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An experimental investigation into mechanical behavior of hybrid and nonhybrid composite semi-elliptical springs

E. Mahdi *, A.M.S. Hamouda

[a] *Mechanical and Industrial Engineering Department, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar*
[b] *Qatar Road Safety Studies Center, Qatar University, P.O. Box 2713, Doha, Qatar*

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ABSTRACT

This study introduces a new composite semi-elliptical suspension spring by utilizing fiber reinforced composite strength in principal direction instead of shear direction. Three types of composites were tested, namely, carbon/epoxy, glass/epoxy and glass/carbon/epoxy. A comprehensive experimental investigation of composite semi-elliptical suspension springs has been carried out. Typical behaviors of their compression, tension, torsion and cyclic tests are presented and discussed. The results showed that the fiber type and ellipticity ratio significantly influenced the spring stiffness. After 1.15 million fatigue cycles, composite semi-elliptical suspension spring's useful stroke is reduced by only 2%. The relaxation of the composite elliptic spring found to be very sensitive to the compression rate.

1. Introduction

Applications of fiber-reinforced composites in automotive industry can be classified into three groups: body components, chassis components, and engine components [1–10]. Among the chassis components, the first major structural application of fiber-reinforced composites is the rear leaf spring; introduced first in 1981, in which Daugherty developed composite leaf springs for heavy trucks [1]. Therén and Lundin [3] summarized the advantages of leaf springs made of glass fiber reinforced composites. A mono-leaf E-glass-reinforced epoxy has been used to replace a steel leaf spring with nearly an 80% weight savings. Tanabe et al. introduced leaf springs made of hybrid fibers of carbon and glass reinforced plastics [3]. However, for spring such as in cars or trucks, the service life would probably be based on a certain minimum level of stiffness. A composite suspension of curved beam type was developed first by Bertin and others in 1981 for family cars [4]. Another composite suspension of circular and elliptic rings have been invented and examined experimentally and theoretically by Charrier et al. [5,6]. They calculated numerically spring constants of elliptic rings subjected to the compressive load along a principal radius of the spring by using the finite element method and showed good agreement between the predicted and the experimental results. Tse and his group introduced closed-form solutions from complementary strain energy are derived for the spring stiffness's of mid-surface symmetric, filament-wound, composite circular rings under unidirectional loading [11]. It is proven that composite spring life significantly exceeds metal spring life. This shows a quantifiable economic advantage for composite springs. Another important advantage of composite springs over metal springs is that if composite springs are used beyond their service life based on required minimum stiffness, they will not fail by breaking, whereas metal springs will break without warning. Composite springs will give clear warning by deforming excessively far before they fail by breaking. Thus, composite springs have a built-in stiffness reserve along with an automatic warning of impending difficulty [8]. The elliptical composite springs described by Mallick [7] represents the first step in introducing fiber reinforced composite elliptic springs for automotive applications. He reported the mechanical performance and failure modes of composite elliptic spring elements under static load conditions. Key design parameters, such as spring rate and failure load were also measured as a function of spring thickness. An analytical study using the energy method to evaluate the spring constants of elliptic composite rings was undertaken by Akasaka et al. [10]. Spring constants in the directions of the principal axes and for bending-shear and bending – torsion were measured for elliptic rings made of carbon fiber-reinforced thermoplastics. Good agreement was obtained between the experimental and the predicted results. They also found that the value of elliptical spring constants are higher than spring constants for leaf and coil springs made of steel. These

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* Corresponding author. Tel.: +974 4034309; fax: +974 4852110.
E-mail address: elsadigms@qu.edu.qa (E. Mahdi).

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findings are important factors behind the current study. Therefore, the main objective of this study is to extensively investigate the performance of composite semi-elliptical spring.

2. Development of composite semi-elliptical spring

2.1. Design requirements

The proposed composite semi-elliptical spring is anticipated to provide the necessary deflection to improve the dampening ability together with a sufficient rigidity. Accordingly, the design requirements are specified to be related to the metallic leaf spring design objectives:

- Design load, $W = 2500$ N.
- Distance between eyes in straight condition, $H = 160$ mm.
- Maximum allowable vertical deflection, $\delta_{max} = 150$ mm.
- Spring rates range, $K = 60–80$ kN/m.

