TENSION / TORSION FATIGUE BEHAVIOR OF UNIDIRECTIONAL GFRP AND CFRP

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Abstract

This research examines the feasibility of CFRP as a future flexbeam material. The torsion behaviors of unidirectional CFRP and GFRP with the same matrix resin were investigated. The behavior of both CFRP and GFRP is comprised of linear / non-linear domains. The initial torsional rigidity of CFRP was almost the same as that of GFRP, because the shear stiffness of CFRP was almost the same as that of GFRP. The nonlinear torsional behavior was observed above 0.5 % of the shear strain, and it is due to visco-plastic and plastic deformation of the matrix resin. Torsion / tension fatigue behaviors of unidirectional GFRP and CFRP laminates were also evaluated. Catastrophic failure was not observed for GFRP and CFRP, whereas the decrease in torsional stiffness was clearly observed. This is due to propagation of splitting cracks during the cyclic torsional loading. In order to compare the stiffness degradation of CFRP with that of GFRP, fatigue life was defined as the 10% of torsional stiffness degradation. The torsional fatigue lifetime of CFRP was much better than that of GFRP. The experimental results suggest that CFRP is preferable for helicopter flex beam material because of its excellent fatigue resistance under torsion as well as tension loading conditions.

1 Introduction

A helicopter rotor hub is subject to complex loadings. The predominant loads are a static tension load due to the centrifugal force, an alternating torsional load due to the feathering motion, a bending moment due to the flapping motion, and an in-plane bending moment due to the lead-lag motion.

In order to accommodate all these three motions, a conventional helicopter rotor system consists of three sets of bearing system. On the other hand, a simple helicopter rotor concept for small helicopters, designed to reduce complexity and cost through the elimination of all hinges and bearings of a conventional articulated rotor system, has been developed utilizing the unique anisotropic modulus characteristics of fiber reinforced composites[1-3].

Helicopter bearingless rotor flexbeams have been made of glass-fiber reinforced plastic composite (GFRP) until now. Therefore, the torsion / tension behavior of GFRP has been investigated in detail for designing rotor hub systems [4-6]. In the near future, carbon fiber reinforced plastic composites (CFRP) may replace the GFRP in the bearingless rotor flexbeam, due to their superior tensile fatigue strength [7-9] and lower weight, which is desirable for more improvement in the performance of bearingless rotor systems. However, few researches on the torsional behavior of CFRP have been reported, and the behavior has not been understood sufficiently.

The authors have conducted the feasibility study of a unidirectional CFRP as a future candidate material for a bearingless rotor flexbeam. For the first step, static torsion tests of unidirectional CFRP and GFRP with the same matrix resin and elastic/plastic behaviors under torsional loading were investigated in detail [10]. The experimental result suggested that GFRP could be replaced by CFRP as torsional elements of a helicopter flex beam without an increase in torsional rigidity. This paper presents the results of the second step research regarding the tension/torsion fatigue behavior of the unidirectional CFRP and GFRP.

2 Experimental procedure

2.1 Materials

Carbon and glass fibers used in this study are T1000G (Toray Industries Inc., Japan) and T-glass (Nitto Boseki Co. Ltd., Japan). T1000G is the highest tensile strength commercial carbon fiber in the world, suitable for tensile strength critical applications. T-glass is a high performance glass fiber developed for aerospace applications. Mechanical properties of the fibers, which were obtained from the material suppliers, are summarized in Table 1. A toughened epoxy resin (#3651, Toray, Japan) was applied for both CFRP and GFRP. Number of plies of unidirectional prepreg tapes was 5 for tensile test specimens, and 16 for torsion test specimens. Fiber volume fraction was 55 % for CFRP, and 57 % for GFRP, respectively

Table 1. Mechanical properties of T1000G and T-Glass fibers

	T1000G	T-Glass
Supplier	Toray Industries Inc.	Nitto Boseki Co. Ltd.
Tensile strength	6.4 GPa	3.14 GPa
Tensile modulus	294 GPa	90.2 GPa
Failure strain	2.2 %	3.5 %
Density	1.80 g/cc	2.49 g/cc

