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Serviceability analysis of RC beams reinforced with GFRP bars: A review

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Abstract—*Now a day, corrosion is the governing factor in the deterioration of the structure in the saline and cold environment. To overcome this problem FRP reinforcement is extensively used in construction industries. The objective of this study is to asses the behavior of the FRP reinforced structures in the serviceability limit state design both for shear and flexure. Moreover deflection control is also considered.*

Keywords—*Fiber reinforced concrete, Flexure, Shear, Deflection*

I. INTRODUCTION

Fiber-reinforced polymer (FRP) has been available as reinforcement for concrete from the last 20 years.[1]Due to the lack of well-established standards, a wide there are many types of FRP bars are available in market, like simple smooth, helically deformed bars and bars externally treated bars with sand coating. Today, more than 10 million meters of FRP reinforcement are used in construction every year.[1]These FRP products have a wide range of mechanical properties and different surface configurations. Most of the design codes and guides use equations for the steel-reinforced members with some modifications to account for the differences in the mechanical properties between FRP and steel bars. Furthermore, serviceability checks such as crack widths and deflections involve assessing the tension stiffening effect, which directly arises from bond behavior.[2]Thus, employing an equation to predict the performance may yield reasonable predictions with one type of FRP bars but discrepancies with another.

At the ultimate limit state, most of the design codes and guides recommend the over-reinforced section design,[3,4]where concrete crushing is the dominant mode of failure. This is preferred because it is less catastrophic and yields higher deformability before failure. Some codes, however, permit the under-reinforced section design[5]. The distinction between both modes of failure is achieved through the balanced reinforcement ratio $\square_{fb}$, which is influenced by the mechanical properties of the FRP bars and concrete strength. Due to the lower modulus of elasticity of the FRP bars compared to that of steel, for the same reinforcement ratio $\square_{f}$, FRP-reinforced concrete (RC) members will exhibit larger deflections and crack widths. Thus, the design of FRP-RC members is usually governed by serviceability. For deflection, a number of studies[6-8] Branson's original equation[9]for the effective moment of inertia and introduced modification factors for FRP-RC members. Other studies[10-12]proposed an equivalent moment of inertia derived from curvatures. For cracking, modifications were proposed to the original Gergely and Lutz[13]equation or strain limits were introduced to control the crack width.[14]Furthermore, Feeser and Brown[15]concluded that sections reinforced with multiple layers of glass FRP (GFRP) reinforcement might be more attractive and should be explored. They also proposed that multiple layers of reinforcement would enable a GFRP-RC section to accommodate larger $\square_{f}$ for compression-controlled failure. Besides, using higher concrete strengths to make more efficient use of the GFRP tensile strength is more applicable to designs with multiple layers of reinforcement.

II. HISTORICAL BACKGROUND

During world war-2 aerospace engineers have searched for ways to reduce the weight of aircraft structures. They developed FRPs as lightweight materials with the strength and stiffness of the materials that they were accustomed to. The automotive, naval, defense, and sporting goods industries have since adopted the use of advanced composite materials on a wide basis.

The expansion of the national highway systems in the 1950s increased the need to provide year-round maintenance. It became common to apply deicing salts on highway bridges. As a result, reinforcing steel in these structures and those subject to marine salt experienced extensive corrosion, and thus became a major concern. Various solutions were investigated, including galvanized coatings, electro-static- spray fusion-bonded coatings, polymer-impregnated concrete, epoxy coatings, and glass FRP (GFRP) reinforcing bars. Of these options, epoxy-coated steel reinforcement appeared to be the best solution, and was implemented in aggressive corrosion environments. The FRP reinforcing bar was not considered a viable solution and was not commercially available until the late 1970s.

In 1983, the first project funded by the U.S. Department of Transportation (USDOT) was on "Transfer of Composite Technology to Design and Construction of Bridges".

Marshall-Vega Inc. led the initial development of GFRP reinforcing bars in the U.S. Initially, GFRP bars were considered a viable alternative to steel as reinforcement for polymer concrete due to the incompatibility of thermal expansion characteristics between polymer concrete and steel. In the late 1970s, International Grating Inc. entered the North American FRP reinforcement market. Marshall-Vega and International Grating led the research and development of FRP reinforcing bars into the 1980s.

