MECHANICAL PROPERTIES OF NOVEL CARBON/GLASS FIBER HYBRID ROD FOR TENDONS

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Keywords: Tensile strength, Fatigue strength, Weibull modulus, Volume fraction, Hybrid material

Abstract
In the present work, novel carbon/glass hybrid thermoplastic composite rods have been developed. Three types of the hybrid rod with different carbon/glass ratios were fabricated. To investigate mechanical properties of the hybrid rods, tensile tests and fatigue tests were conducted. In the tensile tests, tensile modulus and strength increased with increasing volume fraction of carbon fiber. The Weibull statistical distributions of the tensile strength indicated that the hybrid rod with smaller volume fraction of void and higher strength showed the narrow strength distribution. Fatigue tests were carried out under stress ratio of R = 0.1 until 10^7 cycles. Fatigue strengths of the hybrids rods were almost 30% of the tensile strength, and that was lower than anticipated. To investigate the reason of the lower fatigue strength, cross section of the hybrid rods were observed in detail. As a result, there existed voids in the polymer mainly due to the volatilization of solvent. Small voids were also existing in the carbon fiber bundles. Void can affect the force transmission between the fibers, and it can also be an initiation site of crack. The results indicate that production process strongly affect the mechanical properties of the hybrid rods.

1. Introduction

Tendons have been widely used as tension members for marine structures [1]. A Tension Leg Platform (TLP) is a floating platform suitable for deep-water oil and gas field development, and the platform is vertically moored to the seabed by pre-tensioned tendons which allow very little vertical motion. Consequently, the tension loadings are common environmental conditions in the tendons under the structure operations. As the oil and gas industries move to explore and develop ultra-deep-water reservoirs, weight and performance of critical systems become increasingly important. Generally, high tensile strength steel tubes are used for the tendons, and become increasingly heavy at ultra-deep-water depths due to the requirement to resist collapse of the tube. Since weight saving in components provide a significant operational improvement, composite materials, which have the advantage of being stronger and lighter than steel, will provide alternatives for ultra-deep-water projects.

In this study, fundamental research on novel carbon/glass hybrid thermoplastic composite rods were carried out. The morphology and mechanical properties of the materials were evaluated. The 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 hybrid rods were estimated using a specific gravity measurement a thermogravimetric analysis. Tensile tests of the hybrid rods were performed to investigate mechanical properties of the materials. The Weibull statistical distributions of tensile strength for the hybrid rods were examined. Fatigue properties were also investigated based on the cyclic load testing and observation.

Excerpt from ISBN 978-3-00-053387-7

2. Materials

Novel carbon/glass hybrid thermoplastic composite rods called “CABKOMA” have been developed by KOMATSU SEIREN Co., Ltd [2]. 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 thermoplastic epoxy resin is evenly impregnated as a matrix, as shown in Fig. 1.

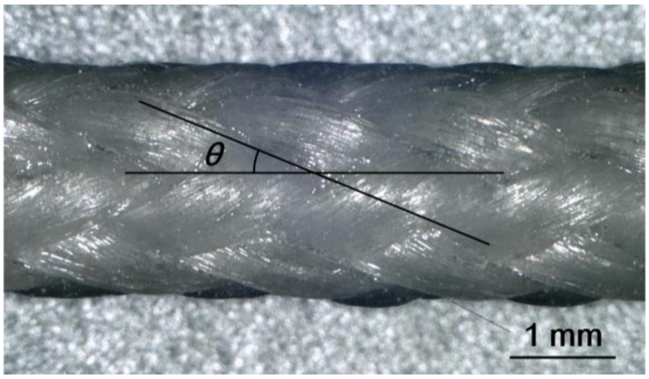

Figure 1. Surface of the hybrid rod.

The core bundles are made of the unidirectional polyacrylonitrile (PAN)-based carbon fiber from Toray Industries, Inc., and consist of 24000 (hereinafter called 24K1P), 48000 (24K2P) or 72000 (24K3P) filaments. The outer part is made of the E-class glass fiber, and a bundle is supplied from Nippon Electric Glass Co., Ltd. The bundles are twisted by Taniguchi Seichu Co., Ltd., and the outer part of the hybrid rod is fabricated using a maypole braiding machine. The impregnated resin consists of difunctional epoxy and compound supplied from Nagase ChemteX Corporation.

