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Flexural Behaviour of BFRP Reinforced Beams

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Abstract— **Basalt Fiber Reinforced Composite Bars (BFRP) offer a promising alternative to traditional steel bars in many special applications and aggressive environments. The inherent corrosion resistance of BFRP composites is of particular interest in predominantly hot and humid environments. In addition, basalt, as a naturally occurring volcanic rock is an environmentally friendly choice for use in FRP composites. The current design guide ACI440.1R covers the design and construction of concrete members reinforced with Aramid FRP (AFRP), Glass FRP (GFRP) and Carbon FRP (CFRP), but does not address BFRP- reinforced concrete members as more fundamentals research is still needed. This paper addresses the current state of knowledge on flexural response of BFRP reinforced beams relative to traditional reinforcing steel**

Keywords— ***Basalt Fiber Reinforced Polymer Composites, Sustainability, Flexure***

I. Introduction

Fiber Reinforced Polymer (FRP) composite bars have been studied extensively in the past three decades as alternative to traditional reinforcing steel. Corrosion resistance of FRP bars is often quoted as the primary motivation in many parts of the world. Initial studies focused on retrofitting of existing concrete structural elements using FRP sheets to enhance performance under seismic forces. More recently, reinforcing bars that are made of FRP composites for new concrete structures were studied as alternative to traditional reinforcing steel. The earliest studies were conducted on concrete reinforcing bars made of Glass FRP (GFRP) and Carbon FRP (CFRP). American Concrete Institute (ACI) publishes a guide for the design and construction of structural concrete reinforced FRP bars [1].

Reinforcing bars made of Basalt Fiber Reinforced Polymer (BFRP) offer solutions to some concerns related to the use of traditional reinforcing steel and improved properties compared to AFRP/CFRP/GFRP. Similar to GFRP and CFRP, BFRP offers corrosion resistance, fatigue endurance. Low thermal conductivity of BFRP compared to AFRP/CFRP/GFRP is particularly advantageous in construction industry. In addition, all FRP composite bars are much lighter than traditional reinforcing steel.

Some of the demerits of using BFRP bars include lack of ductility, low modulus of elasticity, and possible susceptibility to fire depending on the type of resin used.

In addition, unlike traditional reinforcing steel, FRP bars in general are not recommended for use as compression reinforcement in flexural members. FRP bars are also not recommended at the present time as primary reinforcement in columns. This is because the compression modulus of FRP bars is lower than its tension modulus of elasticity. In addition, the creep-rupture performance of FRP under sustained load must be particularly considered in design [2]. Furthermore, unlike traditional steel bars, once manufactured bending and shaping of FRP bars is not easy.

From strength point of view basalt fibers are about 30% of the strength carbon fibers and 60% of the strength of glass fibers. However, BFRP bars are still 2 to 3 times stronger than traditional reinforcing steel. BFRP with ultimate tensile strength of 1100 MPa is common.

Under high temperature, BFRP bars are more stable and the resulting loss of strength is limited compared to GFRP and CFRP [3]. At high temperatures (250 ^{o}C) both GFRP and CFRP lose more than 20% of their ultimate strength. In addition, BFRP is considered a more environmentally friendly option compared to GFRP and CFRP. This is because the volcanic rock basalt, used to make the reinforcing fibers, is a natural material.

The cost of FRP bars decreased significantly in recent years due to increased production in many parts of the world. Increased production prompted accelerating research on behaviour of concrete reinforced with FRP bars. ACI 440.1R [1] does not currently include design and construction guidelines for concrete reinforced with BFRP bars.

The purpose of this paper is to present the current-state-of-knowledge on the flexural behaviour of concrete reinforced with BFRP bars.

II. Properties of BFRP

BFRP is linear elastic material that does not exhibit any yielding until fracture, as shown in Fig. 1 and is therefore considered a brittle material. Tensile strength of BFRP bars from 1100 MPa to 1750 MPa is common, which may reach 4 times that of traditional reinforcing steel. A common range of BFRP moduli of elasticity is 70 MPa to 85 MPa, which is far less than 200 MPa for traditional reinforcing steel. However, lower or higher tensile strengths and moduli are also available for BFRP bars. On average, tensile strength and modulus of elasticity of BFRP is somewhere between CFRP and GFRP.

Unlike traditional reinforcing steel, the tensile strength of BFRP composite bars may vary with diameter. In addition, because fibers in FRP composites are the primary load-carrying elements, the ratio of the volume of fibers to FRP volume affects the tensile strength.

