), the commentary Section R4.11.1 provides recommendations for non-bond-critical details to prevent anchorage failures during a fire event. These details aim to adequately insulate the GFRP reinforcement in anchorage zones (such as areas at bar terminations where development and embedment length is critical and at lap splices where anchorage is required to transmit stress from one bar to another). Additionally, Section R4.11.1 recommends that the maximum bar stress (at any location) under service loads be limited to $0.3f_{fu}$. This is to address the issue of bars between anchorage locations losing tensile strength once the polymer softens or decomposes under high temperatures. The bars between anchorages need to possess enough reserve of tensile capacity to resist service loads in these conditions.

The non-bond-critical details in the commentary use either additional concrete cover (through a haunch or drop panel) or additional insulation at anchorage locations. These methods are intended to keep the average temperature of the bar to below 210°F for the fire endurance duration. The details shown in Fig. 6.1 is reproduced from the commentary (refer also to commentary Fig. R4.11.1a through d). The commentary provides dimensions for these details for the specific case of providing 2 hours of fire endurance to the anchorage zone when the clear cover to the remaining section is at least 1.5 in., the concrete compressive strength is at least 4000 psi, and the maximum bar stress due to service loads is 35 ksi.

The commentary also provides alternate recommendations for providing embedment into areas not exposed to fire. The embedment is recommended to be the bond development length calculated using a bar stress of 1.3 times the maximum stress in the bars due to the full service loads ($1.0D + 1.0L$).

From a practical standpoint, it may not always be possible to know where all anchorage zones and splice locations will occur in a typical member. Thus, the use of insulation over entire members may be more practical. Fire protection materials for steel construction are common and these types of approaches may be applicable to GFRP-reinforced concrete as well. The commentary suggests that insulation of vertical elements (columns and walls) can be achieved with protective coverings that keep the surface temperature of the concrete below 300°F during the fire endurance period.

It should again be stressed that the details in ACI CODE-440.11 are not mandatory and do not result in achieving code-required fire resistance ratings. These details must be evaluated and approved by building officials when GFRP-reinforced concrete is to be used in fire rated construction.

