Composites Part B 82 (2015) 42–49

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Numerical method for optimizing design variables of carbon-fiber-reinforced epoxy composite coil springs

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ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form
30 April 2015
Accepted 6 August 2015
Available online 14 August 2015

Keywords:
A. Polymer-matrix composites (PMCs)
B. Elasticity
C. Finite element analysis (FEA)
D. Mechanical testing

ABSTRACT

To successfully reduce a vehicle's weight by replacing steel with composite materials, it is essential to optimize the material parameters and design variables of the structure. In this study, we investigated numerical and experimental methods for determining the ply angles and wire diameters of carbon fiber/epoxy composite coil springs to attain a spring rate equal to that of an equivalent steel component. First, the shear modulus ratio for two materials was calculated as a function of the ply angles and compared with the experimental results. Then, by using the equation of the spring rate with respect to the shear modulus and design variables, normalized spring rates were obtained for specific ply angles and wire diameters. Finally, a finite element model for an optimal composite coil spring was constructed and analyzed to obtain the static spring rate, which was then compared with the experimental results.

1. Introduction

Much progress has been achieved in the area of weight reduction across a wide range of industrial applications. Automotive companies in particular have focused on weight reduction through structural optimization, improving manufacturing systems, and the use of lightweight materials. Reducing the weights of automobiles is very important because it saves energy and improves vehicle performance. Furthermore, for electric and hybrid vehicles, it is essential to reduce the weight of components to improve efficiency.

For the application of lightweight materials instead of steel, it is important to consider environmental and mechanical properties such as recycling, specific strength, specific stiffness, and impact resistance. Many researchers have been working on the development of composite suspension components for vehicles [1,2]. In particular, composite leaf springs have been studied and used in some light vehicles. Mahmood et al. [3] designed and analyzed unidirectional E-glass fiber leaf springs that reduce the weight by 80%. Choi et al. [4] studied the validity of finite element modeling for leaf springs considering the interleaf contact and friction and compared the results with those obtained through experiments. Gebremeskel [5] introduced a prototype of a single composite leaf spring for a lightweight vehicle using the design rules of the composite material considering a static load only. For more than a decade, various optimization and CAE tools have been used to design leaf springs [6–11].

However, there has been limited research on helical composite coil springs. Chiu et al. [12] and Mallick [13] conducted experiments to determine the mechanical behaviors and performance of helical composite springs with structures of different materials. Yildirm and Sancaktar [14] studied the free vibration characteristics of symmetric cross-ply-laminated cylindrical helical springs, and Yildirm [15] performed a parametric study on the natural frequency of helical springs. Calim [16,17] studied the dynamic behavior of composite coil springs with various geometries using the traditional Timoshenko beam theory. Various optimization techniques such as the Tagichi method, genetic algorithms, response surface model, and neural networks are commonly applied to design industrial structures (e.g., Cai and Aref [18]), including composite springs. Zebdi et al. [19] reported the optimization of the design of composite helical springs with three braided reinforcements using a multi-objective evolutionary algorithm. Sardou et al. [20] presented the practical applicability of composite coil springs for reducing the weight of automotive models by considering their manufacturing, properties, and cost effectiveness. Taktak et al. [21] modeled the dynamic behavior of an isotropic helical spring using optimization algorithms for mechanical properties as well as geometric constraints.

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http://dx.doi.org/10.1016/j.compositesb.2015.08.005
1359-8368/

This study deals with the application of a composite of carbon fiber and epoxy resin to coil springs considering the static spring rate. Because of the nature of the composite materials, their mechanical properties can vary depending on the manufacturing method, fiber and void volume fraction, fiber orientation, and so forth. Therefore, designers should determine the spring geometry, ply angles, thickness of the laminated textiles, weaving structure, and composition ratio of the composite material to attain carbon-fiber composite materials with the desired mechanical properties [22–26]. This paper proposes effective deterministic processes for developing composite coil springs through the application of computational and experimental methods. The basic mechanical properties of carbon-fiber composite materials were tested using five types of coupon models. The optimal design parameters of the composite coil spring were determined based on a beam model. Finally, the feasibility of applying a carbon-fiber and epoxy resin composite coil spring was investigated through a finite element analysis (FEA) and practical experiments [27].