The 1980s market demanded nonmetallic reinforcement for specific advanced technology. The largest demand for electrically nonconductive reinforcement was in facilities for MRI medical equipment. FRP reinforcement became the standard in this type of construction. Other uses developed as the advantages of FRP reinforcement became better known and desired, specifically in seawall construction, substation reactor bases, airport runways, and electronics laboratories (Brown and Bartholomew 1996).

The concern for the deterioration of bridges due to chloride- ion-induced corrosion dates back to the 1970s, and its effects on aging bridges in the U.S. has become apparent (Boyle and Karbhari 1994). Additionally, detection of corrosion in the commonly used epoxy-coated reinforcing bars increased interest in alternative methods of avoiding corrosion. Once again, FRP reinforcement began to be considered as a general solution to address problems of corrosion in bridge decks and other structures (Benmokrane et al. 1996).

III. PROPERTIES OF STEEL AND GFRPBARS

PROPERTIES	STEEL	GFRP
Density(g/cm^3)	7.90	1.35 to 2.10
Nominal yield stress (MPa)	276 to 517	N/A
Tensile strength (MPa)	483 to 690	483 to 1600
Elastic modulus×10^3(GPa)	200.0	35.0 to 51.0
Yield strain, %	0.14 to 0.25	N/A
Rupture strain %	6.0 to 12.0	1.2 to 3.1

IV. CURRENT APPLICATION OF FRPBARS

3.1 Marine Structures

The FRPs are noncorrosive in nature, whichmakes them an excellent reinforcing material in the marine structures. One application of FRP in marine structure is shown in Fig. 1, where the GFRP reinforced concrete is used for Ice Harbor lock and dam fish weir (Walla Walla, Washington).Another application of FRP in marine structures is given in Fig. 2, where the bars are used in the off shore loading Quay. The FRP bars can also be used in conjunction with other corrosion-resistant reinforcement, like epoxy-coated bars.

Fig. 1 GFRP Ice Harbor lock and dam fish weir

Fig. 2 off shore loading Quay (Walla Walla, Washington)

3.2 Bridges

FRP composites have been used widely in bridges. Canada is currently one of the leader countriesin the use of FRP bars; mainly as reinforcement of RC bridge decks (Benmokrane, Desgagne, and Lackey 2004); Figure 9 and Figure 10 show some recent bridge applications in USA and Canada.

Fig. 3 GFRP reinforced-concrete bridge deck (Morristown, Vermont)

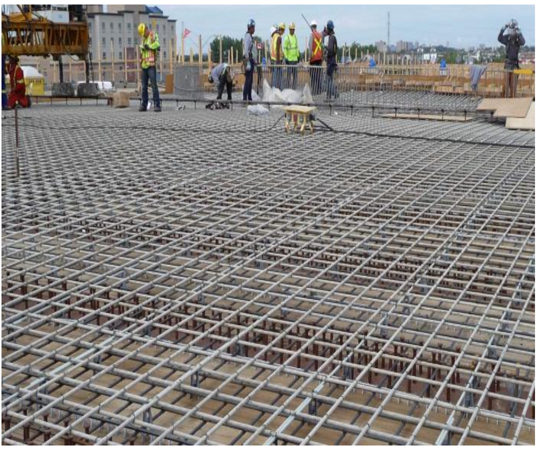

Fig. 4 GFRP reinforced-concrete bridge deck (Edmonton,AB)

3.3 Other Applications

The use of FRP reinforcing bars is also particularly advantageous for buildings that contain equipment sensitive to electromagnetic fields, such as magnetic resonance imaging (MRI) units. Fig 5 shows GFRP reinforced concrete slab for MRI rooms in hospital. Fig. 5 shows the use of GFRP in for MRI rooms in hospital.

Fig. 6 shows tunnel work where GFRP reinforcement is used in the portion of the concrete wall to be excavated by the tunnel boring machine (TBM) have become common in many major urban areas of the world, including Asia (for example, Bangkok, Hong Kong, and New Delhi) and Europe (for example, London and Berlin).