(The technical data were provided from the suppliers)

2.2 Static tension/torsion tests

Torsion tests were conducted on a combined axial and torsion hydraulic load frame (Model 8850-002, Instron, USA) with hydraulic grips. Specimen width, thickness and overall length were 15mm, 5 mm, and 200 mm, respectively. Plain-woven GFRP tabs (15mm width, 2mm thickness, 50 mm length) were bonded on both sides of the grip areas. Specimens were mounted in the hydraulic load frame with a 100 mm gage length between the upper and lower grips. The specimen was twisted up to peak twist angle under a constant twist rate of 0.5 deg/sec, and then unloaded. The peak twist angle was raised step by step, for example, 5°, 10 °, 15°, and so on. During a torsion test, the axial load was held under a load control mode. The axial tensile load was 0kN, 10kN, 20kN and 30kN, which correspond to 0, 133, 267, 400 MPa, respectively. The shear strain γ_{12} at the center of a specimen was measured using two strain gages bonded at the center of a specimen at ±45° to the longitudinal axis on both sides of the specimen. All of tests were conducted at room temperature.

2.3 Tension/torsion fatigue tests

Tension/torsion fatigue tests were carried out on the same combined axial and torsion hydraulic load frame. Specimen width, thickness, and overall length were 15 mm, 5 mm, and 150 mm, respectively. Plain woven GFRP tabs (15mm width, 2mm thickness, 50 mm length) were bonded on both sides of the grip areas. Specimens were mounted in the hydraulic load frame with a 50 mm gage length between the upper and lower grips.

The test matrix of tension/torsion fatigue tests is summarized in Table 2. The fatigue tests were carried out by torsion angle control mode ($\pm\theta$) of sinusoidal wave under a constant tensile axial load of 0, 10 and 20 kN.

Table 2 Test matrix of torsion / tension fatigue tests

Tensile axial load (kN)	Torsion angle * (deg/mm)	Frequency (Hz)
0, 10, 20 (constant)	±0.08, ±0.10 ±0.12, ±0.14 (amplitude)	3 Hz

*Torsion angle is defined as a ratio of amplitude angle (deg) to gauge length (=50 mm).

3 Experimental results

3.1 Elastic moduli of CFRP and GFRP

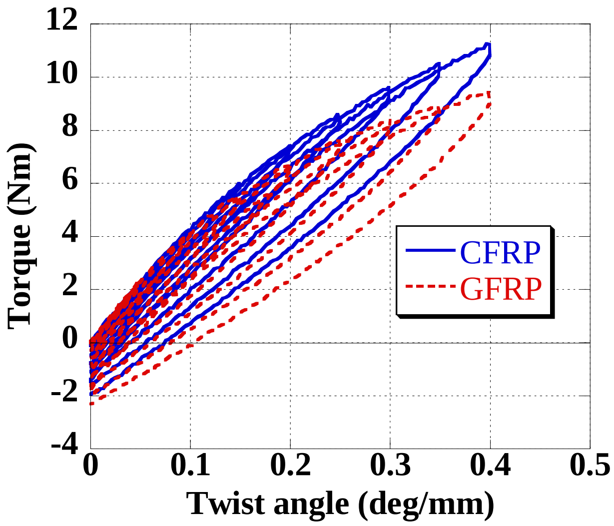
Elastic moduli obtained from 0° and 90° on-axis tests, and 45° off-axis tensile tests are shown in Table 3 under the assumption of transversely isotropic in the 2-3 plane.

