STRUCTURE-PROPERTY RELATIONSHIPS OF COMPOSITE COIL SPRINGS PROCESSED BY RTM

Byung-Sun. Kim [*], Joon-Hyung Byun [*], and Byung-Ha Kim [*]

[*] *Composite Materials Group, Korea Institute of Machinery & Materials(KIMM), P. O. Box 66, Changwon, Korea, 641-010*

SUMMARY: Textile technology and resin transfer molding (RTM) process have been combined to manufacture composites coil springs. Preforms for coil springs were made by braiding process, in which axial yarns are located in the central region and braiding yarns covered them circumferentially. The geometric and process parameters that are related with the fiber orientation and fiber volume fraction of the braided composites have been identified. The carbon fibers and aramid fibers were utilized for fabricating the spring preforms with the wire diameter <5mm. For the RTM process, braided preform was wrapped into the five-piece mold cavity designed. The resin was injected into the mold at 120^{o}C for cure. In order to assess the mechanical performance of the composites spring, an analytic method for predicting the spring constant has been developed. The model prediction compared favorably with experimental results.

KEYWORDS: Composite Coil Spring, Braided Preform, RTM, Spring Constant.

INTRODUCTION

Composites coil springs have many advantages over the conventional ones: they are light and have better performance in fatigue and dynamic response. In addition to the structural benefits, composite springs can be designed to render the optimal mechanical properties by tailoring the orientations and content of reinforcing fibers. They have been typically manufactured by the filament winding (F/W) process. Although this process can be cost-effective, the reinforcing fibers maybe limited in the longitudinal direction for a small composite springs, which results in low strength and stiffness in the transverse direction. Also, due to the limitation of reinforcing direction, optimized structure is hardly achieved in the F/W process.

In this study, the textile technology was used to produce preforms and resin transfer molding (RTM) process was used to manufacture composites coil springs. Preforms for coil springs were made by braiding process, in which axial yarns are located in the central region and braidng yarns covered them circumferentially. The geometric and process parameters that are related with the fiber orientation and V_f of the braided composites have been identified. They include the number and the bundle size of respective axis and braiding yarns, and the take-up length of the preform. The carbon fibers and aramid fibers were used, respectively, to braid the preforms with the wire diameter <5mm. For the RTM process, the five-piece mold was designed, and braided preform was wrapped in the mold cavity. The resin was injected into the closed mold, and cured in the oven at 120°C.

In order to assess the mechanical performance of the composites spring, an analytic method to predict the spring constant has been developed. The analysis includes the geometric model of a unit cell, the coordinate transformation of the crimp yarns, and volumetric averaging of stiffness and compliance constants of the constituent materials. The model prediction compared favorably with experimental results. This analytic model is very effective for designing the composites coil spring which requires specific performance.

Molds for Coil Spring

Five - piece mold is designed to fabricate the composite coil spring (Fig. 1) whose wire thickness is less than 5mm by RTM process. Five-piece mold(Fig. 2a, b) is composed of external & internal molds, resin injection port, air vent and eject pin. To allow easier resin injection and air flow, the resin injection port was located at upper end of the spring. Interior of the 5 piece mold was crome coated for better surface finish.

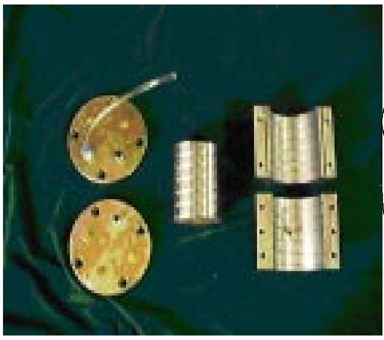

Fig. 1 Composite Coil Spring (Unit : mm)

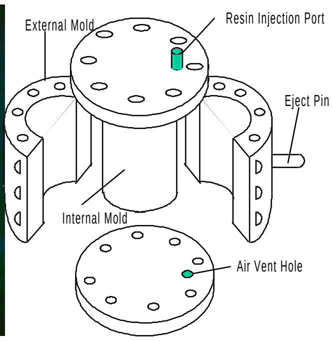

Fig. 2a. Schematic drawing of 5-piece mold

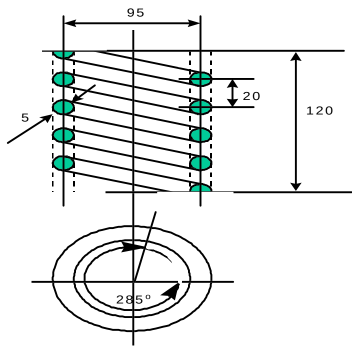

Fig. 2b. 5-piece mold for composite coil spring

PREFORM

Braiding machine (Fig. 3) was used to make the carbon and kevlar preforms(Fig. 4) for composite coil spring, respectively[1]. For carbon preforms, braiding and axial yarns used were Nippon Carbon/300f. For kevlar preforms, kev49 were used. The braiding conditions are summarized in Table 1.