Fig. 5 GFRP reinforced concrete slab for MRI rooms in hospital (York, Maine)

Fig. 6 GFRP soft-eyes for tunnel excavation

V. STRUCTURAL BEHAVIOR OF FRP

4.1 Flexure

Irrespective of member configuration, reinforcement geometry, or material type flexural behavior is the best-understood characteristic of FRP-reinforced concrete, with basic principles applying. Two possible flexural failure modes can be controlled. Portions with smaller amounts of reinforcement fail by FRP tensile rupture, while the portions with larger amounts of reinforcement result in failure by crushing of the compression-zone concrete earlier than getting ultimate tensile strain in the outermost layer of FRP reinforcement. As in the case with steel reinforcement, the absence of plasticity in FRP materials indicates that under reinforced flexural sections experience a sudden tensile rupture in place of a gradual yielding. Therefore, because of enhanced energy absorption and greater deformability, the concrete crushing failure mode of an over reinforced member is slightly more desirable, leading to a more gradual failure mode. Resulting from large deformations, member recovery is necessarily elastic with little or no energy dissipation.

Assuming that, the tensile strength of the concrete is negligible, a perfect bond exists between the concrete and FRP, and strain is proportional to the distance from the neutral axis, Nominal flexural capacity is computed from the constitutive behaviors of concrete and FRP reinforcement by strain compatibility and internal force equilibrium principles. The form

of the analytical expression will depend upon the prevailing failure mode.
Ductility for steel-reinforced concrete can be defined as the ratio of total deformation □□at failure to deformation at yielding. Members with ductility ratios of four or more show significant signs of distress earlier to failure. Since FRP reinforcement does not yield; different means of computing the warning signs of imminent failure must be used. Deformability ratios of about eight have been stated for over reinforced beams with glass FRP bars (GangaRao and Vijay 1997)[19]. An overall performance factor (*J* factor), calculated as the ratio of the product of moment and curvature at ultimate to moment and curvature at a concrete strain of 0.001 (corresponding to the concrete proportional limit) is used in the Canadian Highway Bridge Design Code. The Canadian code suggests minimum acceptable values for the performance index, which is four for rectangular sections and six for T sections (Bakht et al. 2000)[20]. Another method considers the magnitude of the net tensile strain in the outer layer of FRP bars because the concrete compressive strain reaches the ultimate limit state. The section is ‘‘tension-controlled’’ when the net tensile strain is 0.005 or greater, and a lower resistance factor is needed to balance for the rapidity of FRP tensile rupture (ACI Committee 440 2001).

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4.2 Deflections and Cracking

Because of lower elastic modulus of FRPs, Deflections and crack widths are usually larger in FRP- reinforced concrete beams and slabs (particularly glass FRP) than in steel-reinforced concrete beams. Limits on deflection or crack width often control designs and are generally satisfied by using over-reinforced sections. Deflection prediction equations made for steel-reinforced concrete usually underestimate immediate deflections, with differences increasing as the load approaches ultimate. Such behavior relates with observations that crack patterns at lower load levels are similar to those of steel-reinforced sections, but relative to steel reinforcement crack spacing decreases and crack width increases as loads increase beyond the service level. Various modified expressions for the effective moment of inertia have been proposed for use with FRP (Masmoudi et al. 1998)[21].

For FRP-reinforced members, creep and shrinkage behavior is similar to the steel-reinforced members. For long-term deflection, American Concrete Institute (ACI) code equations can be used for FRP reinforcement, with modifications to account for differences in concrete compressive stress and the elastic modulus and bond characteristics of the FRP reinforcement (ACI Committee 440 2001).

4.3 Shear

In beams with FRP longitudinal reinforcement, the concrete contribution to shear strength is reduced because of smaller concrete compression zones, wider cracks, and smaller dowel forces. A reduction factor proportional to the modular ratio, E_{FRP}/E_{steel}, is typically applied to concrete shear contribution equations for conventional beams, although such an approach underestimates the shear strength in flexural members with larger amounts of FRP longitudinal reinforcement (Michaluk et al. 1998)[22].Shear failures occur in beams with FRP stirrups either by FRP rupture at the bend points or by shear-compression failure in the shear span of the beam. Failure from stress concentrations at stirrup bends may limit the effective capacity to as little as 35% of the strength parallel to the fibers (Shehata et al. 2000)[23]. Multidirectional FRP grids can also be used as shear reinforcement (Bank and Ozel 1999; Razaqpur and Mostofinejad1999)[24,25].

VI. CONCLUSION

- Large amount of research work has been done to examine the performance of FRP as primary reinforcement for concrete structures, but limited research work have been conducted on the shear behavior of concrete members reinforced with FRP stirrups.
- Due to the lack of well-established standards, there are many types of FRP bars are commercially available in market. Therefore, serviceability-related issues need to be investigated and validate the accuracy of design codes and guidelines are necessary.

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