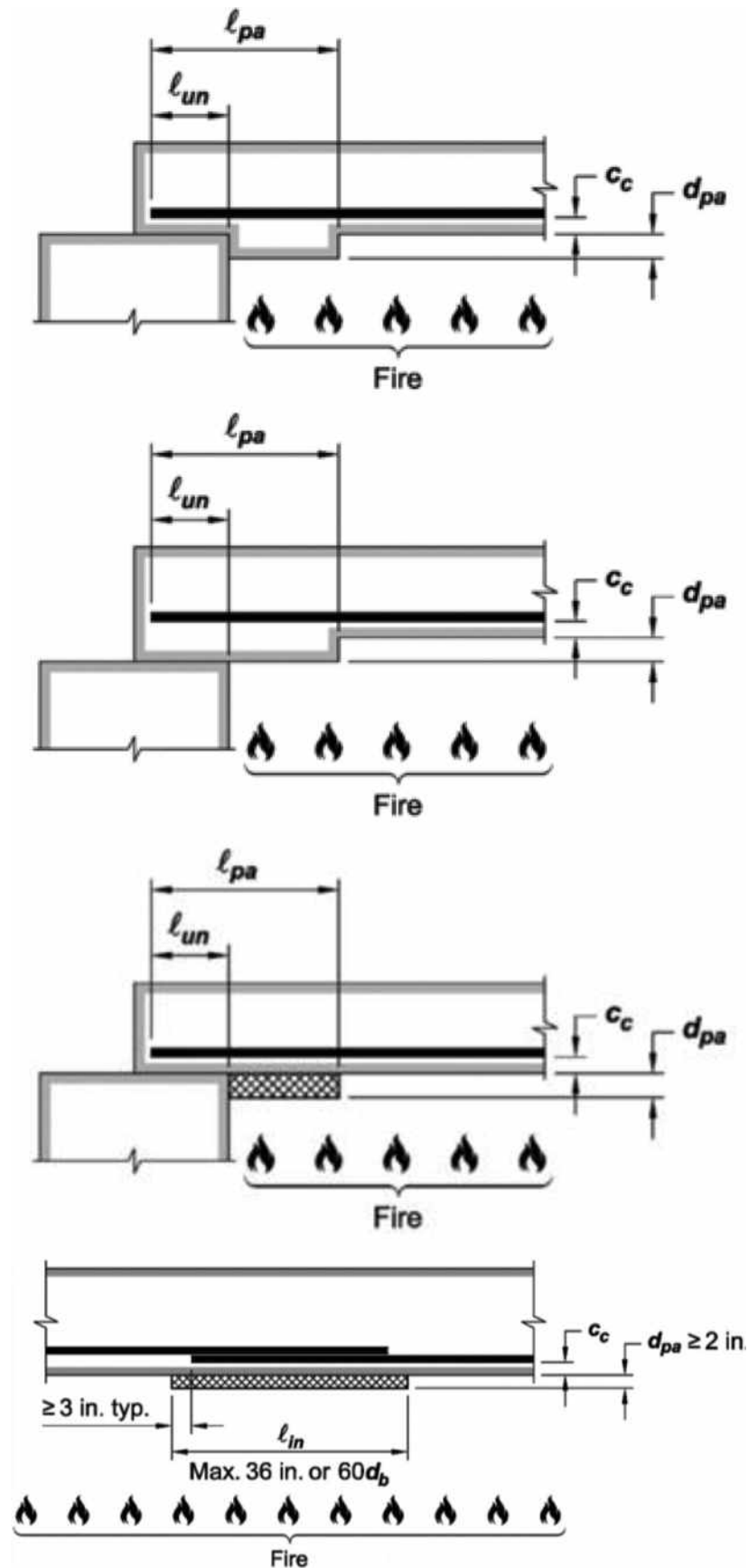


Fig. 6.1—Fire protection of GFRP bars in anchorage zones from commentary to ACI CODE-440.11.

6.2—Other fire protection strategies

Beyond the recommendations in the commentary to the code, there are other fire protection strategies that have been suggested.

(a) Using hooked or inclined anchorages (similar to steel truss bars used in older concrete construction) can effectively increase the cover in anchorage zones and improve the fire resistance.

(b) Hybrid approaches using steel reinforcement in the bottom of members and GFRP reinforcement in the top of members may provide better fire resistance. Temperatures within concrete in a fire are highest on exposed faces of members above a fire. Using steel reinforcement where these temperatures are greatest and GFRP reinforcement where temperatures are lower is an approach to fire resistance. (In applications where GFRP reinforcement is used to avoid corrosion from deicing chemicals, it is common to use GFRP near the top of the concrete where chloride exposure is high and steel in the bottom of the concrete where chloride exposure is less. This also becomes a more ideal arrangement for fire protection.) The design of members with both steel and GFRP reinforcement is not covered in ACI CODE-440.11.

(c) Numerical modeling and calculation procedures can also be used to determine fire resistance ratings. ACI CODE-216.1 provides methods for determining fire ratings of steel-reinforced concrete. Aspects of these methods may be applicable to GFRP-reinforced concrete as well. Specific numerical models have also been suggested (Bisby et al. 2005) that can provide practical solutions to fire protection of GFRP-reinforced concrete elements.

All these approaches require testing and validation to be considered by building officials. ACI CODE-216.1 under Section 1.2 provides requirements for alternative methods for fire protection of steel-reinforced concrete. These include qualification by testing in accordance with the requirements of ASTM E119. The criteria in ACI CODE-216.1 are specific to steel-reinforced concrete, but would be reasonable criteria for GFRP-reinforced concrete as well.

CHAPTER 7—ONE-WAY SLABS

The basic principles for flexural design and shear design of GFRP-reinforced concrete beams are described in detail in Chapter 9 and apply to GFRP reinforced one-way slabs as well. The design example in this chapter illustrates these principles and the additional provisions of the code that apply specifically to one-way slabs.

Chapter 7 of ACI CODE-440.11 provides the specific provisions for one-way slabs. It applies to non-prestressed slabs reinforced for flexure in one primary (longitudinal) direction.

