Tensile properties of novel carbon/glass hybrid thermoplastic composite rods

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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.

Keywords: carbon fiber; glass fiber; thermoplastic epoxy; hybrid; tensile properties; Weibull modulus.

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 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 fields¹. 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 CFRTTP 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

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.

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 $d_f = 6.87 \mu\text{m}$ as one bundle of 24000 filaments for 24K1P, two bundles of 48000 filaments for 24K2P, and three bundles of 72000 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 $d_f = 9.20 \mu\text{m}$ 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 ($\text{XNR6850V/XNH6850V} = 100/6.5$) (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 $30\text{--}1000^\circ\text{C}$ at a heating rate of 10°C/min under atmospheres of N_2 (400 mL/min), Ar (400 mL/min), and $\text{N}_2/\text{O}_2(4:1)$ (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:

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

$$\varepsilon_L = \frac{U^*}{L^*} \quad (2)$$

$$\nu_{LT} = -\frac{\varepsilon_{L(gauge)}}{\varepsilon_{T(gauge)}} \quad (3)$$

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 non-contact video extensometer (DVE-201, Shimadzu). The DVE-201 extensometers perform precise, non-contact elongation measurements using CCD cameras to capture digital images of test specimens. The longitudinal (tensile) strain ($\varepsilon_{L(gauge)}$) and transverse strain ($\varepsilon_{T(gauge)}$) were also measured using strain gauges.

The tensile strength of the hybrid rods ($\sigma_{L,ult}$) was calculated as

$$\sigma_{Lult} = \frac{P_{max}}{S} = \frac{P_{max}}{\left(\frac{\pi d^2}{4}\right)} \quad (4)$$

where P_{max} is the maximum fracture load of the specimen.

After testing, the fracture surfaces of the hybrids rods were examined using a digital microscope (VHX-5000 and VH-ZST, Keyence).

3. Results

Typical longitudinal images of the hybrids rods clearly show that the glass fibers in the hybrid rods are of a braid structure (**Figure 1**). The biaxial construction has two sets of yarns running in opposite directions, where yarns in one direction are passing under and over the other. The braid interlacement patterns are very similar to woven structures [27]. The braids were observed to have a 2/2 twill weave.

The braid angle (θ) is the orientation angle of the interlacing yarns with respect to the braid axis. The braid angles of the hybrid rods were measured by taking their image under the digital microscope. The braid angles of hybrid rods are summarized in **Table 1**. The θ values were determined to be 22.3 ° (24K1P), 30.2 ° (24K2P), and 35.2 ° (24K3P), respectively.

Typical cross-sectional images of the hybrids rods clearly show that the individual carbon and glass fibers are well dispersed in the thermoplastic epoxy matrix (**Figure 2**). Some partial voids were observed at four sites at the boundary between the carbon fiber and glass fiber components.

The densities of 50-mm lengths of the hybrid rods as measured via ethanol immersion (ASTM D792) [25] are summarized in **Table 1**. ρ_h values were determined to be 1.759 g/cm³ (24K1P), 1.737 g/cm³ (24K2P), and 1.698 g/cm³ (24K3P).

TGA was employed to estimate the weight fraction of the hybrid rods. The thermogravimetry (TG) curves of the hybrid rods are shown in **Figure 3**. Thermal decomposition of hybrid rods under N₂/O₂ atmosphere can be divided into the following four stages: (I) the desorption of water and other small molecules (<180 °C); (II) the decomposition of organic (matrix) substances (200 °C–600 °C); (III) the decomposition of organic carbonaceous (carbon fiber) substances (600 °C–900 °C); and (IV) the residual inorganic (glass fiber) evolution (900 °C–1000 °C). Thermal decomposition of

the hybrid rods under both N₂ and Ar atmosphere can be divided into the following three stages: (I) the desorption of water and other small molecules (<180 °C), (II) the decomposition of organic (matrix) substances (200 °C–500 °C), and (III) the residual organic carbonaceous (carbon fiber) and inorganic (glass fiber) evolution (500 °C–1000 °C).

