# Comparing Global Codes for FRP Reinforced Concrete

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**Abstract.** Globally, the advancement of FRP reinforcement for concrete structures has resulted in several international code-writing bodies to put forth new design codes and standards for this technology. The American Concrete Institute (ACI) has recently published ACI Code-440.11–22 Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars. In Europe, EN 1992 (Eurocode 2) Annex R is being proposed to cover Embedded FRP Reinforcement. And in Canada, the Canadian Standards Association has published a code on Design and Construction of Building Structures with Fibre-reinforced polymers (most recently in 2012) under CSA S 806. This presentation will provide an objective overview of these three international standards with the aim of highlighting differences in scope and in design approaches utilized. Comparative design examples will illustrate where these codes provide similar outcomes and where they differ.

**Keywords:** Codes · Design · Design guidelines · GFRP · Structural concrete

## 1 Introduction

Over the past several years, efforts to codify the design and construction of concrete structures reinforced with fiber reinforced polymer (FRP) bars have resulted in several new global standards for FRP reinforced concrete. The Canadian Standards Association (CSA) published the first design standard, CSA S 806 *Design and construction of building structures with fibre-reinforced polymers*, in 2002 [1]. It was subsequently reapproved in 2021. Accompanying that design standard was a material standard, CSA S 807, published in 2019 [2]. In the United States, the American Concrete Institute (ACI) recently published ACI CODE 440.11 *Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars – Code and Commentary* in 2022 [3]. This design and construction standard centers around the use of GFRP bars that conform to the ASTM D 7957 material standard [4]. A new Annex R on *Embedded FRP Reinforcement* to EN 1992 (Eurocode 2) [5] is currently being proposed that would cover the design of FRP reinforcement tested according to the ISO 10406-1 standard [6]. All of these standards are coming at a time when the use of FRP reinforcement is expanding globally and creating the need for codified design and construction practices for this technology.

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All of these standards are based on similar engineering principles that account for the unique properties of FRP reinforcement. However, there are significant differences in the scope of these standards both in terms of the types of FRP reinforcement that are covered and in the types of structural members and actions that are covered. Understanding these differences in scope is useful for further development of these codes and standards, and this paper aims to highlight these differences.

Additionally, while the basic engineering considerations for designing with FRP reinforcement are similar for these three standards, the way in which they are applied are quite different. This leads to significant differences in the final design of FRP reinforced concrete members when using the three codes. Thus, this paper also aims to illustrate those differences and demonstrate how those differences impact the design of structural members.

## 2 Format and Scope of Design Standards

Both ACI 440.11 and Annex R of EC 2 take the approach of modifying existing concrete codes to provide special provisions for FRP reinforcement. In the case of ACI 440.11, the code is the same format and structure as ACI 318 *Building Code Requirements for Structural Concrete* [7]. Specific provisions of ACI 318 that require change due to the use of FRP reinforcement are modified, provisions that are not affected by using FRP reinforcement are left unmodified, and some provisions that do not apply or are excluded are removed. Similarly, EC 2 Annex R clauses and subclauses are similar to the main part of EC 2, again only modifying those clauses that would require a different requirement when using FRP reinforcement. CSA S 806 on the other hand is a stand-alone code but references other standards such as CSA A23.3 *Design of Concrete Structures* [8]. It should also be noted that CSA S 806 covers a broad range of other FRP applications in construction including FRP strengthening systems and FRP cladding. These are separate documents in ACI and EC2.

The overall scope of the three design standards is different in terms of the types of FRP reinforcement covered, the types of structural members covered, and the structural actions covered. CSA S 806 is the most broad covering numerous types of FRP reinforcement, FRP prestressing, and seismic design of FRP reinforced concrete. ACI 440.11 is very specific in the type of FRP reinforcement covered focusing only on solid, round, glass FRP bars. But it does give broad guidance on the use of this reinforcement in a variety of applications. EC2 Annex R covers carbon and glass bars also in a broad range of applications.