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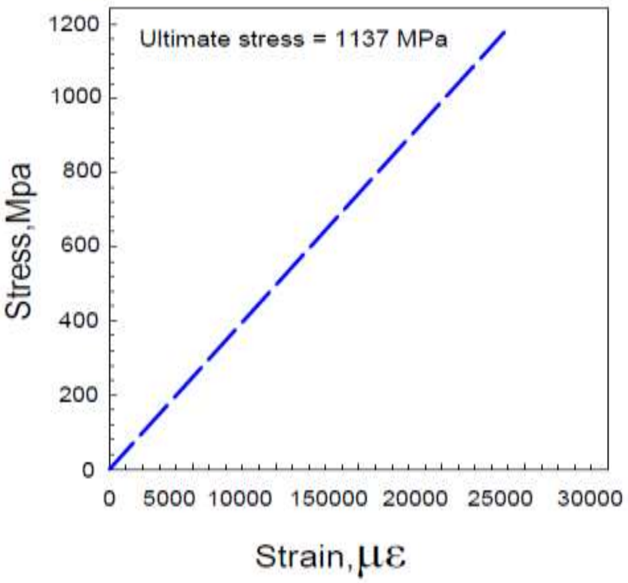

Fig. 1. Stress-strain relationship for BFRP bar

III. Flexural Properties of BFRP-Reinforced Beams

This section discusses topics related to flexural response of BFRP reinforced concrete including cracking moment and flexural capacity.

A. *Cracking Moment*

Cracking moment and corresponding loads are important for a number of reasons. For example, FRP reinforced concrete beams in general are known to have a relatively small stiffness after cracking begins. Therefore, service load deflection may control the design. Experimental studies confirmed that cracking load and cracking stiffness of flexural concrete members reinforced with BFRP bars is the same and does not vary with reinforcement ratio. It is also not affected by the amount or even the presence of shear reinforcement. However, once flexural cracking began, post-cracking stiffness increased with reinforcement ratio. Flexure cracks begin at service load levels which are estimated differently by different researchers. Some of the common assumptions include:

- Service load moments equal to 60% of the nominal flexural capacity of the cross.
- Service load moments occur at load levels corresponding to deflection limits, such as span/180 for roofs or L/360 for floors.
- Service load moments cause concrete strain less than 0.001. Concrete is considered to become nonlinear when concrete strain reaches 0.001 [4].

The theoretical cracking moment is given by (1):

$$M_{cr} = \frac{f_r I}{y_t} \qquad (1)$$

Where:

$f_r = 0.62\sqrt{f_c'}$ is the modulus of rupture

f_c' is the 28-day compressive strength (MPa)

I is the gross moment of inertial of the section

B. *Characteristics of Flexural Cracking and Failure Modes*

In general, width of flexural cracks in beams reinforced with BFRP composite tends to be larger compared to concrete with similar traditional reinforcement. This is attributed, in part, to the lower modulus of elasticity. Crack spacing in constant moment regions depends on type of FRP used. Crack spacing in constant moment region for BFRP reinforced beams tends to be similar to traditional steel reinforced beams.

Unlike steel-reinforced beams, under-reinforced beams with BFRP bars fail by brittle rupturing of BFRP in catastrophic manner.

C. *Bond and Development Length of BFRP Bars*

Bond of BFRP bars to surrounding concrete is the most important consideration in flexural design. In computing the nominal moment capacity of concrete reinforced with BFRP, perfect bond between reinforcing bars and surrounding concrete is assumed. Proper bond of BFRP to surrounding concrete is essential for BFRP-concrete composite action to occur and for the BFRP bars to develop their tensile strength. Similar to traditional steel bars, bond force between reinforcing BFRP bars and surrounding concrete transfers through: 1) Chemical adhesion resistance of the interface, which resists slip at small load levels, 2) frictional resistance of the interface against slip, which occurs after chemical adhesion is lost, and 3) mechanical interlock due to surface irregularity. The bond strength between FRP composite bars and surrounding concrete is less than the bond between traditional steel and surrounding concrete [5].

It was reported in the literature that BFRP bars have higher bond strength compared to CFRP and GFRP bars [5]. Further research is needed to validate this conclusion.

The two flexural bond failure modes recognized in research and practice are: 1) pull-out of bars from the surrounding concrete, and 2) splitting of concrete surrounding the FRP bar.

Bond strength of FRP bars may be tested using ASTM specified pull-out test or hinged-beam test.

Methods of manufacturing BFRP bars vary significantly producing different bar surface shapes and conditions. Bar surface conditions significantly affect mechanical bond characteristics for FRP bars. Bond tests conducted by Harajli and Abouniaj [6] showed that ribbed GFRP bars failed by splitting, while thread-wrapped GFRP bars failed by pull-out. Ribbed bars develop better mechanical interlock and higher bond strength compared to thread-wrapped bars [6]. Although both rips and wraps enhance bond strength of BFRP bars to concrete, they create local stress concentrations. Plain (undeformed) FRP bars, which are rarely produced, provide very limited bond strength to concrete.