TG of the hybrid rods under N₂/O₂ atmosphere indicated weight losses of 42.67 % (24K1P), 56.69 % (24K2P), and 65.48 % (24K3P) at 900–1000 °C, indicating that the weight fraction (weight content) of glass fibers (W_{GF}) in the rods are 57.33 % (24K1P), 43.31 % (24K2P), and 24.52 % (24K3P). The TG of the hybrid rods under both N₂ and Ar atmosphere indicated a weight loss of 17.38 % (24K1P), 16.95 % (24K2P), and 16.48 % (24K3P) at 900–1000 °C, indicating that the weight fractions of glass fiber (W_{GF}) and carbon fiber (W_{CF}) are 82.62 % (24K1P), 83.05 % (24K2P), and 83.52 % (23KP3). Subtracting the TG results, the weight fraction of carbon fiber (W_{CF}) is 25.29 % (24K1P), 39.74 % (24K2P), and 49.00 % (24K3P), and the weight fraction of matrix (W_M) is 17.38 % (24K1P), 16.95 % (24K2P), and 16.48 % (24K3P).

The volume fraction of carbon fiber (V_{CF}), glass fiber (V_{GF}), matrix (V_M), and void (V_V) in each type of hybrid rod (**Table 1**) was calculated based on ASTM D2734 [28] using the following equations:

$$V_{CF} = \frac{W_{CF} \cdot \rho_h}{\rho_{CF}} \quad (5)$$

$$V_{GF} = \frac{W_{GF} \cdot \rho_h}{\rho_{GF}} \quad (6)$$

$$V_M = \frac{W_M \cdot \rho_h}{\rho_M} \quad (7)$$

$$V_V = 1 - V_{CF} - V_{GF} - V_M \quad (8)$$

For the 24K1P hybrid rod, the volume fractions of the elements were determined to be 24.58% (V_{CF}), 39.75% (V_{GF}), 25.49% (V_M), and 10.18% (V_V). For the 24K2P hybrid rod, they were determined to be 38.34% (V_{CF}), 29.63% (V_{GF}), 24.54% (V_M), and 7.49% (V_V). For the 24K3P hybrid rod, they were determined to be 46.18% (V_{CF}), 23.15% (V_{GF}),

23.39% (V_M), and 7.28% (V_V)².

Typical tensile stress-strain (σ_L - $\varepsilon_{L(gauge)}$) and longitudinal strain-transverse strain ($\varepsilon_{L(gauge)}$ - $\varepsilon_{T(gauge)}$) curves for the hybrid rods are shown in **Figure 4**. For all types of hybrid rods, the stress applied to the specimen was linearly proportional to the strain until failure. The tensile modulus (E_L) was calculated using a least square method for the straight line section of tensile stress-strain curve, and Poisson's ratio (ν_{LT}) was calculated using a least square method for the straight line section of the longitudinal strain-transverse strain curve. The average tensile modulus and Poisson's ratio of the hybrid rods are summarized in **Table 1**. The average tensile modulus of the hybrid rods was found to be 65 GPa (24K1P), 87 GPa (24K2P), and 91 GPa (24K3P), and the average Poisson's ratio of the hybrid rods was found to be 0.39 (24K1P), 0.41 (24K2P), and 0.45 (24K3P), respectively.

The average tensile strength ($\sigma_{L,ult.ave}$) and failure strain ($\varepsilon_{L(gauge),ult.ave}$) of the hybrid rods are summarized in **Table 1**. These results show that the average tensile strength of the hybrid rods was 1.42 GPa (24K1P), 1.80 GPa (24K2P), and 1.84 GPa (24K3P). The average failure strain of the hybrid rods was 2.18 % (24K1P), 2.13 % (24K2P), and 2.08 % (24K3P). The tensile modulus and strength increased with increasing V_{CF} . However, the Poisson's ratio and failure strain were similar between the hybrid rod types. The hybrid rods show carbon-fiber-dominated behavior of the tensile properties in the longitudinal direction of the fiber reinforcements.

