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Design recommendations for bond between GFRP/steel wire composite rebars and concrete

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ABSTRACT

Due to significant advantages over GFRP rebars, namely high tensile strength, high elastic modulus, and good ductile properties, GFRP/steel wire composite rebars offer a superior alternative to ordinary steel rebars. However, experimental researches on this new type of rebar have been limited, especially those on the bond performance. This research is designed to investigate the bond behavior between GFRP/steel wire composite rebars and concrete. According to American Concrete Institute (ACI) code, a total of 180 pull-out specimens were tested under monotonic static loading conditions. The test parameters were the rebar rib spacing, rebar diameter, embedded length, concrete compressive strength, concrete cover thickness, and concrete cast depth. Based on the numerical analysis of the test results, new criteria for acceptable bond performance of GFRP/steel wire composite rebars to concrete were developed. Designed recommendations for the modification factor of concrete cover thickness, the modification factor of concrete cast depth, and the critical value of bond slip at both free and loaded ends were derived. The calculation formula of bond strength and the basic development length were proposed, and the calculation principle of development length of concrete structures reinforced with GFRP/steel wire composite rebars was suggested.

1. Introduction

Many concrete structures such as marine structures, bridge and parking garages are subjected to aggressive environments, combined with moisture, temperature, and chlorides, reducing the alkalinity of the concrete and resulting in corrosion of ordinary steel rebars [1,2]. Glass Fiber Reinforced Polymer (GFRP) rebars which have been produced in recent years appear to be a suitable candidate and have great potential to fill such a need. Relative to conventional reinforcing steel rebars, GFRP rebars present a high tensile strength, a light weight, non-corrosive, anti-fatigue, non-magnetic, and electrical insulation [3–5].

However, the relatively low elastic modulus and the absence of a well-defined yield plateau are fatal defects of GFRP rebars. And these two shortcomings make these materials incompatible with the established design recommendations which controls the failure hierarchy of RC structures through steel rebar yielding [6]. Therefore, GFRP/steel wire composite rebars were manufactured to enhance the ductility and elastic modulus of GFRP rebars. The tensile strength of non-corrosion GFRP/steel wire composite rebar is larger than that of ordinary steel rebar, and the typical stress–strain relationship of GFRP/steel wire composite rebar exhibits the similar yielding characteristics to that observed for ordinary steel rebar. Therefore, GFRP/steel wire composite rebars offer a superior alternative to ordinary steel rebars in concrete structures.

So far, few studies recommending design guidelines for bonding GFRP/steel wire composite rebars to concrete have been reported in the literature. And the lack of information and design guidelines on their bond properties to concrete is one of the important factors limiting the filed application of GFRP/steel wire composite rebars to civil engineering. Moreover, a direct utilization of ACI318-05 for the design guidelines of GFRP/steel wire composite rebar is unwarranted due to the inherent differences in tensile strength, modulus of elasticity, and surface configurations [7].

Thus, a total of 180 pull-out specimens were tested to investigate the effect of rib spacing, rebar diameter, embedded length, concrete compressive strength, concrete cover thickness, and concrete cast depth on bond behavior of GFRP/steel wire composite rebars to concrete. The primary objective of this research project was to study the bond behavior and develop design recommendations for anchorage of GFRP/steel wire composite rebars to concrete. The present paper focuses on the development of a new criterion for accepted bond performance and design recommendations for GFRP/steel wire composite rebars to concrete.

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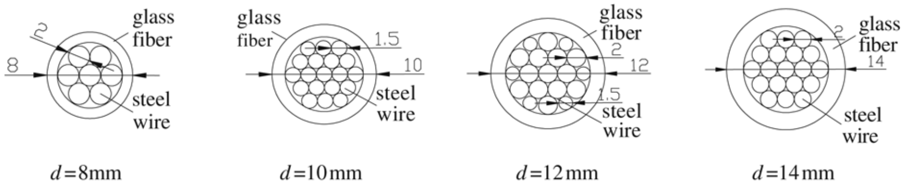

$d = 8\,\text{mm}$ $d = 10\,\text{mm}$ $d = 12\,\text{mm}$ $d = 14\,\text{mm}$

Fig. 1. Schematic of cross section of GFRP/steel wire composite rebars.