2. Material tests and calibration

The material properties of a laminate composite can be measured using specially designed coupon specimens. As described in Table 1, various standard tests were performed to obtain the basic mechanical properties of carbon-fiber composite materials using five types of specimens, as defined in the ASTM International standards. The tests consisted of the application of tensile and compressive loads both in line with and perpendicular to the orientation of the fibers, as well as in-plane shear deformation, because the material is assumed to be transversely isotropic.

Once the aforementioned material tests were performed, the lamina properties could be directly applied to an FEA of the composite structures or to reverse engineering for predicting the corresponding fiber and matrix properties. This reverse engineering for the fiber and matrix properties could be easily performed using GENOA [28], which is a well-known commercial software package for performing virtual testing and simulation [29]. The in-plane ply properties, fiber volume fraction, and fiber/matrix tensile modulus were provided to calibrate the fiber and matrix properties of a composite material. A reverse engineering implementation could be used to obtain a complete set of in-situ fiber and matrix properties that will produce the desired ply properties and enable the prediction of any unknown out-of-plane properties.

Equations (1)–(7) are essential formulations for the material design of laminated structures and represent the relationships between the laminate and fiber/matrix properties [28].

- Elastic modulus

$$E_{l11} = E_{f11}\overline{V}_f + E_m\overline{V}_m \quad (1)$$

$$E_{l22} = E_{l33} = \frac{E_m}{1 - \sqrt{\overline{V}_f}\left(1 - E_m/E_{f22}\right)} \quad (2)$$

- Shear modulus

$$G_{l12} = G_{l13} = \frac{G_m}{1 - \sqrt{\overline{V}_f}\left(1 - G_m/G_{f12}\right)} \quad (3)$$

$$G_{l23} = \frac{G_m}{1 - \sqrt{\overline{V}_f}\left(1 - G_m/G_{f23}\right)} \quad (4)$$

- Poisson's ratio

$$\nu_{l12} = \nu_{l13} = \nu_m + \overline{V}_f\left(\nu_{f12} - \nu_m\right) \quad (5)$$

$$\nu_{l23} = \overline{V}_f\nu_{f23} + \overline{V}_m\left(2\nu_m - \frac{E_{l22}}{E_{l11}}\nu_{l12}\right) \quad (6)$$

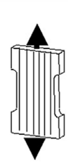
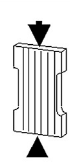
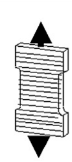
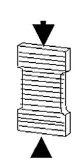
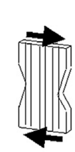
- Modified fiber and matrix volume fractions

$$\overline{V}_f = (1 - V_\nu)V_f, \quad \overline{V}_m = (1 - V_\nu)V_m \quad (7)$$

where subscripts l, f, and m represent the laminate, fiber, and matrix, respectively. Fig. 1 illustrates the material calibration process for a composite material based on the measured data to extract the fiber and matrix properties. First, the stiffness values of the fiber and matrix are estimated, and the fiber and matrix properties are inversely adjusted by comparing the measured data. There are some advantages to using the fiber and matrix constituent properties instead of the ply properties. One advantage is that it enables the evaluation of the variability and environmental effects of the manufacturing processes on the material and structural behavior, while also enabling the detection of damage at the microscale.

Table 2 lists the calibrated fiber and matrix properties as determined from the tests, which were used to predict the ply properties listed in Table 3. The fiber material exhibited orthogonal properties, whereas the matrix behaved isotropically.

Table 1
Standard types of coupon tests for composite material.

Longitudinal Tension	Longitudinal Compression	Transverse Tension	Transverse Compression	In-plane Shear
				
ASTM D3039	ASTM D3410	ASTM D3039	ASTM D3410	ASTM D3518