Guide for the Design and Construction of Concrete Reinforced with FRP Bars (ACI 440.1R-03)

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Abstract

This paper reports on the key features of the "Guide for the Design and Construction of Concrete Reinforced with FRP Bars" issued by the American Concrete Institute (ACI). For new construction, FRP bars have been used as the internal reinforcement in concrete members to replace conventional steel rebars for a host of reasons. The principles for design and construction were first established and proposed to industry in 2001. The third revision of the guide is now under preparation.

The Existing Document

In 2001, the American Concrete Institute (ACI) published the first guide offering recommendations for design and construction of FRP-reinforced concrete (RC) structures as an emerging technology (ACI 440, 2001). The document was re-issued with some minor changes in 2003 (ACI 440, 2003). At present, the ACI Technical Committee 440 is working on the third edition that presents some significant changes from the current document. The current and new ACI documents of reference only address non-prestressed FRP reinforcement. A separate ACI guide is devoted to prestressed concrete using FRP tendons.

General

FRP materials are anisotropic and are characterized by high tensile strength with no yielding only in the direction of the reinforcing fibers. This anisotropic behavior affects the shear strength and dowel action of FRP bars, as well as their bond performance. Design procedures account for a lack of ductility in concrete reinforced with FRP bars. An FRP-RC member is designed based on its required strength and then checked for serviceability and ultimate state criteria (e.g., crack width, deflection, fatigue and creep rupture endurance). In many instances, serviceability criteria may control the design.

Design values. The design tensile strength that should be used in all design equations is given as $f_{fu} = C_E f_{fu}^{*}$, where: f_{fu} = design tensile strength of FRP considering reductions for service environment; C_E = environmental reduction factor given in Table 1 for various fiber types and exposure conditions; and f^{*}_{fu} = guaranteed tensile strength of an FRP bar defined as the mean tensile strength of a sample of test specimens, $f^{*}_{u,ave}$,, minus three times the standard deviation, σ, ($f^{*}_{fu} = f^{*}_{u,ave} - 3\sigma$).

The design rupture strain is determined similarly, whereas the design modulus of elasticity is the same as the average value reported by the manufacturer. Design parameters in compression are not addressed since the use of FRP rebars in this instance is discouraged.

Flexure

Behavior and failure modes. If FRP reinforcement ruptures, failure of the member is sudden and catastrophic. However, there would be some limited warning of impending failure in the form of extensive cracking and large deflection due to the significant elongation that FRP reinforcement experiences before rupture. The concrete crushing failure mode is marginally more desirable for flexural members reinforced with FRP bars since the member does exhibit some plastic behavior before failure. In conclusion, both failure modes (i.e., FRP rupture and concrete crushing) are acceptable in governing the design of flexural members reinforced with FRP bars provided that strength and serviceability criteria are satisfied. To compensate for the lack of ductility, the suggested margin of safety against failure is therefore higher than that used in traditional steel-RC design.

Φ factor. When concrete crushing controls, a strength-reduction factor of 0.70 is adopted. Furthermore, a Φ factor of 0.50 is recommended for FRP rupture-controlled failure. While a concrete crushing failure mode can be predicted based on calculations, the member as constructed may not fail accordingly. For example, if the concrete strength is higher than specified, the member can fail due to FRP rupture. For this reason and in order to establish a linear transition between the two values of Φ, a section controlled by concrete crushing is defined as a section in which the reinforcement ratio, ρ_f, is greater than or equal to 1.4 times the balanced reinforcement ratio, ρ_{fb}, ($\rho_f \geq 1.4\ \rho_{fb}$,) and a section controlled by FRP rupture is defined as one in which $\rho_f < \rho_{fb}$.

Minimum reinforcement. If a member is designed to fail by FRP rupture, $\rho_f < \rho_{fb}$, a minimum amount of reinforcement, $A_{f,min}$, should be provided to prevent failure upon concrete cracking (that is, $\Phi M_n \geq M_{cr}$ where M_{cr} is the cracking moment).

Crack width. For FRP-reinforced members, the crack width, w, can be calculated from the conventional Gergely-Lutz expression with the addition of a corrective coefficient, k_b, for the bond quality. The k_b term is a coefficient that accounts for the degree of bond between the FRP bar and the surrounding concrete. For FRP bars having bond behavior similar to steel bars, k_b is assumed equal to one. When k_b is not known, a value of 1.2 is suggested for deformed FRP bars.

Creep rupture and fatigue. Values for safe sustained and fatigue stress levels are given in Table 2. These values are based on experimental results with an imposed safety factor of 1/0.60.

Shear

When using FRP as shear reinforcement, one needs to recognize that: FRP has a relatively low modulus of elasticity; FRP has a high tensile strength and no yield point; tensile strength of the bent portion of an FRP bar is significantly lower than the straight portion; and FRP has low dowel resistance.

According to ACI 318, the nominal shear strength of a steel-RC cross section, V_n, is the sum of the shear resistance provided by concrete, V_c, and the steel shear reinforcement, V_s. Similarly, the concrete shear capacity $V_{c,f}$ of flexural members using FRP as main reinforcement can be derived from V_c multiplied by the ratio between the axial stiffness of the FRP reinforcement ($\rho_f E_f$) and that of steel reinforcement ($\rho_s E_s$). The equation for $V_{c,f}$ is that shown in Eq. (1) (noting $V_{c,f}$ cannot be larger than V_c).

$$V_{c,f} = \frac{\rho_f E_f}{\rho_s E_s} V_c \qquad (1)$$

The ACI 318 method used to calculate the shear contribution of steel stirrups, V_s, is applicable when using FRP as shear reinforcement with the provision that the stress level in the FRP shear reinforcement, f_{fv}, should be limited to control shear crack widths, maintain shear integrity of the concrete, and avoid failure at the bent portion of the FRP stirrup, f_{fb}. The stress level in the FRP shear reinforcement at ultimate for use in design is given by $f_{fv} = 0.002E_f \leq f_{fb}$. An expression for f_{fb} is given in ACI 440.1R-01 [1].