Table 3 Elastic moduli of CFRP and GFRP

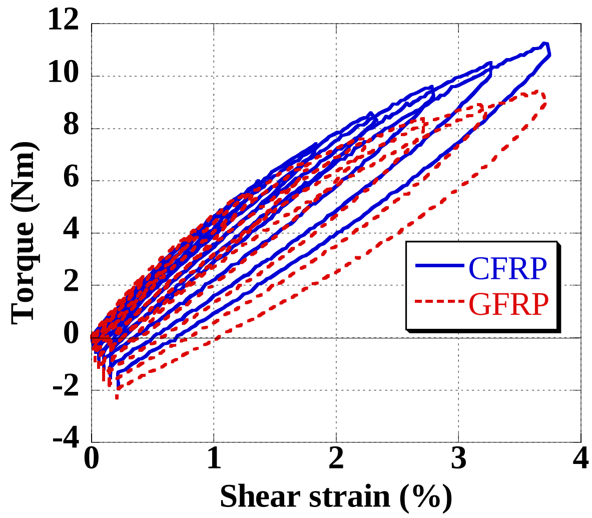
	E_{11} GPa	E_{22} GPa	ν_{12}	ν_{23}	G_{12} GPa
CFRP	148	8.37	0.33	0.54	4.4
GFRP	52.2	14.05	0.28	0.44	4.9

3.2 Static torsion behavior under a constant tensile stress

The torque versus twist angle, and the torque versus shear strain under zero axial load are shown in Figure 1(a) and (b). Note that the twist angle (deg/mm) was defined as the angle (deg) per gauge length (mm), and shear strain was measured by strain gages bonded on a specimen. The torque / twist angle, and torque / shear strain curves are linear in initial stage, whereas the torsion response is nonlinear for both CFRP and GFRP above 0.05 deg/mm twist angle, or 0.5 % shear strain. Hysteresis loops are obviously observed under the loading/unloading torsion tests. The residual strains at zero torque of CFRP and GFRP are plotted in Figure 2 (a) and (b) as a function of the peak torque. The residual strains significantly increase above 2

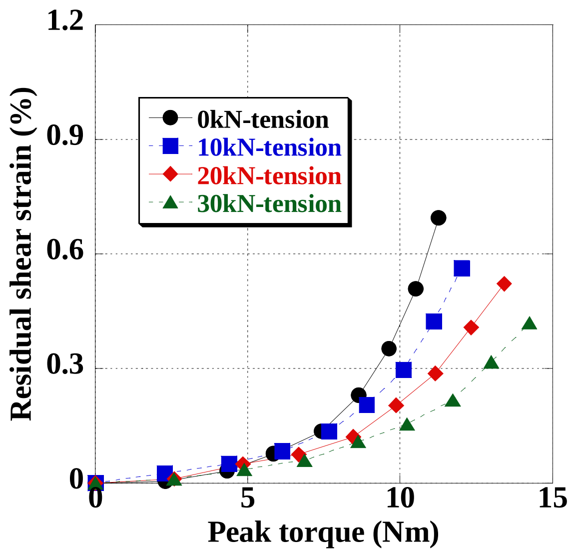


(a) Torque versus twist angle per gage length under zero axial load

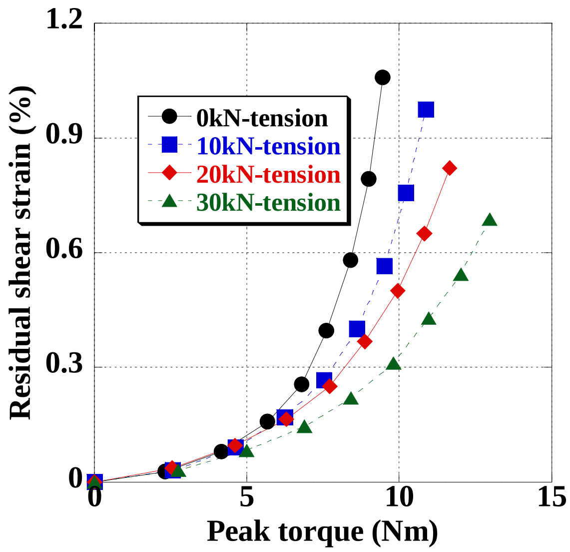


(b) Torque versus shear strain at the center of a specimen under zero axial

Fig.1 Linear and nonlinear response of CFRP and GFRP under zero axial tensile load