2.2. Design concept

For composites to play a successful role in designing vehicle suspension applications, it is essential to control their failure by utilizing their strength in principal direction instead of shear direction. This can be achieved efficiently by employing a new configuration instead of existing one such as leaf spring or coil springs. It is proven that designing a composite spring in an elliptic configuration will eliminate the delamination and override the weakness of matrix properties [11–15]. In the case of new configuration system, the layers definitely experience compression/tension state and the failure will be dominated by the compression and tensile properties of fibers, while for the leaf spring, the layers experience a delamination and the failure will be dominated by matrix quality [16–19]. These can draw a very important conclusion regarding the cost of elliptical spring, because the matrix will only play the role of binding. Therefore, the springs is designed with a lamina containing a high volume fraction of fibers, in which there will be interactions of stress fields from neighboring fibers. The essential steps in designing a composite laminate are selection of constituents, fiber volume fraction, optimum fiber orientation in each ply, the lamina stacking sequence and the number of plies needed in each orientation, which also determines the final thickness of the part. The maximum principal stress increases with increasing fiber volume fraction. The transverse modulus of the composite has a similar trend. Accordingly, this study marries between an elliptical configuration and the woven roving composites. It can be seen from Fig. 1 that since the load is applied between A and B, the external side of the spring experiences pure tension state while the internal surface experiences pure compression state. Analyzing the forces as shown in Fig. 1d, one can observe that F_c and F_D resolved into $\boldsymbol{f_{1cy}}$ and $\boldsymbol{f_{2dy}}$ which vanishes each other, and $\boldsymbol{f_{1cx}}$ and $\boldsymbol{f_{2dx}}$ which sum up each other and serves as compaction forces. This will eliminate any hypothesis of delamination [8]. Woven–fabric composites composed of three structural elements, namely, longitudinal strand (warp), transverse strand (fill) and pure matrix regions. The structural elements' warp and fill can be considered as equivalent unidirectional composites. Therefore,

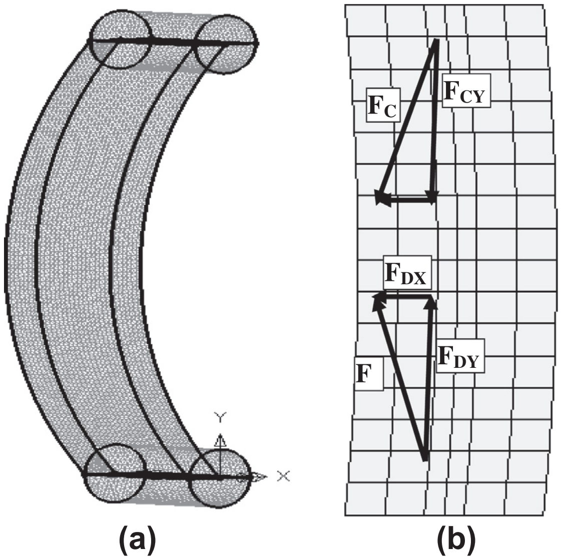

Fig. 1. Composite semi-elliptical spring. The new configuration of composite semi-elliptical spring. Free body diagram showing the force analysis of the laminated composite semi-elliptical spring.

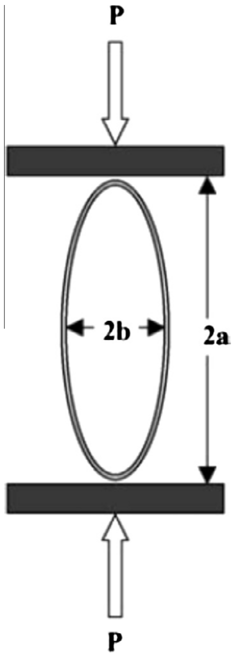

Fig. 2a. Compression test setup.

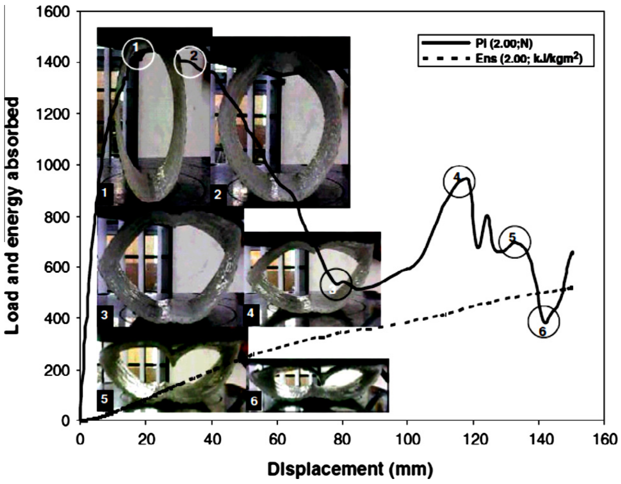

Fig. 2b. Typical load and absorbed energy vs. displacement curves and deformation history for a tube with $a/b = 2$.