Digital micrographs of longitudinal views of the tensile fractured surfaces of the hybrid rods are shown in **Figure 5** and show few differences between the hybrid rods. Axial tension failure in unidirectional CFRP specimens led to fracture in the transverse direction at several points and was associated with longitudinal splitting of the composite [29]. A similar fracture morphology (longitudinal splitting) was observed for all hybrid rods. The hybrid rods failed by extensive longitudinal splitting, resulting in a brush-like fracture surface, suggesting that the higher-strength T700SC PAN-based carbon fiber dominated the fracture behavior and increased fiber efficiency. We

² The composite (carbon/glass) fractions and large void contents (four sites at the boundary) were also estimated from the cross-sectional images of the hybrid rods using the digital microscope, and these values were observed to be comparable with calculation results. However, the diameters of the hybrid rods obtained from the volume-fraction measurements were 2.18 mm (24K1P), 2.48 mm (24K2P), and 2.75 mm (24K3P), respectively. They were 5.3% (24K1P), 9.6% (24K2P), and 10.9% (24K3P) smaller than those obtained from micrometer measurements. The shape of the hybrid rods was assumed to be circular, although they actually appeared to be circular with unevenness. The diameter (d) of the hybrid rods obtained from the micrometer measurements was measured on the large side, and there was a possibility that this result had influenced the measurement of the mechanical properties.

observed a distinct difference in morphology between the unidirectional CFRP rectangular specimens and the hybrid rods. The hybrid rods were covered with E-glass braid structure. The fractured surfaces of the hybrid rods showed splitting surfaces with a delaminated braid structure at several points.

The results shown in **Table 1** clearly indicate appreciable scattering of tensile strengths for the hybrid rods³. The statistical distribution of fiber and composite strengths is usually described using the Weibull equation⁴ [31]. The two-parameter Weibull distribution is given by

$$P_F = 1 - \exp \left[- \left(\frac{\sigma_{L,ult}}{\sigma_{L,0}} \right)^{m_L} \right] \quad (9)$$

where P_F is the cumulative probability of failure of a hybrid rod at the applied tensile strength $\sigma_{L,ult}$, where m_L is the Weibull modulus (Weibull shape parameter) of the hybrid rod and $\sigma_{L,0}$ a Weibull scale parameter (characteristic stress). The cumulative probability of failure (P_F) under a particular stress is given by

$$P_F = \frac{i}{n+1} \quad (10)$$

where i is the number of hybrid rods that have broken at or below a stress level and n is the total number of hybrid rods tested. Rearrangement of the two-parameter Weibull statistical distribution expression (Eq. 9) gives the following:

³ The coefficient of variation (standard deviation/average) of tensile strength for the hybrid rods was less than 5%, as shown in Table 1. This is typically considered to be small scattering. For the hybrid rods, the fracture of the low-elongation unidirectional carbon fiber bundle composites is impeded by the greater ductility of the high-elongation glass fiber bundle composites with a braided structure. The scattering of tensile strengths for the hybrid rods was lower than that for the individual unidirectional CFRPs. Similar results were observed for hybrid fiber/polymer composites [30].

⁴ The Weibull distribution with a flexible two-parameter analytic formula has been found to successfully describe a fracture sample. In this study, it is used for analysis of the Weibull distribution data. However, the Weibull distribution should be considered as an empirical one on an equal footing with other distribution functions [31]. The normal (Gaussian) distribution is another widely used function. Other possible candidates, which can be used for the probability density function of failure, involve lognormal distributions, etc. [32]. For small sample sizes, it is difficult to distinguish between the Weibull, normal, and other distributions. Therefore, the individual tensile strength data are shown in **Table 2**, and the comparison of the Weibull and normal distribution functions in terms of the cumulative probability are shown in **Figure 6**. The results do not show sufficient evidence that Weibull distribution is always preferred to normal distribution. A similar result was observed for brittle materials (Si_3N_4 , SiC , and ZnO) [33].

$$\ln\left(\ln\left[\frac{1}{1-P_F}\right]\right) = m_L \ln(\sigma_{L,ult}) - m_L \ln(\sigma_{L,0}) \quad (11)$$

Hence the Weibull modulus (m_L) can be obtained by linear regression from a Weibull plot of equation (11).

Weibull plots of the tensile strength for the hybrid rods are shown in **Figure 7**. The Weibull modulus (m_L) values for the hybrid rods are summarized in **Table 1**. m_L for the hybrid rods was calculated to be 23.77 (24K1P), 27.29 (24K2P), and 32.50 (24K3P). The Weibull modulus for single carbon fibers were found to be less than 10 [34], and the Weibull modulus for CFRPs was found to be less than 30 [30]. The Weibull modulus is higher for the hybrid rods than for the single carbon fibers and is similar to that of CFRPs. The correlation between the Weibull modulus and the average tensile strength of the hybrid rods is shown in **Figure 8**. The results show that the Weibull modulus increased with increasing tensile strength of the hybrid rods.