(a)CFRP

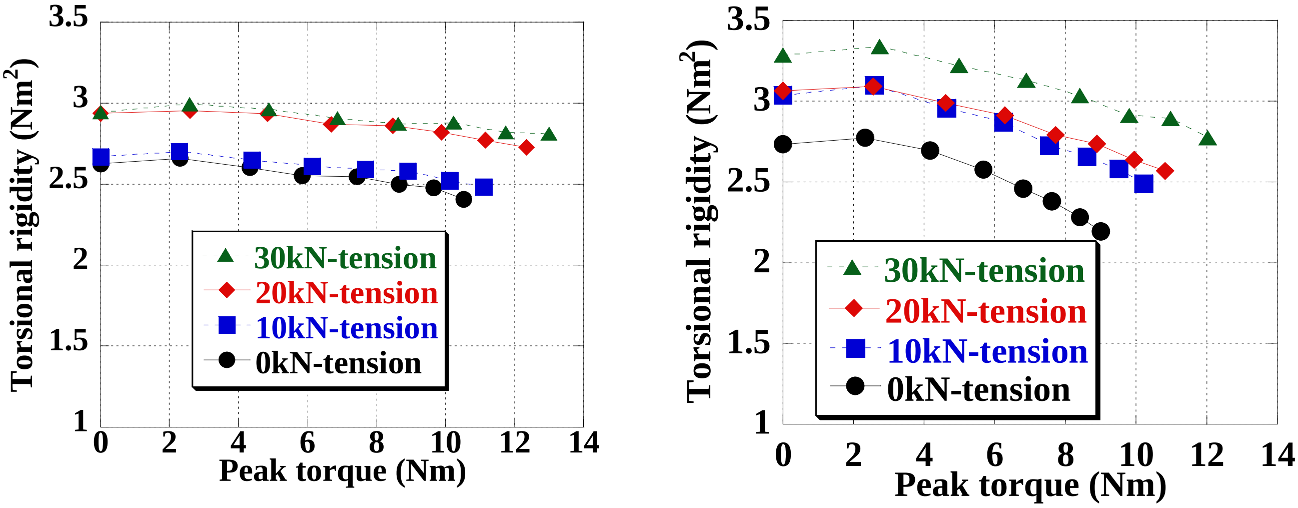


(b)GFRP

Fig. 2 Residual shear strain vs peak torque under axial tensile load of 10, 20, and 30 kN

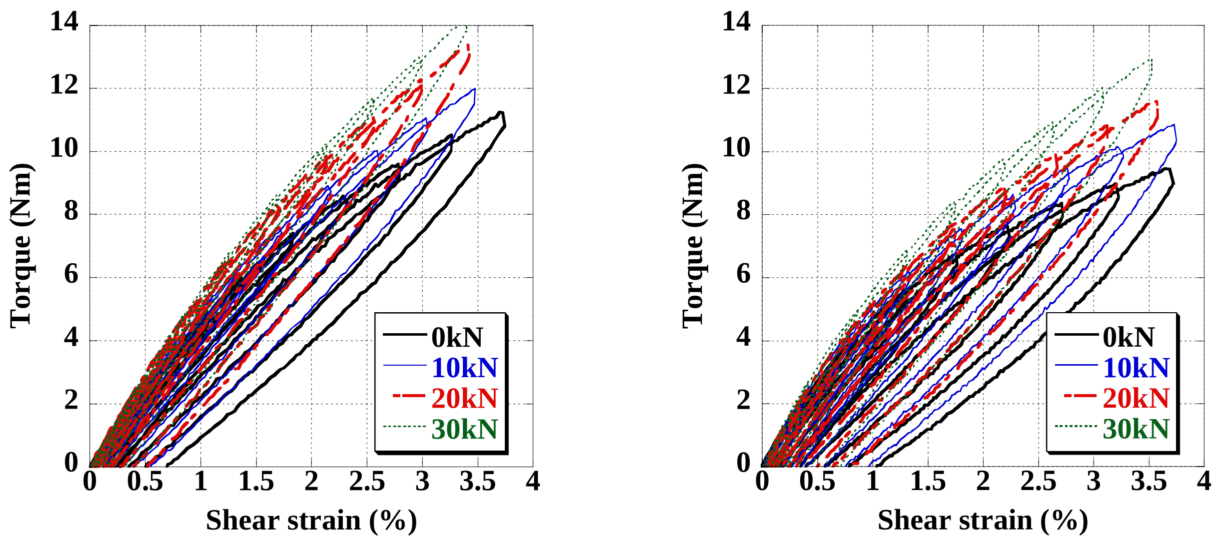
Nm for GFRP, whereas 4 Nm for CFRP. The residual strain of GFRP is larger than that of CFRP at the same torque.