All three codes cover the basic structural actions of FRP reinforced concrete members subjected to flexure, shear, torsion, axial compression, and axial tension (and combinations thereof).

Table 1 provides a comparison of the various types of FRP reinforcement and topics that each code covers.

### 2.1 Seismic Design

ACI 440.11 specifically limits the use of FRP reinforced concrete to structures that have a low risk of damage due to seismic events or to only structural elements that are not

**Table 1.** Topics Covered by Each Code

| | ACI 440.11 | CSA S 806 | EC 2 Annex R |
|---|---|---|---|
| Glass FRP | Covered | Covered | Covered |
| Basalt FRP | | Covered | |
| Aramid FRP | | Covered | |
| Carbon FRP | | Covered | Covered |
| Solid Round Bars | Covered | Covered | Covered |
| Solid Square Bars | | Covered | Covered |
| Grids | | Covered | Covered |
| Seismic Design | No specific design provisions, but limits use of FRP reinforcement in structures with higher seismic risk | Provides design provisions for FRP and hybrid FRP/steel reinforced members | No specific design provisions |
| Fire | Requires fire to be addressed and design guidance provided in commentary | Requires fire to be addressed but no specific guidance provided | No specific guidance provided |
| Fatigue | Not addressed | Not addressed but does include a test method for bar fatigue | Not addressed |
| Strut-and-Tie Models | Not addressed | Covered | Not addressed |
| Prestressing (with FRP tendons) | Not addressed | Covered | Not addressed |
| FRP Reinforced Lightweight Concrete | Not addressed | Not addressed | Not addressed |

part of the seismic force resisting system in structures with moderate risk of damage due to seismic events. It also limits the use of FRP reinforced concrete in all structural members of structures that have a high risk of damage in seismic events.

CSA S 806 on the other hand provides specific design requirements for FRP reinforced concrete members subject to seismic loads. It also provides guidance on hybrid structures reinforced with both FRP reinforcement and steel reinforcement under seismic loading.

## 2.2 Fire

All three codes do effectively require that FRP reinforced concrete structures be evaluated for the potential effects of fire exposure. ACI 440.11, however, provides specific guidance on design and detailing for fire resistance, albeit in the commentary not in mandatory code language.

## 3 Design Approaches

All of these codes consider the unique properties of FRP compared to steel reinforcement and provide appropriate provisions to modify the design approaches for traditional steel reinforced concrete to accommodate those properties unique to FRP. All of the codes specifically address the linear, brittle behavior of FRP reinforcement in tension, the lower shear strength of FRP bars, lower compressive strength of FRP bars, and lower strength of bars at bends. Additionally all of the codes address the specific effects of the elastic modulus and bond of FRP bars on serviceability criteria such as deflections and crack width. Long term effects from ageing and from creep (and potential for creep rupture) are also considerations that each code addresses in detail. The way these topics are addressed do, however, differ somewhat. These differences in approaches are highlighted here.

### 3.1 Environmental Durability of FRP Bars

All three standards recognize that the strength of FRP bars over time may be reduced due to exposure to alkalinity, moisture, heat and other environmental factors. In ACI 440.11 this is addressed by using an environmental reduction factor, $C_E$, of 0.85 applied to the initial, manufacturer reported tensile strength. The $C_E$ factor is applied before any subsequent design calculations or additional limitations are imposed. It is also important to note that this factor is required uniformly and cannot be modified through testing a specific bar.

In EC2 Annex R, there are two separate durability effects considered. A factor considering temperature effects, $C_t$, is applied and equal to 1.0 for indoor and underground applications and equal to 0.80 for outdoor members exposed to heating from sunlight. An additional ageing factor, $C_e$, is also applied that can be taken as 0.70. The ageing factor can, however, be adjusted by appropriate testing per methods in ISO 104060-1. Like in ACI 440.11, these two durability factors are applied to the initial tensile strength before other subsequent design calculations or additional limitations are imposed.

CSA S 806 does not use an environmental factor like the other two codes. However, CSA S 807 does have material requirements for bars that require a certain retention of tensile strength under exposure to a number of accelerated ageing protocols.