4. Discussion

4.1 Tensile modulus

The tensile moduli of the hybrid rods were calculated using a rule of mixture and laminate theory. The carbon fiber (CF), glass fiber (GF), and matrix (M) are assumed to be isotropic materials with the modulus, $E_{CF} = 230$ GPa, $E_{CF}^* = 10$ GPa, $E_{GF} = 70$ GPa, $E_M = 2$ GPa, and Poisson's Ratio, $\nu_{CF} = 0.3$, $\nu_{GF} = 0.3$, $\nu_M = 0.35$ ⁵. According to the results in **Table 1**, the volume fraction ($V_F = V_{CF} + V_{GF}$) of fiber (carbon and glass fibers) was found to be 64.33 % (24K1P), 67.97 % (24K2P), and 69.33 % (24K3P), respectively. The elastic properties of unidirectional CFRP and GFRP allowed for calculations using the rule of mixture.

The tensile modulus in the longitudinal direction (E_L) of unidirectional CFRP and GFRP was estimated using the following equation (a parallel model).

$$E_L = E_F V_F + E_M V_M \quad (12)$$

⁵ For isotropic materials, the in-plane shear modulus (G) is assumed to be $G = E / 2(1 + \nu)$. The carbon fiber (CF) has strong anisotropic material and the transverse modulus is assumed to be E_{CF}^* [35] and $G_{CF} = E_{CF}^* / 2(1 + \nu_{CF})$.

For the modulus in the transverse direction (E_T), Poisson's Ratio (ν_{LT}), and in-plane shear modulus (G_{LT}) of unidirectional CFRP and GFRP, the analytical model was considered as shown in **Figure 9**. They were separated into five parts as shown in **Figure 9** to obtain the material constant X (E_T , ν_{LT} , and G_{LT}). The parallel and series models were then applied.

$$X = \frac{X_M^2(a^2 - ad) + X_F^* X_M ad}{X_M(a^2 - ad + d^2) + X_F^*(ad - d^2)} \quad (13)$$

$$V_F = \frac{\pi d^2}{4a^2} \quad (14)$$

From Eqs. (13) and (14), the material constant X was derived as follows:

$$X = \frac{X_M^2 \left(1 - 2\sqrt{\frac{V_F}{\pi}} \right) + X_F^* X_M 2\sqrt{\frac{V_F}{\pi}}}{X_M \left(1 - 2\sqrt{\frac{V_F}{\pi}} + 4\frac{V_F}{\pi} \right) + X_F^* \left(2\sqrt{\frac{V_F}{\pi}} - 4\frac{V_F}{\pi} \right)} \quad (15)$$

The material constant X_F^* can be expressed as the function of X_F and X_M as follows:

$$X_F^* = X_M + \frac{\pi}{4}(X_F - X_M) \quad (16)$$

The calculated results were found in **Table 3** (Step 1).

The angles of CFRP for hybrid rods were 0° , and the angles (braid angles) of the GFRP for hybrid rods were found to be 22.3° (24K1P), 30.2° (24K2P), and 35.2° (24K3P). The tensile modulus of the hybrid rods were estimated using the laminate theory. The calculated results were found in **Table 3** (Step 2).

The void (V) is assumed to be isotropic materials with the modulus $E_V = 0.1$ GPa and Poisson's Ratio, $\nu_V = 0.1$. According to the result in **Table 1**, the volume fraction of void were found to be $V_V = 10.18\%$ (24K1P), 7.49% (24K2P), and 7.28% (24K3P). The elastic properties of the hybrid rods were also re-calculated using the rule

of mixture. The estimated results were summarized in **Table 3** (Step 3).

The difference between the analytical and experimental results was 5.0 % (24K1P), 5.9 % (24K2P), and 13.7 % (24K3P)⁶ for the tensile modulus, and 3.8 % (24K1P), 4.7 % (24K2P), and 12.4 % (24K3P) for Poisson's Ratio. These experimental results were in agreement with the prediction.

