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Methods to enhance the guaranteed tensile strength of GFRP rebar to 900 MPa with general fiber volume fraction

Young-Jun You [a,b], Jang-Ho Jay Kim [a,*], Sung-Jae Kim [a], Young-Hwan Park [b]

[a] School of Civil and Environmental Engineering, Yonsei University, Engineering Building #A, 134 'Shinchon-dong, Seodaemun-gu, Seoul 120-794, South Korea
[b] Structural Engineering Research Division, Korea Institute of Construction Technology, (Daewha-Dong) 283, Goyangdae-ro, Ilsanseo-gu, Goyang-si, Gyeonggi-do 411-712, South Korea

HIGHLIGHTS

- Some factors influencing the tensile strength of GFRP rebar were examined.
- Filler type may affect the tensile strength of GFRP rebar, yet resin type does not.
- Pre-tensioning fibers during manufacturing can decrease the voids in the cross-section.
- Decreased voids and aligned fibers increase tensile strength.
- GFRP rebar shows a tensile strength of up to 900 MPa with 78% fiber volume fraction.

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ABSTRACT

The corrosion of reinforcement (rebar) in concrete members is one of the governing factors deteriorating the load carrying capacity of concrete members. Fiber reinforced polymer (FRP) has been the subject of much interest from researchers and engineers due to its enhanced durability and non-corrosive characteristics. Corrosion problems in reinforced concrete (RC) members can be resolved through the use of FRP rebar as its reinforcement. In order to expand usage of FRP rebar, rebar with various shapes and sizes has been developed and manufactured for RC structures. However, currently, a limited number of FRP rebar selections are available on the market. The obstacles preventing the wider application of FRP rebar are the relatively high price of FRP rebar compared to steel rebar and insufficient design guidelines for various FRP rebars sold in the market. Since there is a wide variety of unstandardized FRP rebar sold in the market, the application of these rebars in concrete structural design must be carefully conducted by modifying related coefficients and safety factors to assure the safety of the designed structures. Therefore, the enhancement of the performance of FRP rebar by means of efficient manufacturing methods would reduce its cost and increase its usage. Sufficient tensile and bonding strengths are necessary properties of rebar. However, depending on the material and shape of FRP rebar, these properties vary significantly. This study focuses on the tensile performance of rebar realized through enhancements in its constituent materials and manufacturing processes. Constituent materials and manufacturing processes were thoroughly researched and evaluated to maximize the tensile performance. A total of six factors affecting the tensile and bonding capacities of FRP rebar were modified in the study. For the new FRP rebar, a higher target with a guaranteed tensile strength of 900 MPa and a 78% fiber volume fraction by weight, manufactured using E-glass fiber TEX 4400, was chosen. The verification study results showed that the new glass FRP (GFRP) rebar showed better material properties than other types of GFRP rebar currently available on the market.

1. Introduction

According to ACI committee 440 [1], corrosion problems in RC structures began in the 1960s. Corrosion byproducts cause a volume expansion around corroded rebar, resulting in the deterioration of the concrete. A galvanized coating was the first solution to the problem, but it did not become widely used for a variety of reasons. Epoxy-coated steel rebar was used in the early 1970s based on an evaluation of over 50 types of coating materials for steel rebar. Meanwhile, there were several attempts to make rebar using non-corrosive materials, as corrosion is not a structural but a

* Corresponding author. Tel.: +82 2 2123 5802.
E-mail address: jjhkim@yonsei.ac.kr (J.-H.J Kim).

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material problem. Fiber reinforced polymer (FRP) is a composite material made of a polymer matrix reinforced with fibers. The fibers usually consist of glass, carbon, basalt or aramid. The polymer matrix is usually epoxy, vinyl-ester or a polyester thermosetting plastic. FRPs have been used for decades in the aeronautical, aerospace, automotive, and marine industries due to their inherent advantages of high strength, low weights, and non-corrosive properties. FRP products are manufactured in many different forms, such as bars, sheets, or 2D grids. Their usage in civil engineering fields dates back to the 1950s, when glass FRP (GFRP) rebar was first investigated for structural use. However, it was not until the 1970s that FRP was finally used in structural applications. FRP rebar of various shapes and sizes has been developed and is now commercially available [2]. However, its application to concrete structures is still limited, especially as a main structural component.