The average diameter and density of the hybrid rods are shown in Table 1. Densities of the hybrid rods were measured via ethanol immersion according to ASTM D792 [3]. Densities of carbon fiber, glass fiber, and matrix are ρ_{CF} = 1.80 g/cm^3, ρ_{GF} = 2.54 g/cm^3, and ρ_M = 1.20 g/cm^3, respectively.

Table 1. Physical properties of the hybrid rods.

	Diameter d [mm]		Braid angle θ [°]		Density ρ_h [g/cm^3]
	Ave.	SD	Ave.	SD	
24K1P	**2.30**	**0.03**	**22.3**	**1.6**	**1.759**
24K2P	**2.73**	**0.04**	**30.2**	**1.5**	**1.737**
24K3P	**3.09**	**0.03**	**35.2**	**1.8**	**1.698**

The volume fractions of carbon fiber, glass fiber, matrix, and void in each hybrid rods were calculated based on ASTM D2734 [4]. Thermogravimetric analysis (TGA) tests of the hybrid rods were performed from 30 to 1000 °C at a heating rate of 10 °C/min under N_2, Ar, and N_2/O_2 = 4/1 atmosphere using a simultaneous thermogravimetric analyzer (STA7300, Hitachi High-Tech Science Corporation). Volume fractions of the constituent are summarized in Table 2.

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Table 2. Volume fractions of the hybrid rods.

	Carbon fiber V_{CF} [%]		Glass fiber V_{GF} [%]		Matrix V_M [%]		Void V_V [%]	
	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
24K1P	**24.58**	**1.20**	**39.75**	**0.79**	**25.49**	**0.37**	**10.18**	**0.76**
24K2P	**38.34**	**0.68**	**29.63**	**0.41**	**24.54**	**0.32**	**7.49**	**0.60**
24K3P	**46.18**	**2.79**	**23.15**	**1.93**	**23.39**	**0.67**	**7.28**	**1.33**

3. Experimental Procedures

3.1. Tensile Test

Tensile tests of the hybrid rods were carried out using a universal testing machine with a 5 kN load cell, Autograph AG-series, Shimadzu Corporation. The hybrids rods were trimmed to 250 mm for 24K1P, 350 mm for 24K2P, and 450 mm for 24K3P. Glass fiber fabric and epoxy composite gripping sections were fabricated by wet hand layup process to each end of the specimen, and the gauge length was 110 mm. The specimen was set up to the testing machine using active gripping systems. The crosshead speed was 1 mm/min. All tests were conducted under the laboratory environment at room temperature of 23 ± 3 °C, and relative humidity of 50 ± 5 %. Ten specimens were tested for the all types of hybrid rods.

Tensile stress, σ_L and tensile strain, ε_L were calculated as follows:

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

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

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

where P is the tensile load, and S is the total cross-section area of hybrid rod. The area was calculated from the diameter d of the hybrid rod regarded as an elliptical cross-section. U^* is the elongation of the gauge section, and L^* is the initial gauge length. The elongation was measured using a non-contact video extensometer (DVE-201, Shimadzu Corporation). Targets were marked on the hybrid rod, and the initial distance was about 70 mm. The longitudinal (tensile) strain, $\varepsilon_{L(gauge)}$, and transverse strain, $\varepsilon_{T(gauge)}$, were also measured using strain gauges. The ultimate tensile strength of the hybrid rods, $\sigma_{L.ult}$, was calculated by substituting the maximum load, P_{max}, into the Eq. (1).