4.2 Tensile strength and failure strain

The fracture stress of fiber or unidirectional CFRP (fiber-failure stress) is a method commonly used to predict the strength of a laminate. The tensile strength of the hybrid rods was also determined using the laminate theory and fiber-failure stress analysis. The fracture stress of CFRP is $4.90 \cdot V_F$ (3.15 GPa [24K1P], 3.33 GPa [24K2P], and 3.40 GPa [24K3P]) [36].

The estimated tensile strength $\sigma_{L,cal}$ of the hybrid rods was determined to be 1.41 GPa (24K1P), 1.91 GPa (24K2P), and 2.19 GPa (24K3P) GPa. The difference between the calculated and experimental results for tensile strength was 1.0 % (24K1P), 5.7 % (24K2P), and 16.2 % (24K3P)⁶. The experimental results for tensile strength were in agreement with predicted values. The failure strain of the hybrid rods (**Table 1**) is similar to that of the T700SC PAN-based carbon fiber (2.1 %) [36].

4.3 Weibull modulus

The Weibull modulus increased with increasing tensile strength of the hybrid rods, indicating that the greater strength of the hybrid rods caused the narrow strength distribution. This phenomenon is important to consider. The Weibull modulus increased with increasing carbon fiber volume fraction and decreasing void content of the hybrid rods (**Figure 10**).

Although, the hybrid rods exhibit carbon-fiber-dominated behavior for tensile properties in the longitudinal direction of the fiber reinforcements, differences in the Weibull modulus can be attributed to the nature and distribution of the flaws present in the hybrid rods. It is well-known that many defects, including void, fiber breakage, and fiber misalignment [37] are known to be introduced into these laminates during manufacturing and subsequent treatment. The presence of such defects in the laminates results in scattering of the tensile strength data.

The carbon fiber volume fraction of the 24K1P hybrid rod was lowest among

⁶ The modulus and strength differences between the analytical and experimental results for the 24K3P hybrid rod were larger than those for the 24K1P and 24K2P hybrid rods. These discrepancies strongly depended on the diameter differences between the micrometer and the volume fraction measurements. Detail descriptions were given in footnote 2.

the other hybrid rods and the void volume fraction of the 24K1P hybrid rod was quite high. The strength differences between the samples strongly affected the carbon fiber volume fraction and the void distribution. Therefore, the strength distribution for the 24K1P hybrid rod varied from lower to higher stress levels. Consequently, the Weibull modulus of the 24K1P hybrid rod was lower. In contrast, the carbon fiber volume fraction of the 24K2P hybrid rod was intermediate and the fraction of the 24K3P hybrid rod was highest among the hybrid rods. In addition, the void volume fraction of the 24K2P and 24K3P hybrid rods was intermediate in value and the excess strength affected the carbon fiber volume fraction and void distribution. Therefore, the strength distributions of the 24K2P and 24K3P hybrid rods were narrow. Consequently, the Weibull modulus of the 24K2P and 24K3P hybrid rods were higher.

5. Concluding remarks

The morphology of the hybrid rods was investigated, and the fiber, matrix, and void volume fractions of the hybrid rods were determined. The results of tensile tests of the hybrid rods are summarized as follows:

- (1) The hybrid rods have a braid structure, with braid angles of 22.3° (24K1P), 30.2° (24K2P), and 35.2° (24K3P).
- (2) Voids are clearly visible in the cross-sectional view of hybrid rods. For the 24K1P hybrid rod, the volume fractions of elements were determined to be 24.58% (V_{CF}), 39.75% (V_{GF}), 25.49% (V_M), and 10.18% (V_V). For the 24K2P hybrid rod, they were determined to be 38.34% (V_{CF}), 29.63% (V_{GF}), 24.54% (V_M), and 7.49% (V_V). For the 24K3P hybrid rod, they were determined to be 46.18% (V_{CF}), 23.15% (V_{GF}), 23.39% (V_M), and 7.28% (V_V).
- (3) The stress applied to the hybrid rod specimens was linearly proportional to the strain until failure, with a tensile modulus of 65 GPa (24K1P), 87 GPa (24K2P), 91 GPa (24K3P) and a Poisson's ratio of 0.39 (24K1P), 0.41 (24K2P), and 0.45 (24K3P). The tensile strength was 1.42 GPa (24K1P), 1.80 GPa (24K2P), and 1.84 GPa (24K3P), and the failure strain was 2.18 % (24K1P), 2.13 % (24K2P), and 2.08 % (24K3P). The tensile modulus and strength increases with increasing carbon fiber volume fraction. However, the Poisson's ratio and failure strain are similar between the different types of hybrid rods. The tensile modulus, Poisson's ratio, and tensile strength of the hybrid rods could be estimated using a rule of mixture, laminate theory, and fiber-failure stress analysis.

