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Tensile properties of novel carbon/glass hybrid thermoplastic composite rods

Kimiyoshi Naito *, Hiroyuki Oguma

National Institute for Materials Science, Research Center for Structural Materials, Polymer Matrix Hybrid Composite Materials Group, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan

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ABSTRACT

Novel carbon/glass hybrid thermoplastic composite rods consisting of unidirectional PAN-based carbon fiber (T700SC), braids of E-class glass fibers, and thermoplastic epoxy matrix have been developed. Three types of hybrid rods with differing carbon/glass ratios (24K1P, 24K2P, and 24K3P) were fabricated. The cross-sectional morphologies of the hybrid rods were observed using a digital microscope. Volume fractions of carbon fiber, glass fiber, matrix, and void of the hybrid rods were estimated using a specific gravity measurement via ethanol immersion and a thermogravimetric analysis.

The tensile properties and fracture behavior of the hybrid rods were investigated. For all hybrid rods, the stress applied to the specimen was nearly linearly proportional to the strain until failure, with a tensile modulus of 65 (24K1P), 87 (24K2P), and 91 GPa (24K3P) and tensile strengths of 1.42 (24K1P), 1.80 (24K2P), and 1.84 GPa (24K3P). The tensile modulus and strength increased with increasing carbon fiber volume fraction. The Weibull statistical distribution of tensile strength for the hybrid rods was examined. The Weibull modulus of the tensile strengths for the hybrid rods were 23.77 (24K1P), 27.29 (24K2P), and 32.50 (24K3P). The Weibull modulus increased with increasing tensile strength and decreasing void volume fraction of the hybrid rods.

1. Introduction

Tendons are widely used as tension members for civil infrastructure, buildings, and offshore engineering structures. In civil infrastructure and buildings, prestressed concrete is the main material used for beams and floors of bridges (for automobiles and trains) and piers, floors in high-rise buildings, and cylindrical walls and spherical shells in pressure vessels [1–3]. Prestressing (post- and pretensioning) tendons are used to provide a clamping load that produces compressive stress. Tendons are used for cables in suspension bridges, ground anchors, and repaired/reinforced buildings [1–3]. For offshore structures, prestressed concrete is the main material used in fixed and floating concrete platforms [4–6]. Tension leg platforms (TLP) are compliant structures consisting of a pontoon, columns, and a deck and are vertically moored at each corner by tendons [7–9]. Each tendon is pretensioned, such that it does not slack despite variations in the extreme ocean environment. The tension in the tendons is a function of the environmental conditions under which the structure must operate.

Tendons and traditional reinforced concretes use high-tensile-strength steel wires, bars, and rebars. Corrosion and fatigue of steel cables and classical steel reinforcing bars are serious issues [10–12]. Therefore, the use of fiber-reinforced polymer matrix composites (fiber-reinforced plastics), particularly carbon-fiber-reinforced polymer matrix composites [carbon-fiber-reinforced plastics (CFRPs)] have been proposed [13–16]. The application of CFRPs in construction, particularly in poststrengthening and rehabilitation, is well known and highly appreciated in most applications due to its long-term reliability.

In addition, as the oil and gas industries move to explore and develop ultra-deepwater reservoirs, the weight and performance of critical systems are increasingly important [17]. Generally, high-tensile-strength steel tubes are used for the tendons and become increasingly heavy at ultra-deepwater depths due to the requirement to resist collapse of the tube. Because weight-saving in components provides a significant operational improvement, CFRPs, which have the advantage of being stronger and lighter than steel, will provide alternatives for ultra-deepwater projects [18,19].

Epoxy resins are frequently used as a matrix in CFRPs because they have excellent mechanical properties and good handling properties, including fabrication. Currently, thermosetting epoxy

* Corresponding author.
E-mail address: NAITO.Kimiyoshi@nims.go.jp (K. Naito).

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resins are most often used for CFRP tendons [20,21]. However, the inherently brittle nature of epoxy and other thermosetting polymers and their poor resistance to crack initiation and growth are important issues that largely limit their application in certain fields[1]. Epoxy resins are also generally neither fusible nor soluble after curing due to the presence of cross-links in the chemical structure of cured resin. This property significantly restricts the possibility of post-forming, recycling, or reusing.

In contrast, carbon-fiber–reinforced thermoplastic matrix composites (carbon fiber reinforced thermoplastics, CFRTPs) have great potential to be post-formed, recycled, and reused because thermoplastic resins are toughened and fusible. However, the manufacturing of CFRTPs usually requires higher energy because high temperatures and pressures are necessary for the impregnation process due to its high molecular weight [22]. A new resin that has both good workability of thermosetting and post-formability, recyclability, or reusability, has been desired for use as the CFRTP matrix.

A new thermoplastic epoxy resin has been recently developed by Nagase ChemteX Corporation [23,24], and novel carbon/glass hybrid thermoplastic composite rods called "CABKOMA" have been developed by Komatsu Seiren Co., Ltd. The hybrid rods are the core-in-sheath type and consist of a bundle (or bundles) of carbon fiber surrounded by an outer braided bundle glass fiber in which a new thermoplastic epoxy resin is evenly impregnated as a matrix. The new thermoplastic epoxy resin remains thermoplastic even after curing.