The average bond strength decreases as the bar size increases. Therefore, the bond strength must be specified of the reinforcing bar size. This is due to shear lag effects caused by outer fibers experiencing higher stresses than fibers near the core of the bar.

The force , f_f , developed at the end of the bar length , l_e , is resisted by an average bond stress, u, acting on the surface of the bar as shown in Fig. 2. The equilibrium relationship adopted ACI440.1R is given by (2)

$$l_e \pi d_b u = A_{f,bar} f_f \tag{2}$$

Where: d_b is the bar length

$A_{f,bar}$ is the cross-sectional area of the bar

The ACI 440.1R relationship, in SI Units, between development length, l_e, and bond strength, u, is given by (3). (3) is the official ACI 440.1R equation for bond and development length of FRP bars. However, it must be mentioned that (3) was developed from test results that included GFRP. (3) was developed in manner similar to traditional steel reinforcement. Therefore incorporation of BFRP test data is not likely to change the structure of (3).

$$\frac{u}{0.83\sqrt{f'_c}} = 4.0 + 0.3\frac{c}{d_b} + 100\frac{d_b}{l_e} \tag{3}$$

Where:

C is the lesser of the concrete cover-to-center of bar or one-half of the center-to-center spacing of bars.

f'_c is the 28-day compressive strength of concrete (MPa).

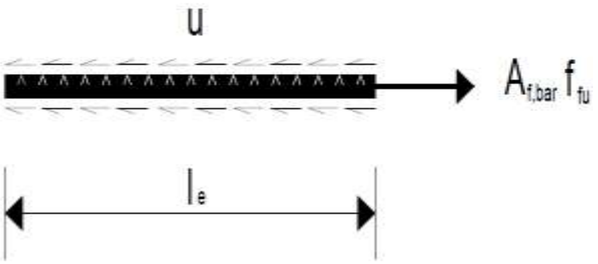

Fig. 2. Forces in Bar Bonded in Concrete

D. *Ultimate Flexural Capacity*

The large rupture strength of BFRP bars leads to higher ultimate flexural capacity of concrete sections compared to concrete reinforced with the same ratio of traditional reinforcing steel [7]. The strength of BFRP reinforced concrete sections depends on whether the section is under-reinforced ($\rho_f < \rho_{fb}$) or over-reinforced ($\rho_f > \rho_{fb}$). The balanced BFRP ratio is given by (4).

$$\rho_{fb} = 0.85\beta_1 \frac{f'_c}{f_{fu}} = \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}} \tag{4}$$

Where:

f_{fu} is the ultimate tensile strength of FRP bar

E_f is the modulus of elasticity of FRP bars

ε_{cu} is ultimate strain in concrete

The flexural capacity of over-reinforced BFRP sections is given by (5). Over-reinforced sections fail by concrete crushing rather than BFRP rupture.

$$M_n = A_f f_f \left(d - \frac{a}{2} \right) \tag{5}$$

Where: $a = \dfrac{A_f f_f}{0.85 f'_c b}$

The stress in BFRP bars at failure of over-reinforced section may be calculated from (6).

$$f_f = E_f \varepsilon_{cu} \frac{\beta_1 d - a}{a} \tag{6}$$

(5) is derived from the stress and strain diagrams at ultimate conditions shown in Fig. 3.

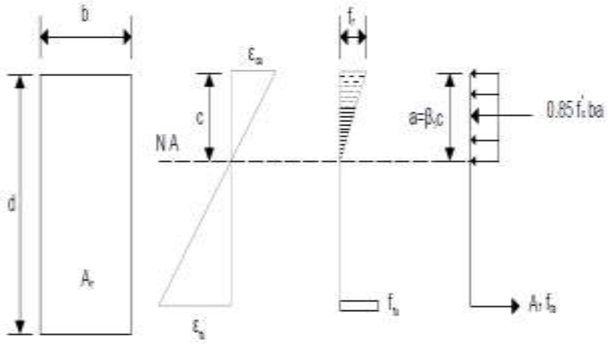

Fig. 3. Stress and Strain at Ultimate Conditions for Concrete Reinforced with FRP Bars [1].

Figure 4 shows the moment-curvature relationships for rectangular concrete section reinforced with:1) traditional steel with section under-reinforced, 2) FRP under-reinforced section, and 3) FRP over-reinforced section.