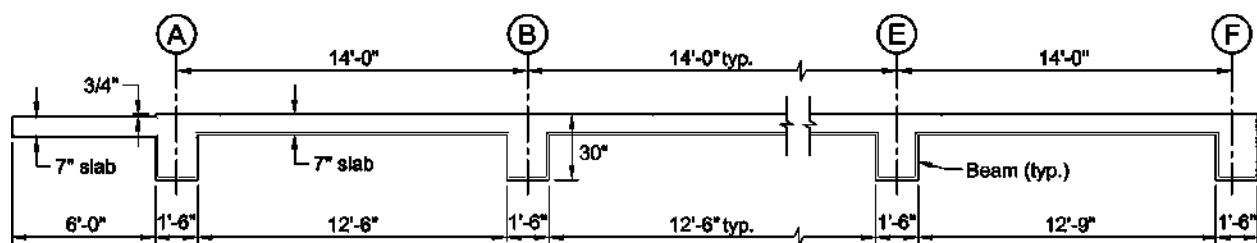
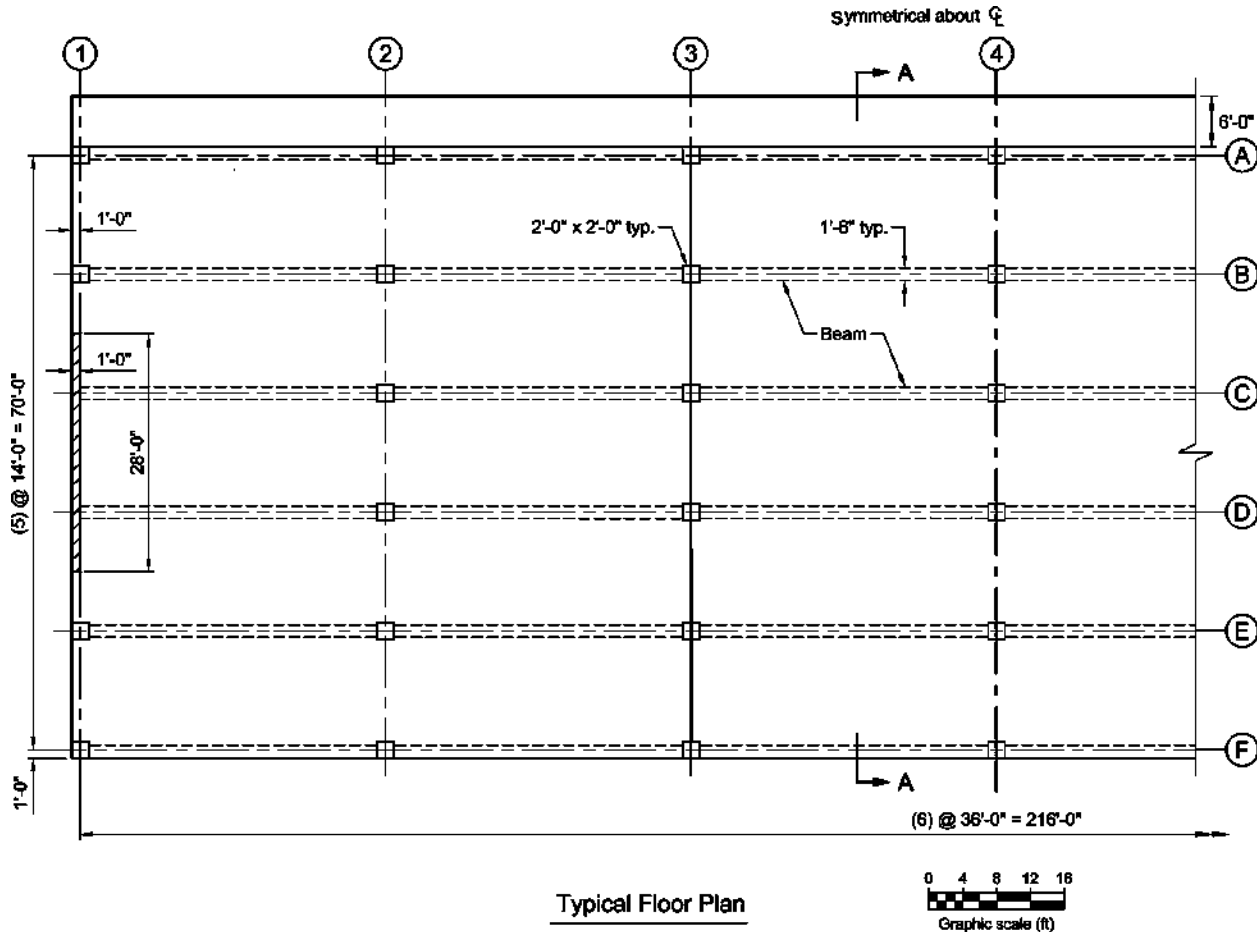
GFRP-reinforced one-way slabs are typically governed by serviceability requirements rather than strength. The design example presented here starts with determining the size and spacing of bars based on crack width requirements. This is generally a good starting point for the design of continuous one-way slabs as this is often the controlling factor in design.

ONE-WAY SLAB EXAMPLE—FIVE SPAN CONTINUOUS SLAB

Design and detail the one-way slab spanning between beams on a typical floor. The one-way slab consists of five spans of 14 ft each. The slab is supported by 18 in. beams. A 6 ft cantilever extends at one end of the slab.

Concrete properties:

$f'_c = 5000$ psi (specified concrete compressive strength)



STEP 1—MATERIAL REQUIREMENTS

Mixture proportions

Concrete mixture design generally follows typical concrete construction practices and must be consistent with ACI CODE-440.11 Chapter 19 durability requirements and strength requirements. ACI 301 is a reference specification that is coordinated with ACI CODE-440.11. It is encouraged to reference ACI 301 specifications into project specifications.

Based on durability and strength requirements of ACI CODE-440.11 Chapter 19, the compressive strength is specified at 28 days to be at least 5000 psi and normalweight concrete is used.

GFRP Bars

ACI 440.11 Section 20.2.1.3 requires that GFRP bars conform to ASTM D7957/D7957M. For design material properties, ACI CODE-440.11 allows either the use of properties as reported by the manufacturer (determined in accordance with ASTM

D7957/D7957M) or to use the minimum properties specified in D7957/D7957M. For purposes of this example problem, the minimum properties specified in D7957/D7957M will be used. This approach would allow for any manufacturer's GFRP bar that conforms to D7957/D7957M to be used and would not require pre-selecting a specific GFRP bar manufacturer.

No. 4 bars will be selected for the flexural (longitudinal) reinforcement of the one-way slab. The tensile properties of GFRP bars vary based on the bar size. The bar size does need to be pre-selected in the design. If the bar size requires change, the material properties must also be changed.