Figure 3 (a) and (b) show the torsional rigidities under tensile load as a function of the peak torque. Torsional rigidities decrease with the torque, and this suggests degradation of the shear modulus caused by microscopic damages such as matrix cracking (split crack), fiber/matrix debonding, and fiber breaking. The onset of decrease in torsional rigidity corresponds to the onset of increase in residual shear strain. The degradation of torsional rigidities of GFRP is more significant than that of CFRP. The experimental results of the torsional tests



(a)CFRP (b)GFRP

Fig.3 Torsional rigidity vs peak torque after loading/unloading torsion tests under axial tensile load (0, 10, 20, 30 kN).



(a)CFRP (b)GFRP

Fig.4 Torque versus shear strain under axial tensile load (0, 10, 20, 30 kN). Shear strain was measured using strain gages bonded at the center of a specimen suggest that the non-linear behavior is caused by microscopic damages in addition to visco-elastic and visco-plastic deformation of matrix polymer. The torque versus shear strain under tensile axial load (0, 10, 20, 30 kN) are shown in Figure 5 (a) and (b). Torsional stiffness increases with tensile axial stress.

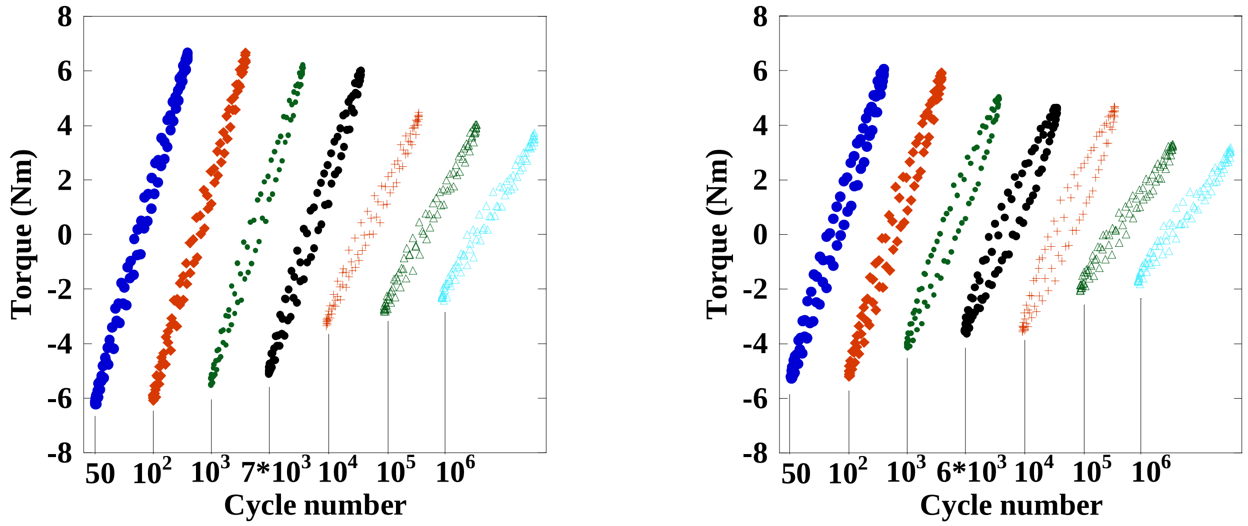
Torsional rigidity of CFRP and GFRP was calculated using a commercial FEA code ABAQUS 6.4 (ABAQUS Inc., USA). The eight node isoparametric solid element was used for the analysis. Number of elements was 7500. An edge of the torsion beam was strictly constrained. At another edge, a torsional moment M_t and axial tensile load was applied through a virtual rigid body.