3.2. Fatigue Test

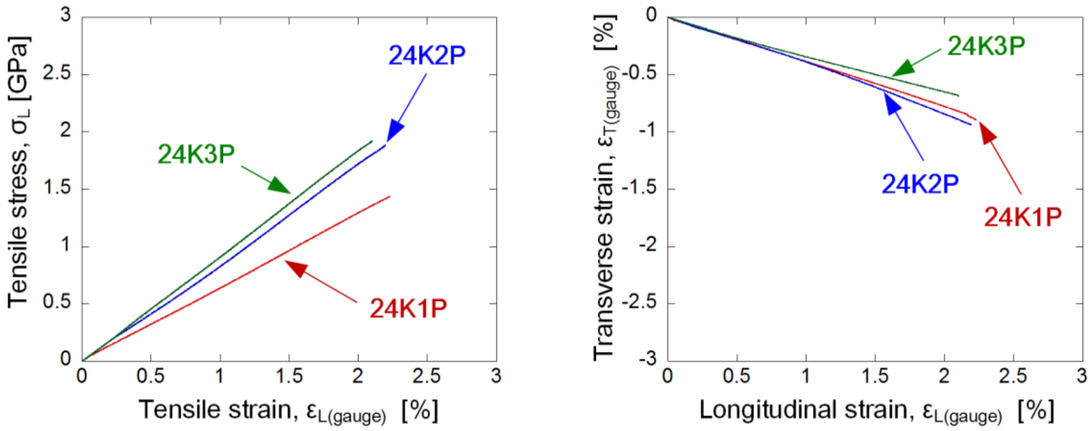
Uni-axial fatigue tests were carried out under sinusoidal waveform loading using an electro-servo-hydraulic-testing machine (SERVOPULSER EHF-E, Shimadzu Corporation) at 10 Hz. A stress ratio

(R = σ_{min} / σ_{max}) was 0.1, and this means that materials were under tension-tension loading conditions. The tests were terminated at 10^7 (ten million) cycles. All tests were conducted under the laboratory environment at room temperature. For the fatigue specimen, the wet-preg process introduced to the specimen for the tensile test was also used for the gripping parts. The gauge length of the fatigue specimen was 40 mm, and specimens broke at the gauge parts.

4. Experimental Result and Discussion

4.1. Tensile Test

Typical tensile test results are shown in Fig. 2, and numerical data is summarized in Table 3. The stress-strain curves for all hybrid rods are almost linear. Referring to the Table 2, the tensile modulus and strength increased with increasing the volume fraction of carbon fiber (V_{CF}). However, the Poisson's ratio and failure strain did not depend on the V_{CF}.



(a) Stress-strain curves (b) Transverse and longitudinal strain curves

Figure 2. Tensile test results

Table 3. Mechanical properties.

	Tensile modulus E_L [GPa]		Poisson's ratio ν_{LT}		Tensile strength $\sigma_{L.ult}$ [GPa]		Failure strain $\varepsilon_{L.ult}$ [%]	
	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
24K1P	**65**	**3**	**0.39**	**0.08**	**1.42**	**0.05**	**2.18**	**0.07**
24K2P	**87**	**7**	**0.41**	**0.10**	**1.80**	**0.06**	**2.13**	**0.15**
24K3P	**91**	**7**	**0.45**	**0.07**	**1.84**	**0.05**	**2.08**	**0.14**

The statistical distribution of fiber and composite strengths is usually described by means of the Weibull equation [5]. Weibull plots of the tensile strength are shown in Fig. 3. The cumulative probability of failure under a particular stress is given by

$$P_F = \frac{i}{n+1} \quad (4)$$

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where *i* is the number of hybrid rods that have broken at or below a stress level, and *n* is the total number of tested hybrid rods. The two-parameter Weibull distribution is represented by following equation:

$$P_F = 1 - \exp\left[-\left(\frac{\sigma_{L.ult}}{\sigma_{L.0}} \right)^{m_L} \right] \tag{5}$$

where P_F is the cumulative probability of failure at the ultimate tensile strength ($\sigma_{L.ult}$), m_L is the Weibull modulus (Weibull shape parameter), and $\sigma_{L.0}$ is the Weibull scale parameter (characteristic stress). The Weibull modulus, m_L, was obtained by performing a linear regression.

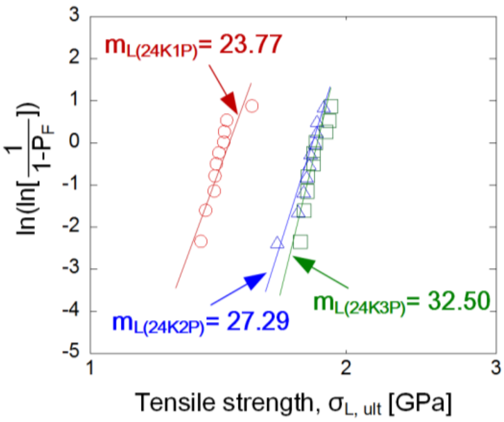

Figure 3. Weibull plots of tensile strength.