The minimum properties specified in ASTM D7957/D7957M for a No. 4, straight GFRP bar are:

$E_f = 6,500,000$ psi	(modulus of elasticity for No. 4, straight GFRP bars)
$T_f = 21.6$ kip	(minimum guaranteed ultimate tensile force for No. 4 straight GFRP bars)
$A_{fb} = 0.2$ in. ²	(nominal cross-sectional area of each No. 4 GFRP bar)
$d_b = 0.5$ in.	(nominal diameter of No. 4 GFRP bars)

The guaranteed tensile strength of the bars can be determined based on the guaranteed ultimate tensile force specified in ASTM D7957/D7957M and the nominal cross-sectional area. The guaranteed values specified in ASTM D7957/D7957M are not, however, the properties used in design. The code requires that the guaranteed properties be reduced by an environmental reduction factor C_E to account for any long-term losses in strength. This reduction factor is applied to the guaranteed strength resulting in the design strength of the bars. The corresponding rupture strain can also be computed by dividing the resulting design strength by the tensile modulus. The tensile modulus is not reduced by the environmental reduction factor.

Calculate guaranteed tensile strength of straight No. 4 GFRP bars:

$$f_{fu}^* = \frac{T_f}{A_f} = \frac{21.6 \text{ kip} \times 1000 \text{ lb/kip}}{0.2 \text{ in.}^2} = 108,000 \text{ psi}$$

Determine the environmental reduction factor:

$$C_E = 0.85$$

Sec. 20.2.2.3

Calculate the design strength of No. 4 GFRP bars:

$$f_{fu} = C_E f_{fu}^* = 0.85(108,000 \text{ psi}) = 91,800 \text{ psi}$$

Sec. 20.2.2.3

Calculate the design rupture strain of No. 4 GFRP bars:

$$\epsilon_{fu} = \frac{f_{fu}}{E_f} = \frac{91,800 \text{ psi}}{6,500,000 \text{ psi}} = 0.0141 \text{ in./in.}$$

20.2.2.5

STEP 2—SLAB GEOMETRY

Slab depth

ACI CODE-318 permits a one-way slab to be designed without having to calculate deflections, if (among certain other criteria) the depth of the beam satisfies ACI CODE-318 Table 9.3.1.1. ACI CODE-440.11, however, requires that deflections be calculated in all cases due to the lower elastic modulus of GFRP bars versus steel bars. In other words, satisfying ACI CODE-318 Table 9.3.1.1 is not sufficient for meeting deflection requirements when using GFRP reinforcement. However, ACI CODE-318 Table 9.3.1.1 can serve as a reasonable starting point for slab depth. Actual deflections must still be calculated and checked against allowable deflection criteria and are part of this example problem.

The slab has five continuous spans plus a cantilevered end. The slab depth is estimated based on the governing conditions of the end span and the cantilever portion.

Estimate the slab depth using ACI CODE-318 for a slab with one end continuous:

$$h \geq \frac{\ell}{24} = \frac{(14 \text{ ft})(12 \text{ in./ft})}{24} = 7 \text{ in.} \quad \text{ACI CODE-318 Table 7.3.1.1}$$

Estimate the depth of the cantilever portion of the slab:

$$h \geq \frac{\ell}{10} = \frac{(6 \text{ ft})(12 \text{ in./ft})}{10} = 7.2 \text{ in., say, 7 in.} \quad \text{ACI CODE-318 Table 7.3.1.1}$$

→ Try $h = 7 \text{ in.}$

STEP 3—LOADS AND LOAD PATTERNS

Self-weight

The unit weight of reinforced concrete is typically taken as the unit weight of concrete alone plus 5 lb/ft³ to allow for the weight of the reinforcing steel (150 lb/ft³ in this case). GFRP reinforcement is much lighter weight than steel reinforcement. For purposes of this example, a conservative unit weight of the structure is taken as 150 lb/ft³. However, it would be acceptable to use 145 lb/ft³ for GFRP-reinforced concrete.

Calculate the self-weight of the slab:

$$w_{sw} = (7 \text{ in.}/12 \text{ in./ft})(150 \text{ lb/ft}^3) = 87.5 \text{ lb/ft}^2$$

Dead loads and live loads

To account for weights from ceilings, partitions, and HVAC systems, add 15 lb/ft² as miscellaneous dead load.

Calculate the uniformly distributed dead load:

$$w_D = (87.5 \text{ lb/ft}^2 + 15 \text{ lb/ft}^2) = 102.5 \text{ lb/ft}^2$$

The service live load is 100 lb/ft² in assembly areas and corridors per Table 4-1 in ASCE/SEI 7-10.

Uniformly distributed live load:

$$w_L = 100 \text{ lb/ft}^2$$

Factored loads

The slab resists gravity only and lateral forces are not considered in this problem. Therefore, only the first two load combinations in ACI CODE-440.11 Table 5.3.1 need to be considered.