Table 1. Braiding Conditions

	Specimen	**Length, L**	**Dia, D**	**Angle, •**	**Braid Yarn**	**Axial Yarn**
Carbon	**C-2000**	**74.01**	**4.40**	**10.58**	**16 ea**	**16 ea**
	C-1500	**51.76**	**4.45**	**15.10**		
	C-1000	**44.09**	**4.50**	**17.78**		
Kevlar	**C-700**	**24.22**	**5.35**	**34.76**		

PROCESSING

In the RTM process(Fig. 5), the epoxy system used were LY564 and HY2954(Ciba-Gygi). Resin injection pressure was 20 Psi and vacuum was applied when oven cured for 2hrs at 120^{o}C. The fabricated springs are shown in Fig. 6.

TESTING OF THE SPRINGS

In order to obtain the spring constants, the deflection tests were carried out as shown in Fig. 7.

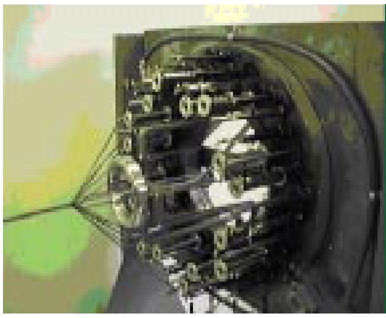

Fig. 3 Preforms being made by Braiding M/C

Fig. 4 Carbon and Kevlar preforms

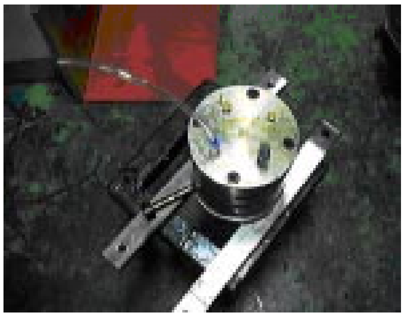

Fig. 5. Processing of Composite Coil Spring

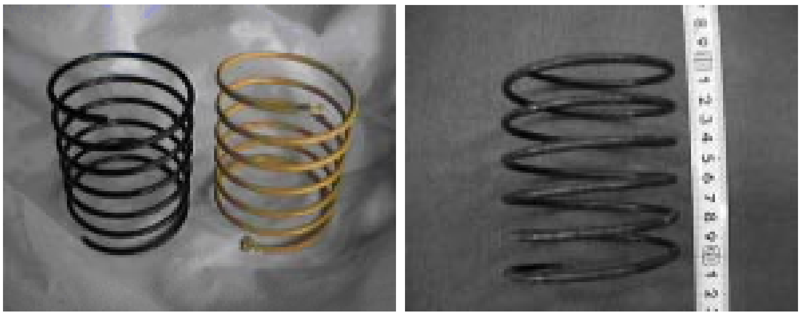

Fig. 6 Fabricated Composite Coil Springs(unit:mm)

Fig. 7. Deflection Test Set Up

GEOMETRIC MODEL

A 2-D braided fabric consists of two sets of yarns passing over and under each other. In addition to the braiding yarns, axial yarns are often inserted for dimensional stability and improved mechanical properties in the longitudinal direction. [2]

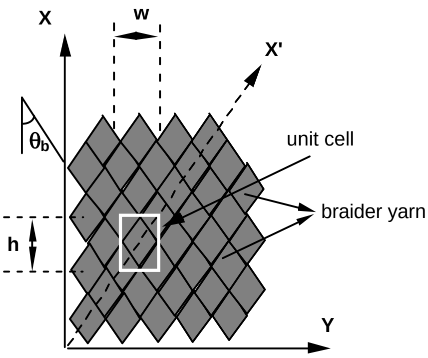

Fig. 8 Geometry of the braid.

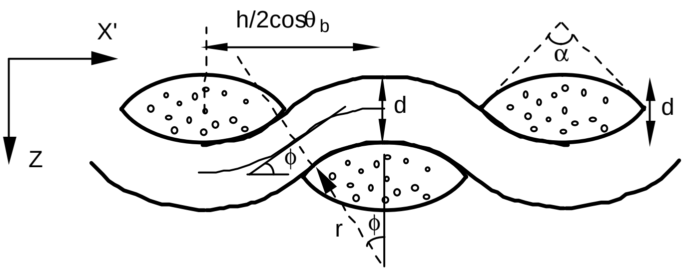

Fig. 9 Schematic of the yarn sections and the yarn crimp.

As shown in Fig. 8, the braid geometry is characterized by the braider yarn angle, •, and the pitch length, h. Braids have the smallest repeating structure termed as a *unit cell*. Fig. 9 shows the schematic of the yarn sections and the yarn crimp. To describe the wavy geometry of the crossing yarn, the axial yarn cross section is assumed to be *lenticular* shape. The parameters given in the braiding process or measured from the microstructure are utilized to determine the yarn crimp angle and the braider yarn length. Thus, volumes of axial yarns (V_a) and braider yarns (V_b) are determined from the yarn sectional area, the yarn length, and the number of axial and braider yarns within the unit cell.