The Weibull modulus, m_L, for the hybrid rods were 23.77 (24K1P), 27.29 (24K2P), and 32.50 (24K3P). In previous studies, the Weibull modulus for single carbon fibers were smaller than 10 [6], and the Weibull modulus for carbon fiber reinforced plastics, CFRPs, were found to be less than 30 [7]. The Weibull modulus for the hybrid rods are larger than that for the single carbon fibers, and they are almost similar to that for the CFRPs. The Weibull modulus increased with increasing the tensile strength. The result indicates that the hybrid rod with smaller volume fraction of void (see Table 2) and higher strength showed the narrow strength distribution. The voids in the rods probably affect the tensile properties of the hybrid rods.

4.2. Fatigue Test

The number of cycles to failure N_f as a function of maximum stress σ_{max} is shown in Fig. 4 for all the hybrid rods. Data of 24K1P is indicated by the cycle, that of 24K2P and 24K3P by the tringle and square, respectively. Tensile strengths are also indicated in the diagram. Regardless of the materials, fatigue lives increase with decreasing applied load. The strength at 10^7 cycles was defined as the average of the maximum stress of censored data at 10^7 cycles and the minimum stress among the failure data below 10^7 cycles. Fatigue strengths of the rods were 300 MPa for 24K1P, 550 MPa for 24K2P, and 650 MPa for 24K3P. Strength ratios (def.: fatigue strength / tensile strength) were almost the same for different carbon/glass ratios, and the fatigue strength at 10^7 cycles was about 30% of the tensile strength. Generally, fatigue strength of unidirectional CF composite is about 50 to 80% of the tensile strength. This result shows that the fatigue strength of the hybrid rod is lower than anticipated.

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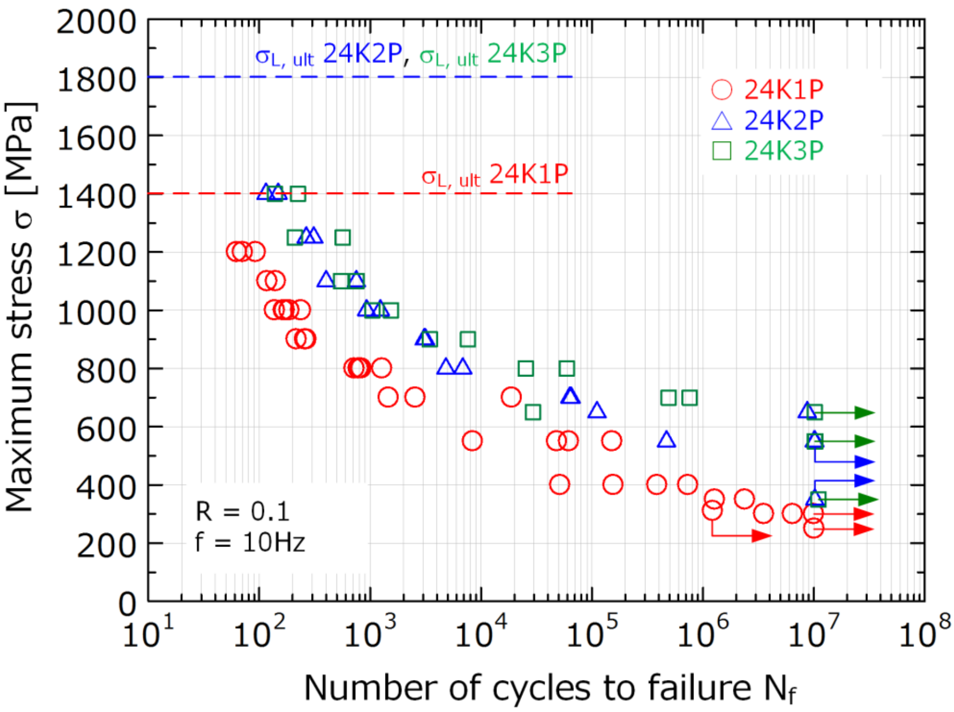

Figure 4. S-N diagram.

4.3. Observation

To investigate the reason of the lower fatigue strength, surface and cross section of the hybrid rods are observed with digital microscope, VHX-5000, KEYENCE Corporation.

