Aerospace Science and Technology 45 (2015) 99–103

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Effect of fiber tension on the deformation of a carbon composite plate for space radio telescopes

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ARTICLE INFO

Article history:
Received 13 February 2015
Received in revised form 21 April 2015
Accepted 27 April 2015
Available online 29 April 2015

Keywords:
Deformation analysis
Fiber tension
Layered structures
Radio telescope
Thermal stress

ABSTRACT

This study examined the influence of fiber tension on the deformation of carbon composite plates used as the specular surface components of space radio telescopes. Applying the standard equations of composite theory, we developed an analytical model for the stress–strain state of carbon composite plates, considering the fiber tension and thermal stresses. The results of experiments performed on square plates fabricated from the carbon composites were in good agreement with the predictions from the proposed model. The fiber tension of the carbon composite was analyzed for different composite structures. Our results indicated that high fiber tension levels in the carbon composite reduced the degree of deformation in the composite structure.

1. Introduction

The most acute problem in aerospace engineering is the ability to obtain perfectly flat specular surfaces for communication purposes. Optimal precision requires that specular surfaces, such as those used in space radio telescopes (Fig. 1), be completely defect-free.

Telescope specular surfaces (e.g., the reflector and reflecting antenna) collect radio emissions from space objects. The antenna of a radio telescope determines its sensitivity (minimal detectable signal). The angular resolution of the telescope refers to the ability of the device to separate the signals from radio sources located very close to one another [2]. The reflector consists of mirror panels attached to composite plates (commonly carbon composite plates) with different dimensions; consequently, a perfectly flat plate surface is required to minimize signal error. The reflecting antenna is also extremely sensitive to signal error; even a fraction of a millimeter misalignment will show distorted results. As such, deformation analysis is important in the process of manufacturing composite plates.

Many scientists and engineers study stress and deformation in composite structures, in an attempt to achieve more accurate measurement systems. Gigliotti et al. [3] introduced a method to characterize the internal stresses induced by hygrothermal loads on composite laminated plates. Jeon et al. [4] analyzed the time-dependent response of fiber-reinforced polymer (FRP) composites undergoing heat conduction and mechanical loading; the effects of thermal stresses were examined with respect to the overall thermomechanical deformation of the FRP composites. Abedian et al. [5] attempted to obtain a better understanding of the nature of stress concentrations and how these stresses contributed to cracking, which is often observed on the free surfaces of fiber-reinforced

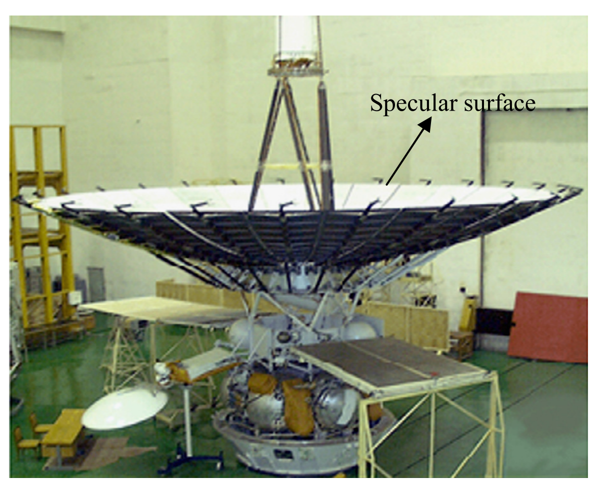

Fig. 1. Reflector of the space radio telescope in the open state [1].

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http://dx.doi.org/10.1016/j.ast.2015.04.019
1270-9638/

Nomenclature

A_{IJ}, B_{IJ}, D_{IJ}	stiffness matrices
K_{HB}	nondimensional coefficient of the fiber tension level
K_i^0	curvature of the panel
M_I^T	thermal moments
M_I^H	tension moments
$m^{(K)}$	trigonometric function of the rotation angle of the coordinate axes of the Kth layer relative to the Cartesian coordinate system (x, y) for the contiguous side
$n^{(K)}$	trigonometric function of the rotation angle of the coordinate axes of the Kth layer relative to the Cartesian coordinate system (x, y) for the opposed side
N_I^T	thermal forces
N_I^H	tension forces
$Q_{IJ}^{(K)}$	layer stiffness for unidirectional fiber-reinforced plastic in elastic symmetry axes
$\bar{Q}_{IJ}^{(K)}$	layer stiffness reduced to arbitrary x and y axes of the Cartesian coordinate system
$U_0\ (x, y, z)$	displacement of the reference plane, if $z = 0$
$V_0\ (x, y, z)$	displacement of the reference plane, if $z = 0$
W	hogging of the composite panel
$\alpha_1^{(K)}$	linear expansion coefficient in the reinforcement direction
$\alpha_2^{(K)}$	linear expansion coefficient perpendicular to the reinforcement direction
$\alpha_6^{(K)}$	tangent expansion coefficient
$\gamma_{x,y}^0$	deformation in the reference plane (tangent)
$\bar{\varepsilon}_B^{(K)}$	admissible deformation of the Kth composite layer
$\varepsilon_x^0, \varepsilon_y^0$	deformation in the reference plane
$\bar{\sigma}_x^{(K)}$	admissible compression stresses
$\bar{\sigma}_y^{(K)}$	admissible tension stresses
$\bar{\tau}_{xy}^{(K)}$	admissible stresses (tangent)