The torsional rigidities calculated by FEA are summarized in Table 4 with the experimental results. The torsional rigidities were calculated using the experimental data in linear regime (< 0.1 % of shear strain). The numerical results are predictable enough with an error within about 5% for an experiment result. Sen reported the model that influence of an axial tensile load under torsion behavior [6]. When an external axial tensile load is superposed on torsion, a significantly higher torque is required to deform the laminate to a given twist angle than under torsion alone. An axial load acting on the twisted cross section of a laminate induces shear forces which resolve into a torque acting opposite to that producing the twist. Since the tension load tends to reduce the twist, additional torque is required to return the laminate to the desired twist angle. This additional torque makes the laminate appear more torsionally rigid. This suggests that GFRP can be replaced into CFRP as the torsional element of a helicopter flex beam without increase in torsional rigidity.

Table 4. Experimental and Numerical results of torsional rigidities of CFRP and GFRP

	Torsional rigidity (Experiment / FEA) (Nm)			
Axial tensile load	0kN	10kN	20kN	30kN
CFRP	2.59 / 2.59	2.67 / 2.76	2.93 / 2.93	2.94 / 3.10
GFRP	2.71 / 2.59	3.04 / 2.73	3.06 / 2.91	3.29 / 3.08

According to the Lekhnitskii's theory [11], the torsional rigidity of transversely isotropic composites is determined by G_{xy} and G_{zx}. The shear modulus G_{zx} of CFRP is similar to that of GFRP as shown in Table 3, therefore the torsional rigidities of CFRP and GFRP are almost same.

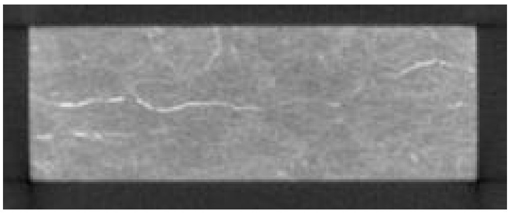


(a)CFRP (b)GFRP

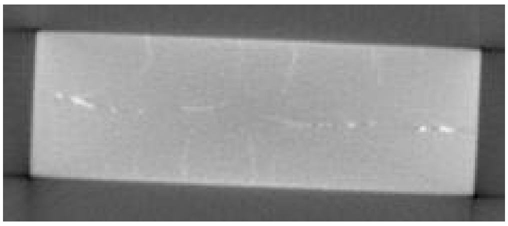
Fig.5 Torsional rigidity reduction under cyclic torsion
(± 0.16deg/mm 10kN, 3Hz, axial load = 0 kN)

3.3 Torsional fatigue torsion behavior

No catastrophic failure occurred during the torsional fatigue tests of CFRP and GFRP up to 1 million cycles under a constant tensile load. On the other hand, torsional rigidity considerably decreased with number of cycles as shown in Figures 5 (a) and (b). After fatigue tests, all of the samples were inspected using an X-ray CT scanner, and matrix cracks (splitting cracks) were observed as shown in Figures 6 (a) and (b). A number of splitting cracks and crack depths were measured for all of the specimens in order to understand the effect of splitting crack on torsional rigidity degradation. Torsional rigidity of a torsion beam with a splitting crack was calculated using FEA. The boundary condition was the same as the above mentioned calculations. The effect of splitting crack depth was examined, and the experimental and numerical results are summarized in Figures 7. The trend of torsional rigidity reduction with splitting crack depth agrees with that of the experimental results. It is concluded that the degradation of a torsion beam is mainly caused by splitting crack propagation.