The present study addresses fundamental research on these carbon/glass hybrid thermoplastic composite rods. The morphology and tensile properties of the hybrid rods were evaluated. The longitudinal and cross-sectional morphology of the hybrid rods were observed using a digital microscope. The volume fraction of carbon fiber, glass fiber, matrix, and void for the rods were estimated using a specific gravity measurement via ethanol immersion and a thermogravimetric analysis. Tensile tests of the hybrid rods were performed, and the Weibull statistical distributions of tensile strength for the rods were also examined.

2. Experimental procedure

2.1. Materials

The novel carbon/glass hybrid thermoplastic composite rods have been developed by the Komatsu Seiren Co., Ltd. Three types of hybrid rods, described as 24K1P, 24K2P, and 24K3P, with differing carbon/glass ratios were fabricated. The hybrid rods are the core-sheath type. Surrounding of the carbon fiber bundle (core) by a glass fiber tubular membrane was achieved by adding a glass fiber bundle with a braid structure (sheath) in which the thermoplastic epoxy was evenly infiltrated as a matrix. The carbon fiber portion of the hybrid rods is made of unidirectional T700SC polyacrylonitrile (PAN)-based carbon fibers (T700SC-24000-50C, Toray Industries, Inc.), which have a diameter of $d_f = 6.87$ μm as one bundle of 24000 filaments for 24K1P, two bundles of 48,000 filaments for 24K2P, and three bundles of 72,000 filaments for 24K3P. The glass fiber portion of the hybrid rods is made of E-class glass fibers (ECG751/01ZY-95T, Z-twist at 1 turn per inch, supplied from Nippon Electric Glass Co., Ltd.), which have a diameter $d_f = 9.20$ μm as one bundle of 400 filaments. The glass fiber portion of the hybrid rods is also twisted clockwise (to give an S-twist) for three bundles (1200 filaments) at 3.5 turns per inch (twisted yarn) and then braided with 16 yarns using a maypole braider (fabricated by Taniguchi Seichu Co., Ltd.). The thermoplastic epoxy in the hybrid rods was made of difunctional epoxy resin and difunctional phenolic compound mixed at a stoichiometric ratio (XNR6850V/XNH6850V = 100/6.5) (Nagase ChemteX Corporation) [23,24]. Dry hybrid rods were immersed in methyl ethyl ketone (MEK) solvent solution of the thermoplastic epoxy and then dried in an oven at 150 °C.

2.2. Characterization

The longitudinal morphology (in plain view) of the hybrid rods was observed using a digital microscope (VHX-5000 and VH-ZST, Keyence). The hybrid rods were cut into roughly 10-mm-long segments using a rotary cutting machine. The specimen for transverse sectional view was embedded in an epoxy resin molding material and then cut and polished on the transverse section. The cross-sectional morphology of the hybrid rods was also observed using a digital microscope (VHX-5000 and VH-ZST, Keyence).

The densities of the hybrid rods (ρ_h) (≈50 mm long) were measured via ethanol immersion (ASTM D792) [25]. The densities of carbon fiber (ρ_{CF}), glass fiber (ρ_{GF}), and matrix (ρ_M) are 1.80 g/cm^3, 2.54 g/cm^3, and 1.20 g/cm^3, respectively. At least three specimens were tested for each type of hybrid rod.

Thermogravimetric analysis (TGA) of the hybrid rods (about 5 mm long) was performed at 30–1000 °C at a heating rate of 10 °C/min under atmospheres of N_2 (400 mL/min), Ar (400 mL/min), and N_2/O_2(4:1) (400/100 mL/min) using a simultaneous thermogravimetric analyzer (STA7300, Hitachi High-Tech Science Corporation). At least three specimens were tested for each type of hybrid rod under each condition.

2.3. Tensile test

The hybrids rods were trimmed to 250 mm for 24K1P, 350 mm for 24K2P, and 450 mm for 24K3P. The glass fabric/epoxy composite tabs were fabricated using the wet hand layup process to each end of the specimen and a gauge length (L) of 110 mm [26]. The specimen was set up on the testing machine using an active gripping system. Tensile tests of the hybrid rods were performed using a universal testing machine (Autograph AG-series, Shimadzu) with a 50-kN load cell. A crosshead speed of 1 mm/min was applied. All tests were conducted in the laboratory environment at room temperature (at 23 ± 3 °C and 50 ± 5% relative humidity). Ten specimens were tested for all hybrid rod types.

The tensile test gives a load (P) as a function of extension (U^*) curve up to failure. Tensile stress (σ_L) and tensile strain (ε_L) were calculated as follows:

$$\sigma_L = \frac{P}{S} = \frac{P}{\left(\frac{\pi d^2}{4}\right)} \tag{1}$$

$$\varepsilon_L = \frac{U^*}{L^*} \tag{2}$$

$$v_{LT} = -\frac{\varepsilon_{L(gauge)}}{\varepsilon_{T(gauge)}} \tag{3}$$

where S is the total cross-sectional area of the hybrid rod, which can be calculated from the diameter (d) of the hybrid rod as measured using a micrometer. The average diameters of the hybrid rods are summarized in Table 1. L^* is the distance between targets (reference marks). The targets were marked on the bundle composites ($L^* \approx 70$ mm). The extension (U^*) was measured using a

[1] The unidirectional CFRPs and CFRP tendons exert no large influence under tensile loading because the fibers fail before the matrix even for thermosetting polymers. However, the flexural/shear loadings act upon applications using the unidirectional CFRPs and CFRP tendons. These statements are important issues for general composite laminates and unidirectional CFRPs and CFRP tendons under flexural/shear loadings. Toughened polymers are better choice than brittle ones.