Calculate the total factored uniformly distributed load:

Factored load is the maximum of:	$w_u = 1.4 w_D$	
	$= 1.4(102.5 \text{ lb/ft}^2)$	
	$= 143.5 \text{ lb/ft}^2$	5.3.1a
	$w_u = 1.2 w_D + 1.6 w_L$	
	$= 1.2(102.5 \text{ lb/ft}^2) + 1.6(100 \text{ lb/ft}^2)$	
	$= 283 \text{ lb/ft}^2$	5.3.1b
		Controls

STEP 4—ANALYSIS

Shear and moment diagrams

Both ASCE/SEI 7 and ACI CODE-440.11 provide guidance for addressing live load patterns. Either approach is acceptable. ACI CODE-440.11 Section 6.4.2 allows the use of the two load patterns shown in Fig. E1.1. Factored dead load is applied on all spans and factored live load is applied as follows:

- (a) Maximum positive M_u near midspan occurs with factored live load on the span and on alternate spans.
- (b) Maximum negative M_u at a support occurs with factored live load on adjacent spans only.

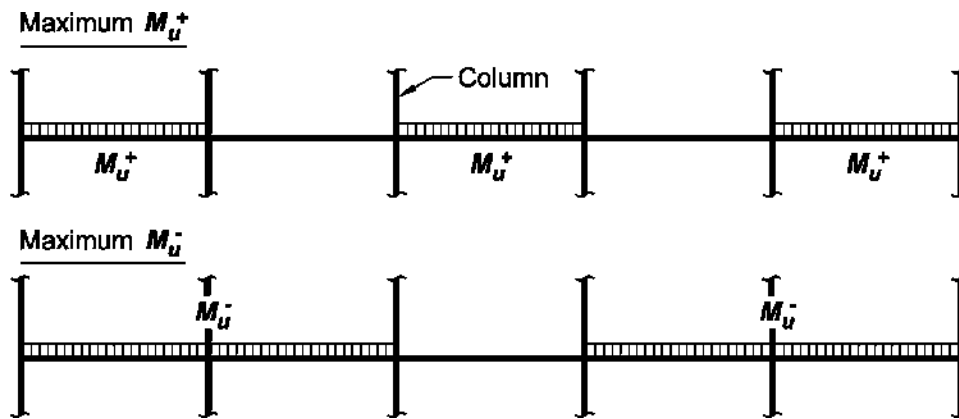


Fig. E1.1—Live load loading pattern

Because the building relies on the building's other members to resist lateral loads, the slab qualifies for braced frame assumptions, as discussed in the commentary to ACI CODE-440.11 Section 6.3. Analysis should be consistent with the overall assumptions about the role of the slab within the building system. Because the lateral force resisting system only relies on the slab to transmit axial forces, a first-order analysis is adequate.

The slab's negative design moments are taken at the face of support as is permitted by the Code Section 7.4.2 (Fig. E1.2).

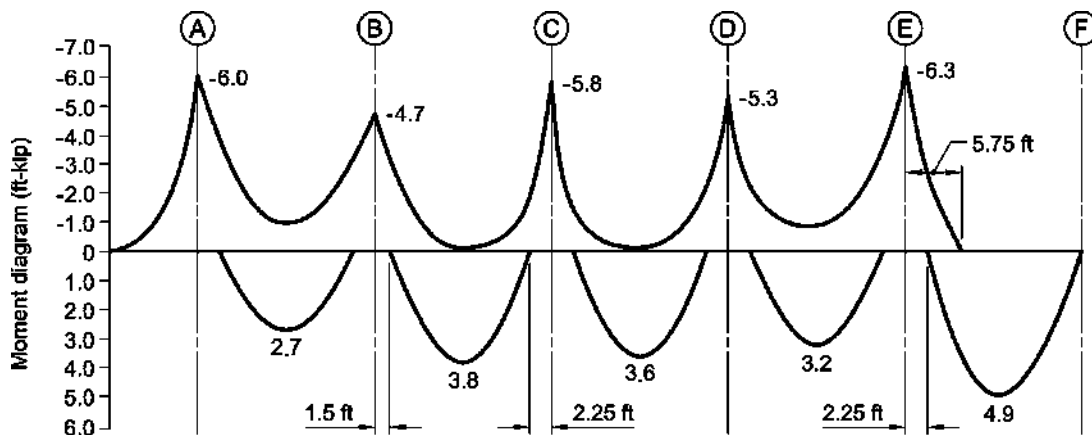


Fig. E1.2—Factored moment envelope

The slab's maximum shear is taken at the support centerline for simplicity. The maximum shear under all conditions is 2.4 kip (Fig. E1.3).