(a) CFRP



(b) GFRP

Fig. 6 Typical X-ray CT radiographies after torsion fatigue tests of unidirectional CFRP and GFRP

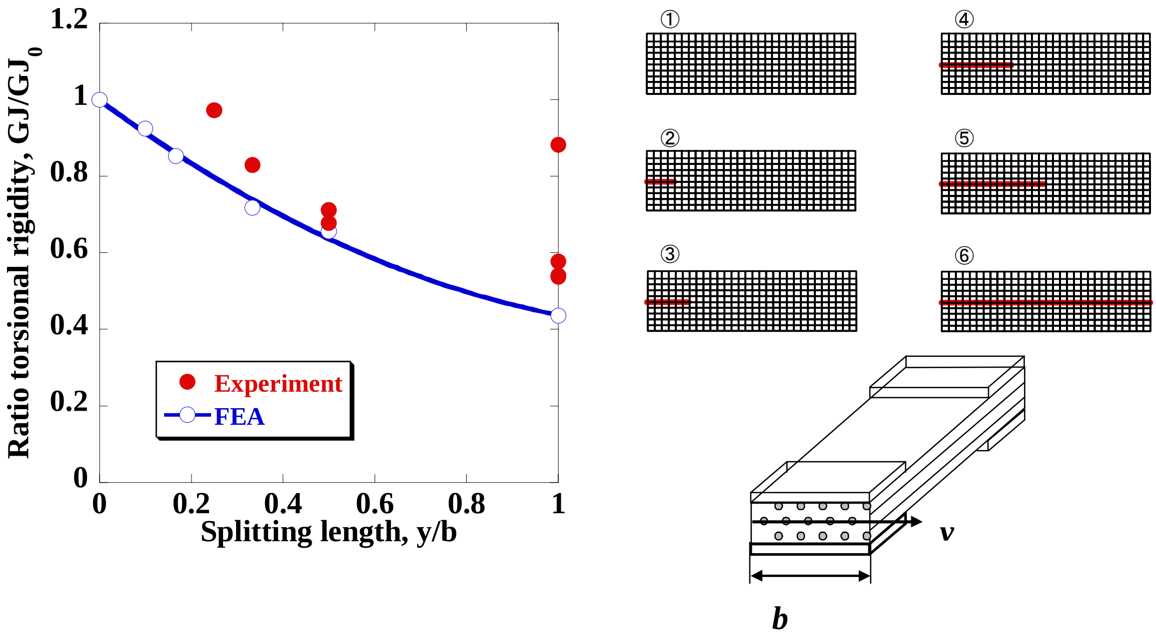


Fig. 7 Experimental and numerical results of torsional rigidities as a function of splitting crack depths

The fatigue lifetime should be defined as the degradation of torsional rigidity because no catastrophic failure occurred. In this study, the fatigue lifetime under cyclic torsion loading was defined as 10 % reduction of torsional rigidity as compared with the initial value. Figure 8 shows fatigue life versus amplitude angle under constant tensile load. The fatigue limit of CFRP under the test condition is approximately ±0.08 deg/mm, and that of GFRP is ±0.04 deg/mm. The range of torsional twist angles of an actual helicopter rotor head system is smaller than ±0.03 deg/mm. The experimental result suggests that the durability of CFRP under cyclic torsion is more excellent than that of GFRP.

Surface temperatures were measured during the fatigue tests using a non-contact type IR thermometer. A significant increase in temperature was observed in GFRP. Surface temperature rise during fatigue tests as a function of alternating twist angle is shown in Figure 9. The surface temperature reached above 40°C for GFRP. This is self-heating caused by visco-elastic behavior of matrix resin and/or interface between fiber and matrix. Temperature rise affects the degradation of matrix resin, resulting in the splitting crack propagation. GFRP exhibits more considerable visco-elastic and hysteresis behaviors compared with CFRP as shown in Fig. 3. In addition, higher thermal conductivity of CFRP is also preferable for preventing the temperature increase during fatigue testing as compared with GFRP.