Table 1
Mix proportions and properties of normal strength concrete

Concrete mix	C20	C30	C40
Water (kg/m^3)	195	195	195
Cement (kg/m^3)	328	413	454
Water-to-cement ratio (w/c)	0.59	0.47	0.43
Sand (kg/m^3)	616	592	609
Aggregate (kg/m^3)	1232	1184	1131
Air content (%)	2.5	2.5	2.5
Compressive strength (MPa)	19.85	26.05	35.43

Detailed results of the research project, such as the rebar's hybrid mechanism, the rebar's mechanical properties, the effect of test variables on the bond behavior, the failure mode, and the bond-slip constitutive model, are presented elsewhere [8–10].

2. Details of experimental program

2.1. Materials properties

2.1.1. Concrete

Normal strength concrete was prepared in the laboratory according to the Chinese standard GB 175-1999. Common Portland cement type 32.5 R, river sand, and drinking water were used for the test specimens. The coarse aggregate was common crushed stone with a maximum size of 20 mm. The concrete mix was designed based on the absolute volume method and the ratio of cement to water (w/c) was 0.59 for mix C20, 0.47 for mix C30, and 0.43 for mix C40. Six compressive tests were completed on 100 mm × 100 mm × 100 mm concrete cube specimens for compressive strength. The mix proportions and properties of concrete are given in Table 1.

2.1.2. GFRP/steel wire composite rebar

The GFRP/steel wire composite rebars used in this test are supplied by Harbin Tider Science & Technology Inc. These rebars had a nominal diameter (d) of 8, 10, 12, and 14 mm. They were generally manufactured using the so-called pultrusion process, and were made of continuous longitudinal glass fibers, steel wire, and epoxy resin. Two kinds of steel wire in nominal diameter of 1.5 mm and 2.0 mm were used. The volumetric fraction of three components in different GFRP/steel wire composite rebars is listed in Table 2, and the cross section of GFRP/steel wire composite rebars can be seen in Fig. 1.

Fig. 2. Surface configuration of GFRP/steel wire composite rebars.

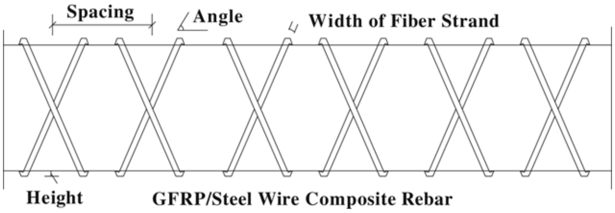

Fig. 3. Schematic of rib geometries of GFRP/steel wire composite rebars.

During manufacturing, surface treatment was adopted to enhance the bond between the GFRP/steel wire composite rebar and concrete. The longitudinal fibers and steel wire were wrapped in a helical pattern with two small strand fibers which were tight to induce indentations on the rebar surface. The surface configurations of GFRP/steel wire composite rebars are shown in Fig. 2.

The rib geometries of GFRP/steel wire composite rebars can be seen in Table 2 and Fig. 3. For each rebar, the rib spacing (RS) is the center-to-center spacing of the rebar ribs. Rib height (RH) is the height of rib above the rebar surface, and is measured as the difference between rebar radius at a rib and radius at midpoint of two adjacent ribs. Rib angle (RA) is the angle that the rebar rib forms with the longitudinal axis of the ribbed rebar. For all rebar sizes, the width of the fiber strand was almost the same.

The ultimate tensile strength and the modulus of elasticity of GFRP/steel wire composite rebars were measured by subjecting coupons to uniaxial tension tests. Results for the ultimate tensile strength, elastic modulus, and the elongation at failure of GFRP/steel wire composite rebars are listed in Table 2. A typical stress–strain relationship of GFRP/steel wire composite rebar is shown in Fig. 4. It is noted that all coupon samples exhibit the yield property in the stress–strain curves when the load level up to the point of failure [9], while the typical stress–strain relationship of

Table 2
Component content, rib geometries and mechanical properties of GFRP/steel wire composite rebars

Diameter (mm)	Volumetric fraction			Rib geometries			Mechanical properties		
	Glass fiber (%)	Steel wire (%)	Epoxy resin (%)	Rib spacing (mm)	Rib height (mm)	Rib angle (°)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)
8	37.95	26.75	35.3	8	0.47	48	1107	80	2.0
8	37.95	26.75	35.3	12	0.47	46	1107	80	2.0
8	37.95	26.75	35.3	16	0.47	44	1107	80	2.0
10	39.78	30.98	29.24	10	0.59	45	1027	80	2.0
12	38.25	28.88	32.87	12	0.49	44	836	80	2.0
14	42.94	23.75	33.31	14	0.57	45	761	80	2.0