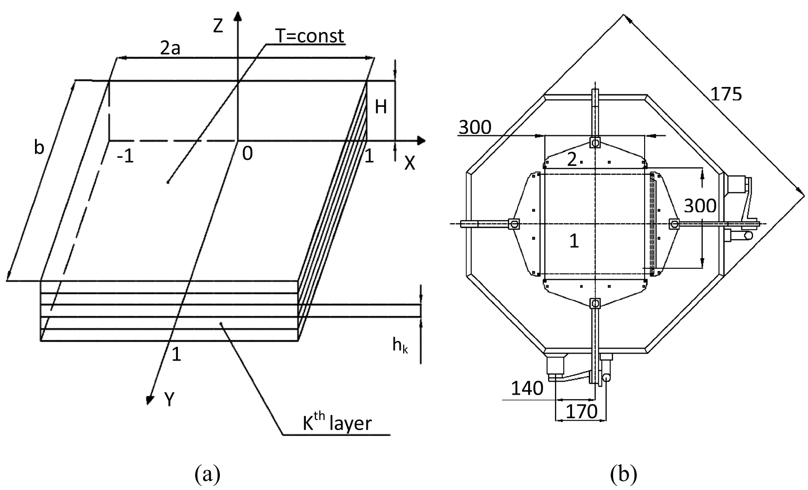

Fig. 2. (a) Composite plate. (b) Custom-designed device for adjusting the fiber tension: 1 – measured panel, 2 – fixing element (all sizes are in mm).

composites with changes in temperature. Greisel et al. [6] investigated the influence of residual thermal stress on the interfacial fracture toughness using push-out measurements; an adapted energy-based method was used to evaluate the interfacial fracture toughness. Reducing the amount of residual thermal stress alters the failure behavior, from brittle failure to quasi-ductile failure. Draiche et al. [7] and Nedri et al. [8] numerically analyzed the natural frequencies of laminated composite plates; shear deformation and stress were included in the analyses, without an emphasis on thermal stress.

Most of these works focused on the influence of shear stress and residual thermal stress on the stress–strain state of the composites. To date, few studies have investigated the combination of thermal stress and fiber tension on the hogging of composite structures. In this study, we evaluated the influence of the thermal stress on deformation/hogging of a carbon composite, focusing on the level of fiber tension in the carbon composite structure.

2. Mathematical method for analyzing the stress–strain state of composites

Fig. 2a shows a composite plate (dimensions 300 × 300 mm ($2a \times b$); plate thickness 1.04 mm (H), layer thickness 0.13 mm (h_k)), fabricated from unidirectional carbon tape (*LU-P*) and an epoxy binder (*ENFB*). The composite plate was manufactured using a curing temperature of ∼170 °C, followed by room-temperature (T) cooling to ∼23 °C. The carbon fibers were pre-tensioned using a custom-designed device (Fig. 2b) equipped with a load frame to fix the semi-finished product and a fixing element to set the carbon fiber tension to a predetermined value. The fiber tension was removed after curing.

The panel edges were free (not fixed) in the natural cooling state. The panel became deformed under thermal loading, and the deformation depended on the characteristics of the material.

Fiber tension is used to increase the load-carrying capability of structures via fiber alignment. The level of fiber tension is characterized by the fiber tension coefficient (K_{HB}), which varies between 0 and 1 in value (Eq. (1)):

$$K_{HB} = \varepsilon_H^k / \varepsilon_B^k \tag{1}$$

where ε_H^k represents the deformation of the Kth layer from tension, and ε_B^k represents the tolerable deformation of the Kth layer.

We modeled the deformation of a composite plate under thermal stress, given a certain level of fiber tension; the model was based on the theory of thin plates, displacement under Kirchhoff's hypothesis, Cauchy's equation, Hooke's law, and the stress transformation equations. In this study, the ratio of the plate thickness