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Reinforced Concrete using FRP Reinforcing Bars: Design Considerations

A brief but important overview of FRP bar reinforced concrete design with a suggestion for improving shear resistance using FRC.

Fiber reinforced polymer (FRP) reinforcing bars are composite materials and a noncorrosive and nonconductive alternative to steel for the reinforcement of structural concrete members. FRP and steel rebar have differences in physical and mechanical properties that engineers should understand when designing with FRP rebar.

FRP Bars

FRP reinforcing bars are manufactured using a variety of fibers in a polymer matrix. Glass fiber is the most popular; however, basalt, carbon, aramid, PBO and other fibers are also used in FRP bars. The matrix is a thermoset compound and is usually epoxy or vinyl ester although other polymer matrices are used. Unlike steel rebar that is manufactured to uniform standards, each manufacturer's FRP reinforcing bars have unique physical and strength characteristics.

A manufacturer's FRP bar product data sheet that identifies these characteristics is required for the calculation of strength and serviceability criteria for FRP reinforced concrete members. A product data sheet should include the fiber type, ultimate tensile strength, tensile modulus of elasticity, and the elongation at break. The manufacturer should also state whether its strength data are average or adjusted statistically in accordance with ACI (average value minus three times the standard deviation of all tests).

Design Methodology

Design loads on a reinforced concrete structure are determined using the same methods whether reinforced using steel or using high strength, fiber reinforced polymer (FRP) reinforcing bars. Steel and FRP reinforced concrete members are analyzed using similar methods to meet the following strength and serviceability criteria: Factored moment, factored shear, crack width, and long-term deflection. Unlike steel reinforced members, FRP reinforced members are analyzed for creep-rupture stress in FRP bars.

In the United States and other countries of the world, the American Concrete Institute (ACI) 440.1-06, “Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars” is used as the design guidance to calculate the design criteria above for FRP bar reinforced concrete members. In addition, The American Association of State Highway and Transportation Officials (AASHTO) provides guidance in its 2009 “AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings, First Edition.” Other standards that provide design guidance are the Canadian Standards Association (CSA) and Federation Internationale du Beton (International Federation for Structural Concrete -- *fib*). FRP*pro*™ RC Design follows the design guidance of ACI 440.1.

For most members, the design of FRP reinforced sections is driven primarily by serviceability requirements: crack width and long-term deflection. This is due to the generally lower modulus of elasticity of FRP bars as compared to steel bars. When these criteria are met, flexural strength (ϕM_n), minimum reinforcement (A_f), and creep-rupture stress criteria are usually easily met. FRP*pro*™ RC Design checks for all these parameters.

Flexural Strength Design

The flexural strength of a section using ACI 440.1 is calculated similarly to ACI 318, “Building Code Requirements for Structural Concrete and Commentary.” Because FRP bars to not yield like steel bars, FRP reinforced members are generally over-reinforced (that is, the ratio of FRP reinforcement to concrete is greater than the balanced ratio) so that concrete crushing of the member controls the failure mode. A FRP reinforced section that is under-reinforced (that is, the ratio of FRP reinforcement to concrete is less than the balanced ratio) may result in a failure mode of FRP rupture, which is not a preferred ductile failure mode.

Because of the relative lack of ductility in FRP reinforced failure modes as compared to under-reinforced, steel reinforced members, the flexural strength reduction factor ranges between a conservative 0.55 and 0.65, based on the ratio of proposed reinforcement to the balanced reinforcement ratio as compared to a strength reduction factor of 0.90 for steel reinforced members. For failure by FRP rupture, the strength reduction factor is 0.55. Where failure is by concrete crushing, the strength reduction factor increases to 0.65 where the ratio of proposed FRP reinforcing is greater than 1.4 times the balanced reinforcement ratio.

Shear Strength Design

Shear strength design is based on familiar ACI 318 methods. ACI 440.1, however, does not allow for dowel action of FRP bars to resist shear, as ACI 318 allows steel bars to resist shear. To resist shear forces a FRP reinforced member must contain ties or stirrups to resist shear, or if not practical as in the case of reinforced concrete tanks, rely only on the shear resistance of concrete. A RC design without shear reinforcing leads to deeper sections where shear is critical.

Although a deeper member may not initially be desired, a deep member corresponds to an increase of the cracking moment of the section. Where a calculated cracking moment is 25 percent greater than the applied service moment, it is reasonable and conservative to use the gross moment of inertia to calculate deflections, and the full, uncracked section of the concrete member be used to resist shear loads as is used in the design of plain concrete. FRP*pro*™ RC Design uses this convention.

Serviceability Design

Although the tensile strengths of FRP bars can be much greater than that of steel, most FRP bars have a much lower modulus of elasticity, or stiffness. Decreased stiffness means that more reinforcing or a deeper member may be needed to mitigate long-term deflections and limit crack widths.

Crack Width Design

Crack width calculations are based on the same concept for FRP bars as it is for steel reinforced members, except that it is modified by a bond quality coefficient, k_b. The bond of FRP bars to concrete was generally less, at the time of the ACI 440.1 publication, than that of steel bars due to less prominent deformations, which according to ACI 440.1 has a long-term affect on crack widths. ACI 440.1 recommends that the crack width calculation be increased by the bond quality coefficient of k_b equal to 1.4, unless a FRP bar manufacturer can prove by testing that its bond with concrete results in a lower bond quality coefficient.

Deflection Design

Long-term deflection calculations are based on ACI 318 section 9.5, direct method of limiting computed deflections. Where the applied, unfactored moment exceeds the cracking moment, the effective moment of inertia is reduced by the reduced tension stiffening in FRP reinforced sections as compared to steel reinforced sections. The degree of tension stiffening in FRP reinforced sections decreases with the amount of reinforcing compared to the balanced reinforcing ratio.

Creep Rupture and Fatigue Design

Creep-rupture and fatigue effects on a FRP reinforced concrete member limit the amount of stress allowed on FRP bars. ACI 440.1 provides creep-rupture strength reduction coefficients for carbon, glass, and aramid FRP bars. Although ACI 440.1 is silent on a creep-rupture stress limit for basalt FRPs, research by Dr. Anil Patnaik at the University of Akron recommended a maximum creep-rupture stress limit on basalt FRPs to 0.15 times the environmentally factored, ultimate tensile strength, f_{fu}. Because crack width and deflection usually control the design of FRP reinforced members, creep rupture and fatigue strength reduction factors are generally not a restricting factor. FRP*pro*™ RC Design checks for creep rupture and fatigue limits.

A Suggested Method for Shear Design

Designing reinforced concrete members using FRP rebar is unique. A drawback of FRP reinforced concrete members can be designing for shear resistance. Bent FRP bars are typically costlier than straight bars, increasing the cost of a structural member designed with shear ties or stirrups. A method to reduce or eliminate the need for shear ties or stirrups, to reduce a FRP bar reinforced concrete member depth, is to combine fiber reinforced concrete (FRC) with standard FRP bar reinforcement.

RC Design with FRC and FRP

Adding macro fibers, a type of fiber reinforced concrete, increases the plain concrete modulus of rupture of a member, and this in turn increases the calculated cracking moment. A large cracking moment may eliminate the need for shear reinforcing, if the cracking moment is larger than the service moment as described above.

Deformed steel macro fibers are well known and can be used to increase the cracking moment of a section; however, if a non-corroding alternative is desired, macro fibers made of FRPs are available from a few manufactures. A simple cost analysis can be used to evaluate whether macro fibers or increased member thickness is preferable. This can be used to estimate whether the cost of macro fibers outweighs the cost of increased concrete volume and forming for deeper sections.

Questions?

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