- (4) The Weibull modulus is 23.77 (24K1P), 27.29 (24K2P), and 32.50 (24K3P). As tensile strength and carbon fiber volume fraction increase and void volume fraction decreases, the Weibull modulus of the hybrid rods increase. The Weibull modulus of tensile strength for the hybrid rods depends on the carbon fiber and void-volume fractions.

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Figures and table legends

Table 1. Physical and mechanical properties of the carbon/glass hybrid thermoplastic composite rods.

Table 2. The experimentally measured tensile strength data, as obtained with the carbon/glass hybrid thermoplastic composite rods.

Table 3. Analytical results for mechanical properties of the carbon/glass hybrid thermoplastic composite rods.

Figure 1. Typical longitudinal images of the hybrids rods. (a) 24K1P, (b) 24K2P, and (c) 24K3P.

Figure 2. Typical cross-sectional images of the hybrids rods. (a) 24K1P, (b) 24K2P, and (c) 24K3P.

Figure 3. Thermogravimetry curves for the hybrid rods. (a) 24K1P, (b) 24K2P, and (c) 24K3P.

Figure 4. Typical tensile stress-strain and longitudinal strain–transverse strain curves for the hybrid rods. (a) tensile stress-strain curve and (b) longitudinal strain–transverse strain curve.

Figure 5. Digital microscope micrographs of longitudinal views for the tensile fractured surfaces of the hybrid rods.

Figure 6. The cumulative probability distributions of hybrid rod tensile strength.

Figure 7. Weibull plots of hybrid rod tensile strength.

Figure 8. Relation between the Weibull modulus and the average tensile strength of the hybrid rods.

Figure 9. Analytical model.

Figure 10. Relation between the Weibull modulus and the volume fractions of carbon fiber and voids in hybrid rods. (a) volume fraction of carbon fiber and (b) volume fraction of voids.

Figure 1: K. Naito

Figure 2: K. Naito

Figure 3: K. Naito

Figure 4: K. Naito

Figure 5: K. Naito

Figure 6: K. Naito

Figure 7: K. Naito

Figure 8: K. Naito

Figure 9: K. Naito

Figure 10: K. Naito

Table 1 Physical and mechanical properties of the carbon/glass hybrid thermoplastic composite rods.

	24K1P	24K2P	24K3P
Diameter d (mm)	2.30 (0.03)	2.73 (0.04)	3.09 (0.03)
Braid angle θ (°)	22.3 (1.6)	30.2 (1.5)	35.2 (1.8)
Density ρ_h (g/cm ³)	1.759 (0.007)	1.737 (0.008)	1.698 (0.009)
Volume fraction of carbon fiber V_{CF} (%)	24.58 (1.20)	38.34 (0.68)	46.18 (2.79)
Volume fraction of glass fiber V_{GF} (%)	39.75 (0.79)	29.63 (0.41)	23.15 (1.93)
Volume fraction of matrix V_M (%)	25.49 (0.37)	24.54 (0.32)	23.39 (0.67)
Volume fraction of void V_V (%)	10.18 (0.76)	7.49 (0.60)	7.28 (1.33)
Tensile modulus E_L (GPa)	65 (3) 67 (3) (video) 64 (3) (gauge)	87 (7) 89 (8) (video) 85 (6) (gauge)	91 (7) 92 (8) (video) 90 (5) (gauge)
Poisson's Ratio ν_{LT}	0.39 (0.08) (gauge)	0.41 (0.10) (gauge)	0.45 (0.07) (gauge)
Tensile strength $\sigma_{L,ult}$ (GPa)	1.42 (0.05)	1.80 (0.06)	1.84 (0.05)
Failure strain $\epsilon_{L,ult}$ (%)	2.18 (0.07) 2.17 (0.08) (video) 2.20 (0.07) (gauge)	2.13 (0.15) 2.09 (0.18) (video) 2.16 (0.12) (gauge)	2.08 (0.14) 2.08 (0.15) (video) 2.07 (0.15) (gauge)
Weibull modulus m_L	23.77	27.29	32.50

() indicate standard deviations

Table 2 The experimentally measured tensile strength data, as obtained with the carbon/glass hybrid thermoplastic composite rods.