As shown in Fig.5, there existed voids in the polymer between carbon fiber and glass fiber bundles as indicated by arrows, due to the volatilization of solvent. Small voids were also existing in the carbon fiber bundles. Void can affect the force transmission between the fibers. It can also be an initiation site of fatigue crack. The voids and cracks grow around fibers under cyclic loadings, and fracture accordingly occurs. The results indicate that the braided bundles of glass fibers and voids in the hybrid rod probably play an important role in the fatigue fracture mechanism, and production process strongly affects the mechanical properties of the hybrid rod.

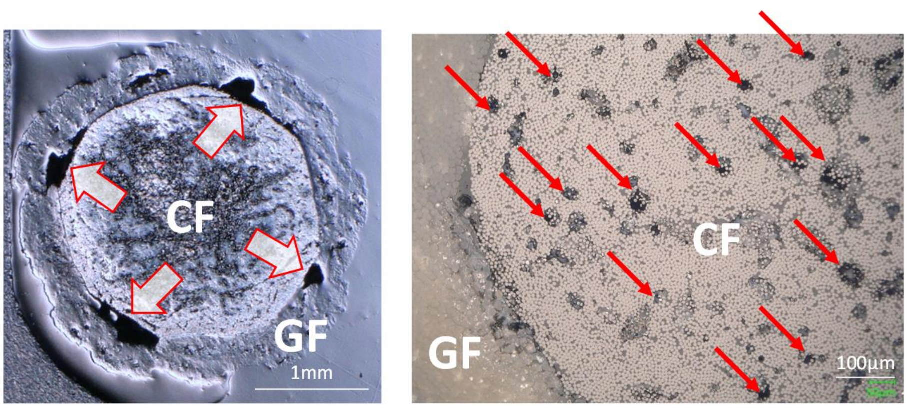

Figure 5. Cross section of the hybrid rod (24K3P).

5. Conclusions

Mechanical testing, including tensile and fatigue tests, and observations were carried out to investigate the mechanical properties of the novel CF/GF hybrid rods. In the tensile tests, tensile modulus and strength increased with increasing the volume fraction of carbon fiber. The Weibull plots of the tensile strength indicated that the hybrid rod with smaller volume fraction of void and higher strength showed the narrow strength distribution. Fatigue strengths of the hybrids rods were almost 30% of the tensile strength. There existed voids in the polymer due to the volatilization of solvent. Small voids were also existing in the carbon fiber bundles. Void can affect the force transmission between the fibers, and it can also be an initiation site of crack. The results indicate that production process strongly affect the mechanical properties of the hybrid rods.

Acknowledgments

This research was promoted by COI program "Construction of next-generation infrastructure using innovative materials -- Realization of a safe and secure society that can coexist with the Earth for centuries -- supported by MEXT and JST.

References

[1] C. Sparks, I. Zivanovic, J. Luyckx, W. Hudson. Carbon Fiber Composite Tendons for Deepwater Tension Leg Platforms OTC 15164. *Offshore Technology Conference, Houston, Texas,* May 5-8 2003.

[2] H. Oguma, K. Naito. Tensile Properties of Novel Carbon/Glass Hybrid Thermoplastic Composite Rods for Tendon. *LIMAS 2015 International Conference on Lightweight Design of Marine Structures, Glasgow, Scotland, UK,* Nov. 9-11 2015.

[3] ASTM International. *Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement*. ASTM D792-13 2013.

[4] ASTM International. *Standard Test Methods for Void Content of Reinforced Plastics*. ASTM D2734-09 2009.

[5] W. Weibull. A statistical distribution of wide applicability. *Journal of Applied Mechanics*, 18: 293-297, 1951.

[6] K. Naito, Y. Tanaka, J. Yang, Y. Kagawa. Tensile properties of ultrahigh strength PAN-based, ultrahigh modulus pitch-based and high ductility pitch-based carbon fibers. *Carbon*, Vol. 46, Issue 2, 189-195, 2008.

[7] K. Naito, J. Yang, Y. Kagawa. Tensile properties of high strength polyacrylonitrile (PAN)-based and high modulus pitch-based hybrid carbon fibers-reinforced epoxy matrix composite. *Journal of Materials Science*, Vol. 47, Issue 6, 2743–2751, 2012.

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