ELASTIC MODEL

The mechanical properties of braided textile composites have been predicted based upon the fiber and matrix properties and the fiber architectures resulted from the geometric model. Since the principal material direction of spatially located yarns do not coincide with the coordinate direction of our interest, transformation of the stress-strain relations from one coordinate system to another is obtained.

$$\left[S^{I}\right] = \left[\mathbf{T}^{c}\right]^{t} \left[\mathbf{S}\right] \left[\mathbf{T}^{c}\right]$$

The effective compliance matrix of a crimp yarn can be obtained by averaging the transformed compliance matrix of the infinitesimal yarn segment through the crimp angle.

$$\mathbf{S}_{ij}^{C} = \frac{1}{\phi} \int_{0}^{\phi} \mathbf{S}_{ij}^{I} \, d\phi^{I}$$

In the unit cell, layers of the braider yarns in q orientations, axial yarns, and matrix materials are arranged in parallel in the longitudinal direction. When load is applied in the x-direction of the composites, each layer can be assumed to be in the state of constant strain. Thus, the stiffness of each layer is averaged based upon the volume to get the effective stiffness of the composites.

$$\mathbf{C}_{ij} = \mathbf{C}_{ij}^{a} \frac{\mathbf{V}_a}{\mathbf{V}_t} + \mathbf{C}_{ij}^{bp} \frac{\mathbf{V}_b}{2\mathbf{V}_t} + \mathbf{C}_{ij}^{bm} \frac{\mathbf{V}_b}{2\mathbf{V}_t} + \mathbf{C}^{m} \left(1 - \mathbf{V}_y\right)$$

where C^a, C^{bp}, and C^{bm} are the inverted stiffness of axial and braider yarns of q orientations, respectively. C^m is the [6x6] stiffness matrix of the matrix material. Then, the stiffness is inverted to the compliance, S_{ij}, which finally results in the following engineering constants of the braided textile composites: for example,

$$E_{xx} = 1/\mathbf{S}_{11}^{C}, \quad \mathbf{G}_{xy} = 1/\mathbf{S}_{66}^{C}$$

ANALYSIS OF SPRING DEFLECTION

For the compression spring of closely coiled type the spring constant can be expressed as the following equation. (G: shear modulus, d: wire diameter, R: spring radius, n: number of coiling, a: coil angle) In the case of orthotropic materials, the shear modulus has the following form [3]

$$\kappa = \frac{F}{\delta} = \frac{G d^4}{64 R^3 n \cos\alpha}, \qquad G = 2\frac{G_{12}\, G_{13}}{G_{12} + G_{13}}$$

CORRELATION

The geometric input data for the model predictions were obtained from the photomicrographs of the sample section. Fig. 10 shows the cross-section of the composites spring. It can be seen the braider yarns surround the axial yarns located in the central part of the composites. Table 1 summarizes the geometric input data and the comparison between the model predictions and the test results for 4 types of composites springs. Relatively good agreement between the model predictions and the test results can be observed. Although the experimental data was not enough to support the predictions due to the limited test results, the methodology proposed in this paper can be effectively utilized in designing the braided composites springs.

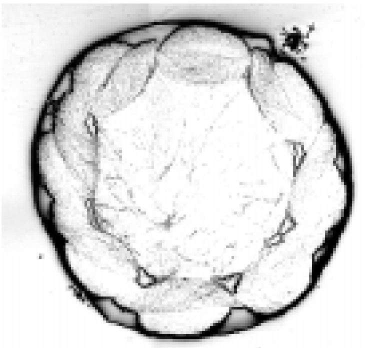

Fig. 10 Composites spring section.

Table 2. The geometric input data, the model predictions, and the test results

Code	Geometric Parameter				k (N/m)	
	d	f	k	V_f	Pred.	Exp.
C-1000	0.265	7.0	0.56	46.6	83.8	99.8
C-1500	0.25	5.0	0.58	45.1	72.6	75.9
C-2000	0.2	6.58	0.53	43.1	64.4	70.6
K-700	0.523	2.7	0.6	44.0	58.2	56.0

Note) V_f is the test results.

CONCLUSION

(1) The carbon and kevlar fibers were braided to a preform of circular cross-sections, respectively. The RTM process was applied on preforms to manufacture small composite coil springs.

(2) The geometric model and the elastic model of 2-D braided textile composites have been proposed to predict the spring constants of composites. From the geometric model the crimp yarn angle, the yarn length, and the fiber volume fraction were obtained. Using the geometric parameters, 3-D engineering constants have been determined from the elastic model, which utilizes the coordinate transformation and the averaging of stiffness and compliance constants based upon the volume of each reinforcement and matrix material.

(3) The predicted spring constants agreed quite well with the tested values.

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