Sample No.	Tensile strength, $\sigma_{L,ult}$ (GPa)		
	24K1P	24K2P	24K3P
1	1.351	1.658	1.766
2	1.368	1.755	1.783
3	1.400	1.781	1.800
4	1.404	1.795	1.801
5	1.409	1.810	1.828
6	1.418	1.815	1.830
7	1.437	1.837	1.841
8	1.440	1.846	1.893
9	1.449	1.848	1.909
10	1.551	1.880	1.921

Table 3 Analytical results for mechanical properties of the carbon/glass hybrid thermoplastic composite rods.

	24K1P	24K2P	24K3P
Step 1	$E_{CFRPL} = 149 \text{ GPa}$ $E_{CFRPT} = 4.70 \text{ GPa}$ $G_{CFRPLT} = 2.12 \text{ GPa}$ $\nu_{CFRPLT} = 0.324$ $E_{GFRPL} = 46 \text{ GPa}$ $E_{GFRPT} = 8.56 \text{ GPa}$ $G_{GFRPLT} = 3.83 \text{ GPa}$ $\nu_{GFRPLT} = 0.324$	$E_{CFRPL} = 157 \text{ GPa}$ $E_{CFRPT} = 4.94 \text{ GPa}$ $G_{CFRPLT} = 2.23 \text{ GPa}$ $\nu_{CFRPLT} = 0.323$ $E_{GFRPL} = 48 \text{ GPa}$ $E_{GFRPT} = 9.46 \text{ GPa}$ $G_{GFRPLT} = 4.23 \text{ GPa}$ $\nu_{GFRPLT} = 0.323$	$E_{CFRPL} = 160 \text{ GPa}$ $E_{CFRPT} = 5.03 \text{ GPa}$ $G_{CFRPLT} = 2.28 \text{ GPa}$ $\nu_{CFRPLT} = 0.322$ $E_{GFRPL} = 49 \text{ GPa}$ $E_{GFRPT} = 9.84 \text{ GPa}$ $G_{GFRPLT} = 4.41 \text{ GPa}$ $\nu_{GFRPLT} = 0.322$
Step 2	$E_{L(LAM)} = 77 \text{ GPa}$ $E_{T(LAM)} = 7.64 \text{ GPa}$ $G_{LT(LAM)} = 5.80 \text{ GPa}$ $\nu_{LT(LAM)} = 0.623$	$E_{L(LAM)} = 100 \text{ GPa}$ $E_{T(LAM)} = 8.16 \text{ GPa}$ $G_{LT(LAM)} = 6.05 \text{ GPa}$ $\nu_{LT(LAM)} = 0.618$	$E_{L(LAM)} = 114 \text{ GPa}$ $E_{T(LAM)} = 8.29 \text{ GPa}$ $G_{LT(LAM)} = 5.66 \text{ GPa}$ $\nu_{LT(LAM)} = 0.570$
Step 3	$E_{L(CAL)} = 69 \text{ GPa}$ $E_{T(CAL)} = 1.45 \text{ GPa}$ $G_{LT(CAL)} = 0.66 \text{ GPa}$ $\nu_{LT(CAL)} = 0.407$	$E_{L(CAL)} = 92 \text{ GPa}$ $E_{T(CAL)} = 1.86 \text{ GPa}$ $G_{LT(CAL)} = 0.83 \text{ GPa}$ $\nu_{LT(CAL)} = 0.427$	$E_{L(CAL)} = 106 \text{ GPa}$ $E_{T(CAL)} = 1.91 \text{ GPa}$ $G_{LT(CAL)} = 0.87 \text{ GPa}$ $\nu_{LT(CAL)} = 0.402$