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Linear and nonlinear torsional behavior of unidirectional CFRP and GFRP

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Abstract

The helicopter bearingless rotor flexbeam is usually made of glass-fiber reinforced plastic composite (GFRP). Carbon-fiber composites (CFRP) are candidate for future flexbeam materials due to their superior tensile fatigue strength. 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. As a result, it was confirmed that the behavior of both CFRP and GFRP is comprised of linear/nonlinear domains. The initial torsional rigidity of CFRP was almost the same as that of GFRP. The torsional rigidities calculated from Lekhnitskii's equations agreed with the experimental results, and they are mainly determined by the shear stiffness of the materials. The nonlinear torsional behavior was observed above 0.5% of the shear strain, and it is due to plastic deformation of the matrix resin. A 3D plasticity model proposed by Sun et al. was applied to the plasticity parameters obtained from off-axis tensile tests. The numerical curves agree with the experimental data below 1.5% of the shear strain. The experimental result suggests that GFRP can be replaced by CFRP as torsional elements of a helicopter flex beam without an increase in torsional rigidity.

Keywords: A. Glass fiber; Carbon fiber; B. Non-linear behavior; Torsion; C. FEA

1. Introduction

A helicopter rotor hub is subject to complex loadings. The predominant loads are a combination of static tension load due to the centrifugal force, and an alternating torsional load (feathering motion) due to the alternating torque applied to the pitch case by the control rods with each revolution of the rotor. The second force is the bending moment (flapping motion) due to the aerodynamic instability around the rotor system, and the third is in-plane bending moment (lead-lag motion) due to drag forces on the rotor.

In order to accommodate all three motions, a conventional helicopter rotor system consists of three sets of bearings. On the other hand, a simple helicopter rotor concept for small helicopters, designed to reduce complexity and cost through the elimination of the hinges and bearings of a conventional articulated rotor system, has been developed utilizing the unique anisotropic modulus characteristics of fiber reinforced composites. Helicopter bearingless rotor flexbeams have been made of glass-fiber reinforced plastic composite (GFRP) [1–3] up to the present time. Therefore, the torsion/tension behavior of GFRP has been investigated in detail for the design of rotor hub systems [4–6].

In the near future, carbon fiber reinforced plastic composites (CFRP) may replace GFRP in bearingless rotor flexbeam, due to their superior tensile fatigue strength [7] 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

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been reported [8,9], and the behavior has not been understood sufficiently.

This study is on the feasibility of unidirectional CFRP as a future candidate material for a bearingless rotor flexbeam. For the first step of the research, torsion tests on unidirectional CFRP and GFRP with the same matrix resin were carried out under a zero axial load condition, and their elastic–plastic behavior under torsional loading were investigated in detail. A three-dimensional (3D) plasticity model was used to predict the nonlinear behavior of the CFRP and GFRP materials.

2. Experimental procedure

2.1. Materials

The 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 such as pressure vessels. 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. The matrix material of the CFRP and GFRP was a toughened epoxy resin (#3651, Toray, Japan). Unidirectional laminates were fabricated from unidirectional prepreg tapes. The number of plies was 5 for the tension and 16 for the torsion test specimens. The fiber volume fraction was 55% for the CFRP and 57% for the GFRP, respectively.

2.2. Torsion test

Torsion tests were carried out on a combined axial and torsion hydraulic testing machine (Model 8850-002, Instron, USA) with hydraulic grips. Specimens were cut from 320 mm by 320 mm panels. Their width, thickness, and overall length for torsion tests were 15 mm, 5 mm, and 200 mm, respectively. Plain woven GFRP tabs (15 mm width, 2 mm thickness, 50 mm length) were bonded on both sides of the grip areas.

The specimens were mounted in the hydraulic testing rig with a 100 mm gage length between the upper and lower grips. The specimen was twisted up to a maximum twist angle at a constant rate of 0.5°/s, and then unloaded. The maximum angle was increased step by step, for example, 5°, 10°, 15°, and so on. The upper limit was 75°. During each torsion test, load control ensured that the axial load was zero. The axial load, axial displacement, torque and angle of twist were recorded. The shear strain at the center of a specimen was measured using biaxial strain gages bonded at ±45° to the longitudinal axis on both faces. All of the tests were carried out at room temperature. A CFRP specimen subjected to axial torsion is shown in Fig. 1. A couple of specimens were tested for each material.

Table 1
Mechanical properties of T1000G and T-glass fibers

	T1000G	T-glass
Supplier	Toray Industries Inc.	Nitto Boseki Co. Ltd.
Tensile strength (GPa)	6.4	3.14
Tensile modulus (GPa)	294	90.2
Failure strain (%)	2.2	3.5
Density (g/cm^3)	1.80	2.49

The technical data were obtained from the suppliers.

2.3. Off-axis tensile test

A number of nonlinear models have been proposed to describe the nonlinear stress–strain relationship [10,11]. In this study, a 3D plasticity model proposed by Sun et al., which is based on the Hill's plasticity theory, is applied to model nonlinear behavior of the unidirectional GFRP and CFRP materials [12–14]. The basic theory is described in detail later on.

The plasticity parameters in the model were determined from tension tests on off-axis specimens [15]. The off-axis angles were 0°, 30°, 45°, 60°, 90°, and the tests were carried out on a servo hydraulic testing machine (Model 8801, Instron, USA) at a constant displacement rate of 0.5 mm/min. Number of specimens was five for 0°, three for 90°, and one for 30°, 45°, 60°.

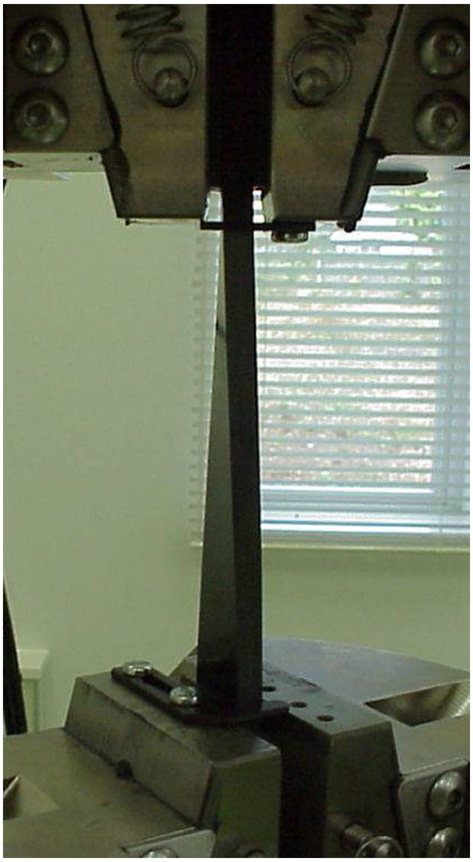

Fig. 1. Unidirectional CFRP specimen subjected to axial torsion.