### 3.2 Creep Rupture

Creep rupture is the phenomenon whereby FRP materials exposed to sustained tensile stresses will creep over time and may suddenly rupture due to the sustained stress and accumulated creep strain. All three codes recognize the importance of limiting the sustained stress in FRP bars, particularly glass FRP (GFRP) bars, to levels that they can safely sustain without experiencing this phenomenon. The way in which this is considered, however, differs significantly in the ACI 440.11 and CSA S 806 standards versus the EC 2 Annex R standard.

Both ACI 440.11 and CSA S 806 place a limitation on the service level sustained stress that the bars are allowed to experience. CSA S 806 limits the total service level tensile stress to 25%, 65%, and 35% of ultimate tensile strength for glass, carbon, and aramid FRP bars respectively. For GFRP it imposes an additional limit on only the sustained portion of service level tensile strain of 0.002 mm/mm (which is roughly 15% to 20% of the ultimate elongation for GFRP bars). ACI 440.11 similarly places a limit of 20% of the ultimate tensile strength (after environmental reduction factors have been applied) on the sustained portion of service level stresses for GFRP bars. These limits in both of these codes are set limits that cannot be adjusted through testing.

EC2 Annex R imposes a coefficient, $C_c$, which is multiplied along with the two other environmental factors, $C_t$ and $C_e$, to the initial tensile strength before other subsequent design calculations or additional limitations are imposed. The value of $C_c$ is the strength under sustained load versus the strength under short-term load and is to be taken as 0.35 for GFRP and 0.80 for carbon FRP (CFRP). Since this value is applied before subsequent design calculations, it has a significant effect on all aspects of the design. In particular it effects the design moment capacity at ultimate or moment of resistance, unlike ACI 440.11 and CSA S 806 which only apply creep rupture limits to sustained service loads. The value for $C_c$ can, however, be adjusted through testing according to ISO 10406-1, Sect. 12. Figure 1 shows the differences in the approaches between ACI 440.11 and EC 2 Annex R.

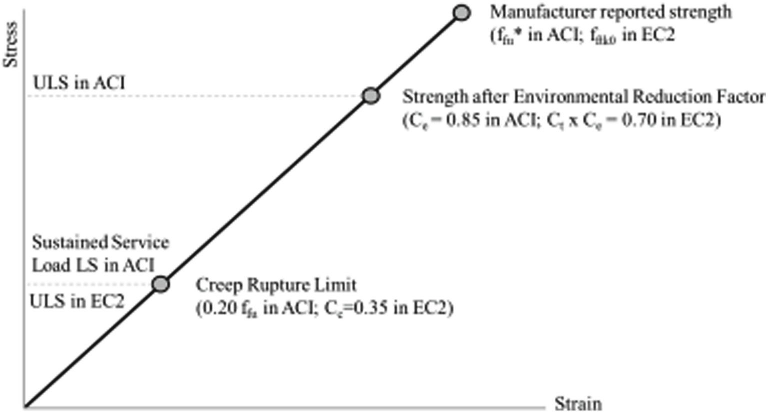


**Fig. 1.** Illustration of the various environmental limits imposed by ACI 440.11 versus EC2 Annex R on the tensile strength of GFRP straight bars in an indoor environment

### 3.3 Crack Width Limitations

Relative to crack width calculations, it should be noted here that the CSA S 806 approach is to limit the “z-factor” based on the Gergely-Lutz expression for crack width [9]. The 1999 and later versions of ACI 318 began to use a maximum spacing requirement in lieu of the “z-factor” approach. ACI 440.11 follows the current ACI 318 spacing approach with some modifications. The differences in these two approaches affect the design in the example problem to follow. For concrete beams with relatively large cover, such as the 40-mm used in the example problem, there can be significant differences in the design of the required reinforcement to control cracking using the two approaches.