Development Length

The development length of FRP reinforcement can be expressed as shown in Eq. (2). This should be a conservative estimate of the development length of FRP bars controlled by pullout failure rather than concrete splitting.

$$\ell_{bf} = \frac{d_b \; f_{fu}}{2700} \qquad (2)$$

$$\ell_{bf} = \frac{d_b \; f_{fu}}{18.5} \qquad \text{for SI units} \quad (3)$$

Manufacturers can furnish alternative values of the required development length based on substantiated tests conducted in accordance with available testing procedures. Reinforcement should be deformed or surface-treated to enhance bond characteristics with concrete.

Application for Internal FRP Reinforcement

The use of GFRP bars for reinforcing concrete bridge decks has captured some interest, particularly for the case of the replacement of the top steel mat. The idea is to eliminate one of the major causes of deterioration (i.e., the steel reinforcement embedded in the concrete region more exposed to chlorides) without significantly increasing cost of construction and without totally removing steel reinforcement.

In underground applications, FRP bars have historically been used as temporary soil anchors and, recently, have become the reinforcement of preference in ground containment walls for tunneling projects. In such projects, the main purpose of a concrete wall of which the soft-eye is part is to contain the ground allowing both the entrance and removal of the Tunnel Boring Machine (TBM). By using concrete reinforced with GFRP bars in the soft-eye region, the cutting operations are simplified due to the low transversal resistance of GFRP materials compared to steel.

Another interesting field of application that has become very common is the use of FRP reinforcement for the RC elements that constitute the containment unit of Magnetic Resonance Imaging (MRI) equipment in hospitals. In this instance, FRP reinforcement is used in lieu of steel for its magnetic transparency.

Proposed Changes to the Third Edition

The proposed changes to the current edition of the guide that may become available in late 2005, address the topics shown below.

Compliance with the 2002 edition of the Building Code (ACI 318, 2002). The historical modification in the load factors in the 2002 version of ACI 318 required that the strength reduction factors introduced in the FRP design guide be revisited to become ACI 318-02 compliant with respect to these new load factors. The selection of the appropriate Φ factors was based on reliability studies. Such studies indicated that the reliability index using the proposed Φ factors was in the range of 3.5 to 4.0 for flexural members, similar to the target reliability index for steel reinforced concrete that should be 3.5 for most components except columns, for which it should be 4.0.

Serviceability requirements. A new equation for the computation of maximum crack width has been proposed. This equation is independent of the type of reinforcement and accounts for the quality of reinforcement-to-concrete bond via an empirical coefficient. Similarly, minimum member depths for deflection control are being proposed and a newly formulated correction factor for the computation of the equivalent moment of inertia according to the Branson model was established.

Shear contribution of concrete. A new equation is proposed for the computation of concrete contribution to shear resistance. This expression is longitudinal reinforcement type independent and is based on the depth of the neutral axis of the cracked cross-section, rather that the depth of the flexural reinforcement.

Detailing. A new development length equation for FRP bars has been proposed that follows the same derivation methodology of that used by ACI 318-02 for steel reinforcing bars. Because FRP bars develop more slowly than steel bars, often the full strength of the FRP bars need not be developed because the failure is controlled by crushing of the concrete, and because there is very little loss in ductility when the failure mode switches from concrete crushing or rebar rupture to bond failure. It seems therefore reasonable to only require development of the stress required for flexure, and not the full strength of the bar.

Conclusions

Even with some unresolved issues that should become a priority for future research, it can be concluded that the availability of design and construction guides developed by ACI for the use of FRP internal reinforcement for new structures allow the construction industry to take full advantage of this emerging technology.

Applications for new construction where internal FRP reinforcement is used are developing in several niche areas including transportation infrastructure (e.g., bridge decks), ground support structures (e.g., soft-eyes), and buildings (MRI hospital rooms). The reasons for such uses are equally broad and include: corrosion resistance, speed of construction, ease of cutting, and magnetic transparency. It is expected that the use of glass FRP bars will dominate in this market.

Acknowledgements

The author, who has drawn freely from the cited ACI documents and his personal notes at technical meetings, wishes to acknowledge the direct and indirect contributions of the members of ACI 440 Committee and all individuals involved in the preparation of its documents.

References

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American Concrete Institute – Committee 318 (2002). Building Code Requirements for Structural Concrete and Commentary, ACI 318-02/R-02, ACI, Farmington Hills, MI, USA.

Table 1: Environmental-reduction factor C_E for various FRP systems and exposure conditions

Exposure condition	Carbon	Glass	Aramid
Interior exposure	1.0	0.8	0.9
Exterior exposure	0.9	0.7	0.8

Table 2: Creep rupture and fatigue stress limits in FRP reinforcement

Fiber type	Glass FRP	Aramid FRP	Carbon FRP
Creep rupture stress limit, $F_{f,s}$	0.20 f_{fu}	0.30 f_{fu}	0.55 f_{fu}