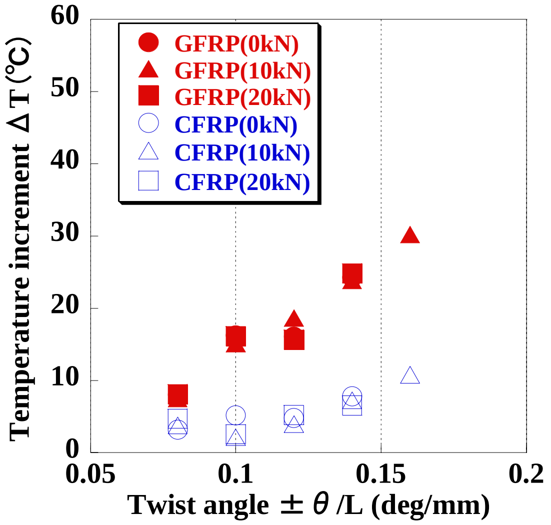
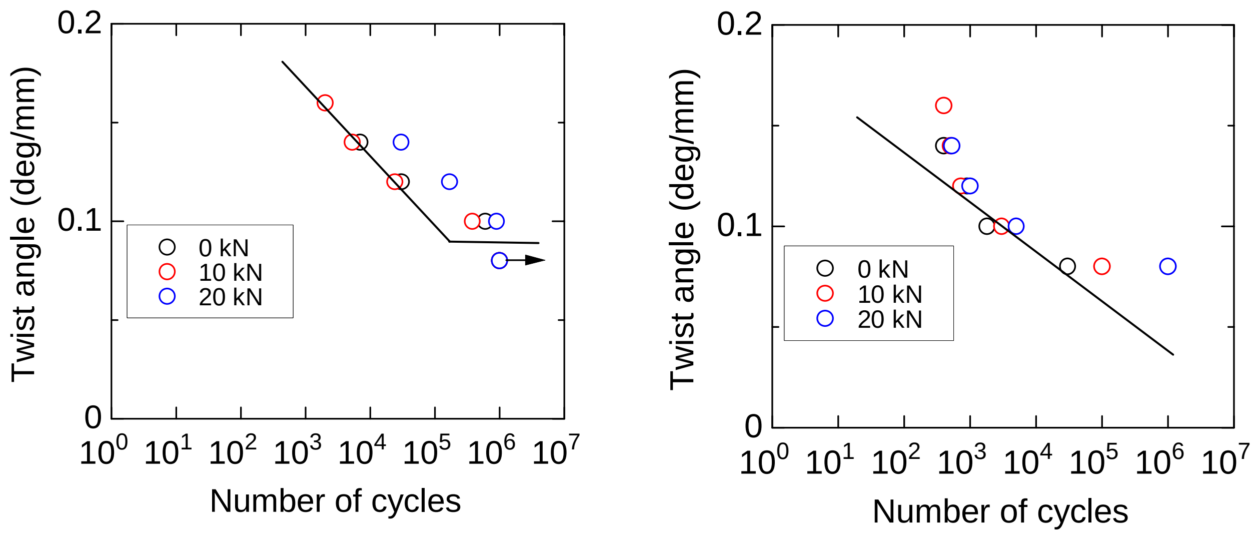


Fig. 9 Experimental and numerical results of torsional rigidities as a function of splitting crack depths



(a)CFRP (b)GFRP

Fig.8 Fatigue lifetime versus twist angle of CFRP and GFRP

4 Conclusion

The torsion behaviors of unidirectional CFRP and GFRP with the same matrix resin were examined. The initial torsional rigidity of CFRP was almost the same as that of GFRP, because the shear stiffness of CFRP was almost the same as that of GFRP. The nonlinear torsional behavior was observed above 0.5 % of the shear strain, and it is due to visco-plastic and plastic deformation of the matrix resin.

Torsion / tension fatigue behaviors of unidirectional GFRP and CFRP laminates were also evaluated. Catastrophic failure was not observed for GFRP and CFRP, whereas the decrease in torsional stiffness was clearly observed. This is due to propagation of splitting cracks during the cyclic torsional loading. In order to compare the stiffness degradation of CFRP with that of GFRP, fatigue life was defined as the 10% of torsional rigidity degradation. The torsional fatigue lifetime of CFRP was much better than that of GFRP.

The experimental results suggest that CFRP is preferable for helicopter flex beam material because of its excellent fatigue resistance under torsion as well as tension loading conditions.

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