Furthermore, ACI 440.11 allows for a somewhat relaxed crack width limitation for GFRP reinforced concrete versus steel reinforced concrete. The provisions in ACI 440.11 are written around a permissible crack width of 0.71-mm with commentary that the designer may want to use stricter limits depending on the application. CSA S 806 similarly does not limit crack width directly, but the "z-factor" limits correspond to a crack width of roughly 0.6-mm for interior applications and 0.5-mm for exterior applications which are again slightly relaxed from steel reinforced concrete requirements. EC2 Annex R uses a more strict limit of 0.4-mm.

### 3.4 Combined Bending and Axial Compression

ACI 440.11, CSA S 806 and the proposed EC 2 Annex R all cover the use of use of longitudinal FRP reinforcement in members under combined bending and axial compression. All three standards also recognize that the compressive capacity of FRP bars is both substantially lower than and less reliable than the tensile capacity of FRP bars. CSA S 806 and EC 2 Annex R both require that the compressive capacity of the FRP bars be completely ignored. Bars that are under compression are essentially treated as voids in the corresponding portion of concrete under compression. ACI 440.11 differs in that it allows bars in compression to be treated as concrete. Bars in compression are assumed to have the same strength and modulus as the surrounding concrete in compression. This allows for some minor utilization of the compressive capacity of FRP bars.

### 3.5 Other Structural Actions

There are also differences in the calculation of other structural actions such as shear capacity, torsion capacity, deflection, and crack width. Most of these differences, however, are due to differences in the way that the "parent" codes (ACI 318, CSA A23.3, and EC2) treat these topics. The three codes generally take an approach to modify provisions in the "parent" code based on the reduced stiffness of FRP bars and in some cases the difference in bond or shear strength of the bars.

## 4 Design Example

The provisions of each of the three codes are used to design the flexural reinforcement for the simply supported concrete beam shown in Fig. 2. The basic proportions (height, width, cover) of the beam were kept consistent to focus on the design of the flexural reinforcement.

The 500-mm wide by 850-mm tall beam spans 10-m and is subject to a uniformly distributed live load or variable load of 15-kN/m and a uniformly distributed dead or permanent load of 2-kN/m plus the self-weight of the beam. The reinforced concrete is assumed to have unit density of 2300-kg/m$^3$ and is in an interior environment.

The longitudinal FRP bars used in this problem are M25 GFRP bars meeting the requirements of ASTM D 7957 (bar diameter = 25.4-mm, cross section area per bar = 510-mm$^2$). The tensile properties for the GFRP bars are assumed to be the minimum values allowed by ASTM D 7957 (initial reported tensile strength = 582-MPa, reported elastic modulus = 44,800-MPa).

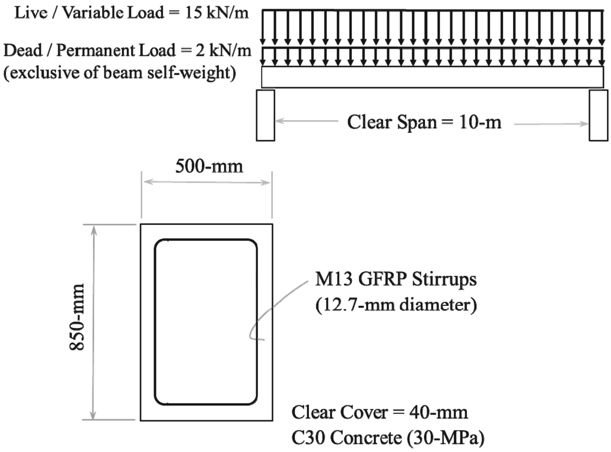


**Fig. 2.** Design parameters for the example problem using a simply-supported beam subject to a uniformly distributed live/variable load and dead/permanent load

The design of this beam using the three codes is summarized in Fig. 3. The required longitudinal reinforcement varies from seven (7) required longitudinal bars in ACI 440.11 to nine (9) bars in CSA S 806 to fourteen (14) bars in EC 2 Annex R.