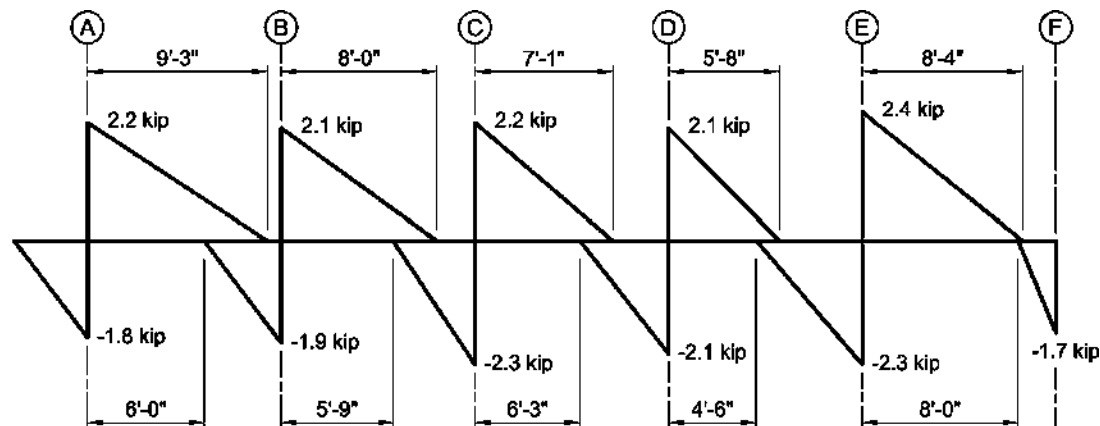


Fig. E1.3—Shear envelope.

STEP 5—FLEXURAL DESIGN FOR CRACK CONTROL

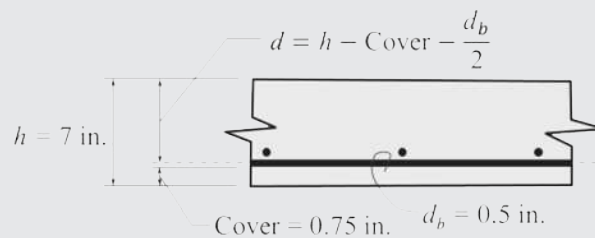
Unlike steel-reinforced concrete slabs, GFRP-reinforced concrete slabs are typically controlled by serviceability, not by strength. The design of GFRP-reinforced concrete slabs thus starts with determining the amount of reinforcement needed to

satisfy serviceability considerations, then strength is checked. This is opposite of the normal manner in which steel reinforcement is determined by starting with designing for strength and then checking the beam for serviceability criteria.

Because there are several factors that influence serviceability, the determination of the amount of required reinforcement is often an iterative process. In this example, an initial layout of flexural reinforcement is assumed. Bar spacing requirements (which are related to crack width) are then checked. Spacing requirements often control the design of GFRP-reinforced concrete slabs, so ensuring that spacing requirements are met is a good first step in the design process. Service level stresses in the bars are then checked against limits and finally deflection limits are checked in this step.

The minimum permissible cover to the flexural reinforcement is 0.75 in. per ACI CODE-440.11 Section 20.5.1.3.1 for slabs not exposed to weather or the ground. Note that this slab is in an interior, conditioned space that will not likely experience wide temperature variations. If wide temperature variations are expected, a larger cover of at least two bar diameters ($2d_b$) would be recommended to account for the high transverse coefficient of thermal expansion of GFRP bars (as noted in Commentary Section R20.5.1.3.1). Also note that it is assumed that a fire rating is not required or that fire protection would be provided by means other than concrete cover. (Table R20.5.1.3.1 in the commentary to the code suggests that 0.75 in. of cover would provide the slab with a 30-minute fire rating.)

Determine the effective depth assuming No. 4 GFRP bars with 3/4 in. clear cover:



$$\begin{aligned} d &= h - \text{Cover} - d_b/2 \\ &= 7 \text{ in.} - 0.75 \text{ in.} - 0.5 \text{ in.}/2 \\ &= 6 \text{ in.} \end{aligned}$$

Note negative moment regions will have the same effective depth, but the reinforcement would have 0.75 in. cover on the topside instead of the bottom.

Crack width is directly related to GFRP tensile stress in a cracked slab under total service loads. To determine the tensile stress, a spacing needs to be assumed and then checked against spacing requirements. An initial spacing of 6 in. is selected and checked.

Determine the area of reinforcement per unit width assuming a trial bar spacing of 6 in. on center:

$$A_f = A_{fb} \left(\frac{b}{s} \right) = 0.31 \text{ in.}^2 \left(\frac{12 \text{ in.}}{6 \text{ in.}} \right) = 0.4 \text{ in.}^2$$

Determine the reinforcement ratio:

$$\rho_f = \frac{A_f}{bd} = \frac{0.4 \text{ in.}^2}{12 \text{ in.}(5.25 \text{ in.})} = 0.0056$$

Determine the concrete modulus of elasticity:

$$E_c = 57,000\sqrt{f'_c} = 57,000(\sqrt{5000 \text{ psi}}) = 4,030,509 \text{ psi}$$

19.2.2.1b

Determine the modular ratio of GFRP to concrete:

$$n_f = \frac{E_f}{E_c} = \frac{6,500,000 \text{ psi}}{4,030,509 \text{ psi}} = 1.61$$

Calculate the ratio of the cracked neutral axis depth to the effective slab depth:

$$\begin{aligned}
 k_{cr,rect} &= k_{cr} = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f \\
 &= \sqrt{2(0.0056)(1.61) + ((0.0056)(1.61))^2} - 0.0056(1.61) \\
 &= 0.125
 \end{aligned}
 \quad \text{R22.5.5.1a}$$