The major problems which arise when using FRP as a rebar material is its high price, low elastic modulus, and more brittle failure behavior than steel rebar. Even though it is possible to improve the elastic modulus of FRP bar by hybridization with fiber with high elastic modulus, this would lead to a price increase of FRP rebar, as high-modulus fibers are generally expensive [3]. Many solutions are available for improving the performance of FRP rebar (e.g., simply using fibers with higher strength or a larger amount of fibers). However, in order to be competitive in the reinforcement market as structural rebar, the most important feature of FRP rebar is its price-to-performance ratio. A reduction in the price is possible either by reducing the production cost while maintaining the performance or improving the performance while maintaining the cost. Moreover, unlike steel reinforcement, the tensile properties of the FRP rebar depend on the content and size of the member. In particular, when a tensile force is applied to a larger diameter rebar, the tensile strength experiences a size effect wherein higher stresses develop in the outer fibers than in the inner ones [4]. Unfortunately, the size effect of the rebar was not considered in this study. However, due to the importance of the topic, effect of rebar size will be studied in-depth in the future work.

In this study, the approach of enhancing the performance of GFRP rebar manufactured using the materials and conditions currently used in the industry while maintaining the production cost is taken. The tensile strength of GFRP rebar is defined as a guaranteed tensile strength equal to the result of subtracting three times the standard deviation of its tensile strength from the average tensile strength. In the new GFRP, rebar with an inner diameter of 12.7 mm and a volume fraction of 78% by weight was manufactured using E-glass fiber with TEX 4400 and a vinyl-ester resin. The rib height of the rebar was excluded from the diameter, because it does not contribute to the tensile strength of the rebar. Although the current guaranteed tensile strength is less than 900 MPa, a target strength value of 900 MPa was selected here to compete with the strength of steel rebar so as to meet the structural tensile and allowable fatigue strength levels stipulated in various design codes and guidelines. For a precise understanding of the factors affecting the performance of the materials, various influential factors were initially investigated. Then, efforts to optimize the constituent materials and manufacturing processes were undertaken. Finally, tensile and bond strength tests were performed to verify the performance enhancement of the new GFRP rebar.

2. Research background

FRP rebar or composite with various shapes and properties was developed by researchers in the past, and several manufacturers are currently selling several types of rebar commercially for construction work [5,6]. For FRP composites having the shape of rebar, Marshall Industries Composites, Inc., based in the US, produces C-Bar, which has a shape similar to that of ordinary steel rebar [7]. Hughes Brothers Inc. and Pultrall Inc., based in the US and Canada, respectively, produce Aslan 100 and V-Rod, respectively, which both use E-glass as the main constituent material, and which have helically wrapped and sand-coated surfaces to enhance the bonding. Schöck Bauteile GmbH based in Germany produces ComBAR, which has continuous spiral pitches on the surface, giving it bonding properties similar to those of deformed steel rebar [5]. Commercially available rebar with various shapes and mechanical properties are shown in Fig. 1 and Table 1 [5,8–10], respectively.

To assist with the systematic use of FRP rebar developed from various studies, the Japan Society of Civil Engineers (JSCE) and EUROCRETE published the concrete structural design guideline for FRP rebar in 1996. Then, in 1998, the Commission on Security and Cooperation in Europe (CSCE) published design recommendations for FRP RC bridges. In 2001, the American Concrete Institute (ACI) and the Canadian Network of Centers of Excellence on Intelligent Sensing for Innovative Structures (ISIS Canada) published the first version of their design recommendations for internal FRP rebar as well as a series of manuals on the use of internal/external and pre-stressed FRP rebar. In 2006, the National Research Council (CNR) published the Italian design recommendations for internal FRP rebar [11]. Presently, there are a variety of national structural design codes available for designs of FRP RC structures, but these codes still do not sufficiently consider fatigue and long-term performance of FRP RC structures [2]. FRP RC design guidelines essentially follow previous design guidelines pertaining to ordinary steel RC structures, though the coefficients and parameters used in the design equations are modified based on research results. For example, when the compression reinforcement ratio is equal to zero, ACI 318–05 [12] calculates the long-term deflection due to creep and drying shrinkage with Eq. (1).

$$\Delta_{(cp+sh)} = \xi(\Delta_i)_{sus} \tag{1}$$

Here, $\Delta_{(cp+sh)}$, $(\Delta_i)_{sus}$, and ξ represent the additional deflection due to creep and shrinkage under sustained loads, the immediate deflection due to sustained loads, and a time-dependent factor for a sustained load, respectively. Based on Eq. (1), ACI 440.1R-06 [4] gives the long-term deflection of FRP RC members by multiplying 0.6 by the ξ coefficient based on experimental results. This expression is given in Eq. (2).

$$\Delta_{(cp+sh)} = 0.6\zeta(\Delta_i)_{sus} \tag{2}$$

The reason for implementing the coefficient modification approach for FRP RC design purposes stems from the lack of a consensus among structural design engineers. Due to the uncertainties

Fig. 1. Pultrall V-Rod, Hughes Bros. Aslan 100 FRP, and Schöck ComBAR (Left to Right) [5].