### 4.1 Design Per ACI 440.11

The design of the beam according to the provisions of ACI 440.11 is governed by deflection limitations and requires seven (7) M25 longitudinal GFRP bars. The computed immediate mid-span deflection is 25-mm compared to a deflection limitation of 28-mm. Serviceability often governs the design of GFRP reinforced concrete beams designed per ACI 440.11. It is commonplace for deflection limitations to control.

ACI 440.11 also requires serviceability checks on the service level stress and the maximum bar spacing which are both related to crack width. The service level stress in the GFRP bars was computed as 130-MPa versus a service stress limit of 134-MPa which is also close to controlling the design of this beam. The maximum center-to-center bar spacing was computed to be 110-mm versus an actual spacing of 53-mm. There is no direct calculation of crack width in ACI 440.11 provisions, but the spacing and service level stresses would correspond to a crack width of approximately 0.70-mm.

At the ultimate limit state, the design moment capacity of the section is computed to be 673.9-kN-m compared to a moment demand of 475-kN-m. The section was determined to be compression-controlled, but in the transition between compression and tension-controlled.

### 4.2 Design Per CSA S 806

The design of the beam per CSA S 806 is governed by the limits on the "z-factor" related to crack width limits and requires nine (9) M25 longitudinal GFRP bars. The calculated "z-factor" is 45-kN/mm which is at the code limit for structures in an interior environment. This again corresponds roughly to a crack width of 0.6-mm.

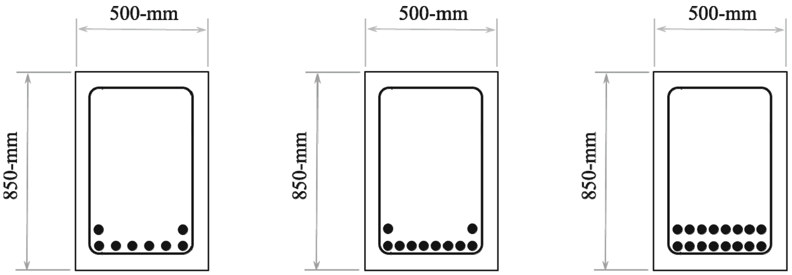
Other serviceability limits are met. Computed immediate deflection is 20-mm versus a limit of 28-mm. The service level stress in the longitudinal bars is computed to be 101-MPa versus a limit of 146-MPa (25% of ultimate strength). The strain level at service is calculated as 0.0012 versus the 0.002 creep rupture limit for GFRP bars.

At the ultimate limit state, the moment of resistance is determined to be 1055-kN-m versus a moment demand of 464-kN-m. The section is compression controlled.

### 4.3 Design Per EC2 Annex R

The design of the beam per EC2 Annex R is governed by the ultimate limit state and requires fourteen (14) M25 longitudinal GFRP bars. The moment of resistance is determined to be 484-kN-m versus a moment demand of 473-kN-m.

The calculated crack width was determined to be 0.19-mm versus a limit of 0.4-mm. The service level stresses must also be limited to 80% of the design tensile strength of the FRP. The computed service level stress is 67-MPa compared to the limit of 76-MPa.



(7) M25 GFRP Longitudinal Bars
**ACI 440.11**

(9) M25 GFRP Longitudinal Bars
**CSA S 806**

(14) M25 GFRP Longitudinal Bars
**EC2 Annex R**

**Fig. 3.** Design parameters for the example problem using a simply-supported beam subject to a uniformly distributed live/variable load and dead/permanent load

## 5 Conclusion

While there are difference in the approach of the three codes considered, the codes do focus on similar requirements and limitations related to the specifics of using FRP reinforcement. There is a significant design implication of how the long term sustained loading on the bars is considered. The limits used in ACI 440.11 and CSA S 806 focus on sustained stresses at the service level limit state, whereas EC2 Annex R focuses on the ultimate limit state. However, both ACI and CSA have set limits that cannot be modified through testing where Annex R does allow this to allow for more efficient use of higher performing bars. These are important considerations as these global codes continue to develop.

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