Calculate the cracked neutral axis depth:

$$k_{cr}d = (0.125)(6 \text{ in.}) = 0.8 \text{ in.}$$

Find cracked section moment of inertia:

$$\begin{aligned}
 I_{cr} &= \frac{bd^3}{3} k_{cr}^3 + n_f A_f d^2 (1 - k_{cr})^2 \\
 &= \frac{12 \text{ in.}(6 \text{ in.})^3}{3} (0.125)^3 + 1.61(0.4 \text{ in.}^2)(6 \text{ in.})^2 (1 - 0.125)^2 \\
 &= 19.5 \text{ in.}^4
 \end{aligned}
 \quad \text{ACI PRC-440.1 Sec. (7.3.2.2a)}$$

From Fig. E1.2, the maximum factored moment in the slab is 6.3 kip-ft per unit width (negative moment at the first interior support).

The associated service level moment can also be calculated:

$$M_s = \frac{w_D + w_L}{w_u} M_u = \frac{102.5 \text{ lb/ft}^2 + 100 \text{ lb/ft}^2}{283 \text{ lb/ft}^2} 6.3 \text{ kip-ft} = 4.5 \text{ kip-ft}$$

Assuming slab is cracked, determine the stress in the bars under the maximum service level moment:

$$\begin{aligned}
 f_{fs} &= M_s \frac{n_f d (1 - k_{cr})}{I_{cr}} \\
 &= (4.5 \text{ kip-ft} \times 12,000 \text{ lb-in./kip-ft}) \frac{1.61(5.25 \text{ in.})(1 - 0.153)}{28.0 \text{ in.}^4} \\
 &= 23,521 \text{ psi}
 \end{aligned}
 \quad \begin{array}{l} \text{Sec. R24.6.1} \\ \text{(with } M_s \text{ instead of } M_{s,sus}) \end{array}$$

Bond factor:

$$k_b = 1.2 \quad \text{Sec. 24.3.2.3}$$

Least distance from surface of reinforcement to the tension face:

$$c_c = \text{cover} = 0.75 \text{ in.}$$

Maximum center-to-center spacing of bars is the greater of the following two expressions:

$$\begin{aligned}
 s_{max} &= \frac{0.032 E_f}{f_{fs} k_b} - 2.5 c_c \\
 &= \frac{0.032(6,500,000 \text{ psi})}{(26,957 \text{ psi})(1.2)} - 2.5(0.75 \text{ in.}) \\
 &= 5.49 \text{ in.} \quad \textbf{Governs}
 \end{aligned}
 \quad \text{Sec. 24.3.2a}$$

$$\begin{aligned}
 s_{max} &= \frac{0.026 E_f}{f_{fs} k_b} \\
 &= \frac{0.026(6,500,000 \text{ psi})}{(26,957 \text{ psi})(1.2)} \\
 &= 5.99 \text{ in.}
 \end{aligned}
 \quad \text{Sec. 24.3.2b}$$

$$s = 6 \text{ in.} > s_{max} = 5.49 \text{ in.} \quad \textbf{NG}$$

Trial bar spacing (6 in.) is greater than the maximum permissible spacing of 5.49 in. and is, thus, not sufficient for crack control. Repeat the calculation process trying a smaller spacing of 5 in. on center.

Spacing of No. 4 bars	A_s , in. ²	k_{cr}	I_{cr} , in. ⁴	f_{fs} , psi	s_{max} (24.3.2a), in.	s_{max} (24.3.2b), in.	Governing s_{max} , in.	OK?
5 in.	0.48	0.136	23.0	19,677	6.93	7.16	6.93	OK

Larger bars with greater spacing could have been selected for this section (for example, No. 5 bars at 8 in. on center). No. 4 bars are used here for consistency with other parts of the structure such as the negative moment reinforcement in beams and due to their smaller development length.

The bar stress at service must also be checked against the code requirements in Section 24.3.2.2. This is to ensure that crack widths do not exceed 0.028 in. Per Commentary Section R24.3.2.2, if a smaller crack width is desired, the limit may be linearly adjusted.

Find the distance from the extreme tension fiber to the center of the reinforcement:

$$d_c = \text{cover} + \frac{d_b}{2} = 0.75 \text{ in.} + \frac{0.5 \text{ in.}}{2} = 1.0 \text{ in.}$$

Calculate the ratio of distance from the neutral axis to the extreme tension fiber to the distance from the neutral axis to the center of the tensile reinforcement:

$$\beta_{cr} = \frac{h - k_{cr}d}{d - k_{cr}d} = \frac{7.0 \text{ in.} - (0.130)(6 \text{ in.})}{6 \text{ in.} - (0.130)(6 \text{ in.})} = 1.19$$

Calculate the bar stress limit to limit crack width to 0.028 in.:

$$f_{fs} \leq \frac{0.014E_f}{d_c\beta_{cr}k_b} \quad \text{Sec. 24.3.2.2}$$

$$f_{fs} = 19,677 \text{ psi} \leq \frac{0.014(6,500,000 \text{ psi})}{(1.0 \text{ in.})(1.19)(1.2)} = 63,637 \text{ psi} \quad \text{OK}$$

Minimum spacing requirements in ACI CODE 440.11 are based on constructability considerations and allowing for space for good flow and consolidation of concrete around the bars. They are the same as requirements in ACI CODE-318. We will assume that the maximum aggregate size, d_{agg} , is 1 in. for this example.