Under-reinforced sections with BFRP fail by rupture of bars. Rupture of BFRP bars is not be accompanied by large deformations, unlike under-reinforced sections reinforced with traditional steel. Rupture of BFRP bars will be accompanied by large cracking which would be the only warning of impending failure. Over-reinforced design exhibit failure by crushing of concrete. For this reason, over-reinforced design with FRP is acceptable or even marginally more desirable than under-reinforced design.

BFRP under-reinforced flexural concrete members possess much higher flexural capacity compared to reinforced concrete sections with the same steel ratio. However, BFRP reinforced flexural member fail in catastrophic manner either by concrete crushing (over-reinforced) or sudden rupture of BFRP bars (under-reinforced) without significant visible deformation. However, large visible cracking will serve as warning.

Designing BFRP concrete sections as over-reinforced leads to stiff sections that generally satisfy deflection and cracking serviceability limits [4].

Figure 4 shows that for FRP reinforced sections, flexural response is linear until flexural cracking begins.

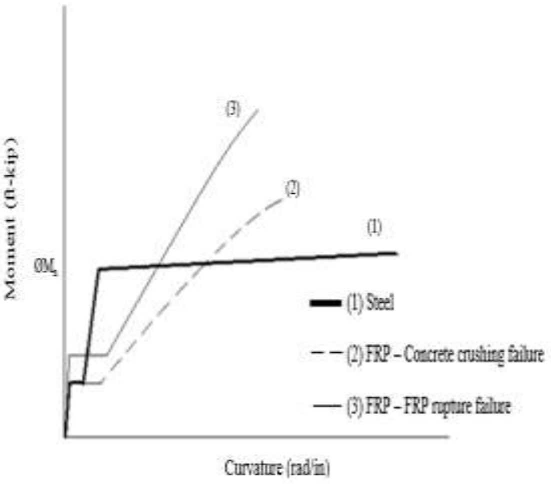

Fig.4. Moment-curvature relationship for steel reinforced versus FRP reinforced rectangular concrete beam

E. Load-Deformation Response of BFRP Reinforced Concrete

Unlike steel reinforcement, BFRP bars are non-ductile; therefore, the traditional concept of ductility index for BFRP-reinforced concrete is not defined. However, BFRP is capable of dissipating large amount of energy during loading while remaining elastic. Therefore, lack of ductility of BFRP bars does not appear to be a problem from load-carrying capacity point of view. As discussed in earlier section of this paper, lack of BFRP ductility affects the response as large deformations do not precede failure. The concept of deformability may be accepted to relate ultimate conditions to service conditions.

Post-cracking load-deformation response of BFRP shows stiffer response compared to CFRP/GFRP, as demonstrated by the BFRP reinforced beam ability to sustain higher loads with smaller deflection. This was attributed to the improved bond strength between BFRP and concrete compared to CFRP and GFRP bars, as reported earlier in this paper.

IV. Recommendations on the Use of BFRP Bars for Structural Concrete

Use of tension reinforcing bars made of BFRP composites provides great advantages for concrete decks of bridges and floors of building structures. BFRP reinforced decks are sustainable and durable alternatives compared to traditionally reinforced concrete floors/decks. In addition, the nonmagnetic characteristics of BFRP composite bars make them ideal for reinforcing concrete used in Magnetic Resonance Imaging (MRI) rooms.

For building, a structural system that uses BFRP bars in certain elements and traditional steel in others is recommended. BFRP bars are recommended in floor/roof Slabs as well as Gravity Beams. Until further research is done on use of BFRP bars as compression members, traditional steel reinforcing bars are recommended for columns, shear walls, and moment resisting frames.

For concrete bridge decks, BFRP bars were used in German, United States, and other parts of the world. It is recommended that such use is expanded in more areas where aggressive environment influencing durability is dominant. Expansion in use of BFRP bars for concrete decks increases confidence on the environmentally friendly basalt fibers while contributing to efforts aiming at reducing the footprint of the construction industry.

V. Future Research

Use of BFRP bars for reinforcing structural concrete offer many advantages. However, further research is still needed in various areas including but not limited to:

- Performance of moment resisting frames reinforced with BFRP bars.
- Effects of surface characteristics of BFRP bars on bond behaviour and on crack width.
- Development of *bond grade*, similar to the current ACI440.1R grades for modulus of elasticity and strength. This is essential in order to mitigate the large variation in manufacturing processes that produce significant differences in surface conditions of FRP bars and leading to difficulties in developing reliable bond models.

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About Author (s):

BFRP reinforcing bars are durable alternatives to traditional steel reinforcement and offer concrete members with higher flexural capacity than similar steel reinforced members.