Calculate the minimum clear spacing requirements:

Clear spacing shall be at least the greatest of:	1 in. $d_b = 0.5 \text{ in.}$ $(4/3)d_{agg} = (4/3)(1 \text{ in.}) = 1.33 \text{ in.}$	Governs	Sec. 25.2.1

Calculated the associated minimum center-to-center spacing of bars:

$$s_{min} = 1.33 \text{ in.} + d_b = 1.33 \text{ in.} + 0.5 \text{ in.} = 1.83 \text{ in.} < s = 5 \text{ in.} \quad \text{OK}$$

Use No. 4 bars at 5 in. on center spacing.

Maximum positive and negative moments have similar magnitudes (<20% difference), use the same bar size and spacing at the top and bottom of the slab.

STEP 6—CHECK DEFLECTIONS

With the spacing of the reinforcement determined for controlling crack width, the calculated deflections can then be checked against code limits. The deflection of the first interior span (from Column Line E to F) and the deflection of the cantilever need to be checked as these are the two controlling cases. Both immediate deflections due to live load and long-term deflections need to be checked.

Basic properties of the section need to be calculated first. Because the reinforcement in the slab is the same top and bottom, the basic section properties will be the same for positive and negative bending.

Calculate the modulus of rupture for the concrete:

$$f_r = 7.5\sqrt{f'_c} = 7.5\sqrt{5000 \text{ psi}} = 530 \text{ psi} \quad \text{Sec. 19.2.3.1}$$

Compute the distance from the elastic, uncracked neutral axis to the tension face:

$$y_t = \frac{h}{2} = \frac{7 \text{ in.}}{2} = 3.5 \text{ in.}$$

Determine section gross moment of inertia:

$$I_g = \frac{bh^3}{12} = \frac{(12 \text{ in.})(7 \text{ in.})^3}{12} = 343 \text{ in.}^4$$

Determine slab cracking moment:

$$\begin{aligned} M_{cr} &= \frac{f_r I_g}{y_t} \\ &= \frac{(530 \text{ psi})(343 \text{ in.}^4)}{3.5 \text{ in.}} \times 12,000 \text{ lb-in./kip-ft} \\ &= 4.33 \text{ kip-ft} \end{aligned} \quad \text{Sec. 24.2.3.5a}$$

Bischoff and Gross (2011) recommend that GFRP reinforced slabs use a reduced cracking moment (80% of code equation) to account for tensile stresses caused by shrinkage. Per Section 24.2.3.5, the effective moment of inertia can only be taken as I_g when the applied moment is less than $0.8M_{cr}$.

Revised cracking moment:

$$0.8M_{cr} = 0.8(4.33 \text{ ft-kip}) = 3.46 \text{ ft-kip} \quad 24.2.3.5$$

The immediate deflections due to live load will be determined based on calculating the deflection due to the total service load then subtracting the deflection due to dead load. For the service load deflection of the first interior span from Column Line E to F, there are two approaches to determining the effective moment of inertia (I_e) of the slab (the deflection of the cantilevered portion will be calculated separately). A weighted average stiffness could be used as described in Section 24.2.3.6 of the code because the applied midspan moment and negative moment at the support will result in different effective moments of inertia. (The code provision is for a slab with both ends continuous. ACI PRC-435 Eq. (4.3.2.5c) gives an additional expression for a slab with one end continuous, as in this case.) Alternately, the effective moment of inertia can be calculated from the maximum service level moment (the moment at the first interior support in this case) and applied across the entire slab per Section 24.2.3.7 of the code. The second option will be used here because there is not a substantial difference between the moment at midspan and the moment at the first interior support.

Deflection of the first interior span (Column Line E to F):

Find the stiffness variation factor for the total service load case. In lieu of more detailed calculations, use the ACI CODE-440.11 equation that conservatively assumes slabs are simply supported:

$$\gamma_s = 1.72 - 0.72 \left(\frac{0.8M_{cr}}{M_s} \right) = 1.72 - 0.72 \left(\frac{3.46 \text{ kip-ft}}{4.5 \text{ kip-ft}} \right) = 1.17 \quad 24.2.3.5b$$

Determine the effective moment of inertia of the slab for the maximum service moment:

Because $M_s = 4.5 \text{ kip-ft} > 0.8M_{cr} = 3.46 \text{ kip-ft}$,

$$I_{e,s} = \frac{I_{cr}}{1 - \gamma_s \left(\frac{0.8M_{cr}}{M_s} \right)^2 \left[1 - \frac{I_{cr}}{I_g} \right]} \quad 24.2.3.5$$