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Measurement of residual stresses in thick composite cylinders by the radial-cut-cylinder-bending method

Jong Woon Kim, Dai Gil Lee *

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, ME3261 Guseong-dong, Yuseong-gu, Daejeon 305-701, South Korea

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Abstract

Thick fabric composite cylinders for nozzle parts in solid rocket motors should be designed to endure the extreme temperature and pressure of combustion gas. As the thickness of the composite cylinder increases, fabricational residual stresses due to the anisotropic thermal expansion or shrinkage of fabric composites also increase, which induces inter-laminar failures. Therefore, the accurate estimation of the residual stresses is indispensable for the development of thick fabric composite cylinders.

In this paper, the residual stresses in thick cylinders made of carbon fabric phenolic composites were measured by a new radial-cut-cylinder-bending method. To obtain the residual stresses from the measured relative strains during the radial-cut operation, a bending test of the cylinder with the radial-cut was performed instead of measuring the material properties with respect to radial positions. The thermal residual stresses were also calculated by finite element method considering shear deformation of fabric layers, and compared with the measured residual stresses by the new method, from which it was found that the new simple method estimated the residual stresses pretty well. Also the inter-laminar tensile strength at the position of maximum radial residual stress could be obtained from the bending test.

Keywords: Thick composite cylinder; Fabric composite; Thermal residual stress; Radial-cut method; Curved beam; Shear deformation of fabric; Inter-laminar tensile strength

1. Introduction

Composite nozzle parts in solid rocket motors should insulate the other parts and endure the internal pressure from the extremely high temperature and pressure of combustion gas passing through the nozzle. In order to satisfy the requirements simultaneously, the nozzle parts are usually made of carbon fabric phenolic composites in thick-walled cylindrical structures for ablation resistance, low thermal conduction, and high load capacity. When the thick carbon phenolic composite cylinders composed of many plies are cured and stored at the room temperature, thermal residual stresses are developed due to large difference of the in-plane CTE (coefficient of thermal expansion) and the out-of-plane CTE of the fabric composites. As the radial thickness of the composite cylinder increases, the radial residual stress also increases up to the inter-laminar tensile strength (ILTS) of the carbon phenolic composite, which eventually induces the delamination. Consequently, the radial thickness of the carbon phenolic composite cylinder is limited, while the thicker structure is desired to the solid rocket motors of better performance. Therefore, the estimation of residual stresses is important for the better design and manufacture of the nozzle parts.

The residual stresses in thick composite cylindrical structures are functions of many parameters such as

* Corresponding author. Tel.: +82 42 869 3221; fax: +82 42 869 5221.
E-mail address: dglee@kaist.ac.kr (D.G. Lee).

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thermoelastic material properties, winding tension, and temperature distribution during the cure process [1–5]. The thermoelastic properties of the fabric composites vary with the state of fiber array in the matrix, and the winding tension and the temperature distribution are closely related to the manufacturing process. Since the reliable estimation of residual stresses in the cylindrical thick composite requires much information on the material properties and processing variables, experimental methods have been devised to measure the residual stresses in the thick composite cylindrical structures by many researchers.

Usually the residual stresses are estimated using the deformation due to the relief of stresses when some part of the structure is machined out. The magnitude of deformation is transformed into the residual stresses in the original structure. There are two representative removal techniques such as the boring method and the radial-cut method which have been applied to the thick composite cylindrical structures. In the boring method, successive deformations due to the relief of radial residual stress on the bored surface are measured when the material is removed layer by layer from the bore of the cylindrical structure. Since Sachs [6] developed the boring method to measure the residual stresses in a cylinder made of isotropic material, the boring method for isotropic structures has been applied and modified [7–9]. Also Olson and Bert [10] derived equations to obtain the residual stresses from the measured strains during boring of cylindrically orthotropic tubes. In the radial-cut method, the amount of relative deformation is measured when the cylindrical structure is cut radially. Fourney [11], Dewey and Knight [12], and Aleong and Munro [13] transformed the measured relative strain either on the inner surface or on the outer surface during the radial-cut into the residual stresses and residual strains in filament-wound composite rings using elasticity equations.

When material properties in the thick fabric composite cylinder are homogeneous, both the boring method and the radial-cut method yielded almost same result [14], and thus the radial-cut method was preferred because it is quite simple and inexpensive while the boring method is not only complicated and time-consuming but also requires machining equipment and large volume of material removal. However, for the cylindrical composite structures, the migration of fibers is caused by the radial thickness reduction during consolidation so that the material properties may be changed during manufacturing process. Particularly, large through-thickness compaction due to sparse structure of fabric layers accompanies with large in-plane shear deformation of the fabric layers during the compaction process of the thick fabric composite structures. Then the relations between the deformation and the stresses require an enormous amount of data including the in-plane and out-of-plane elastic properties with respect to the migrated state of yarns. Even though the data may become available after many tests or complicated calculation [15–18], in-plane shear deformation and degree of through-thickness compaction should be measured at each layer and the transformation of the measured deformation into the residual stresses is still complex.

In this paper, a new radial-cut method was proposed to measure the residual stresses in thick fabric composite cylinders. Thick cylinder specimens with and without radial variation of material properties were fabricated with carbon fabric phenolic prepregs. The relative strains between before and after the radial-cut were measured both on the inner and outer surfaces, which were transformed into the distributions of hoop and radial residual stresses using the stress-moment relations and moment–strain relations obtained from the hoop bending tests of cylinders with the radial-cut rather than using the stress–strain relations which require a large amount of material properties of the fabric composites. Also the inter-laminar tensile strengths of the thick composite cylinders were obtained from the cut-cylinder-bending test. For verification of the measured residual stresses, the thermal residual stresses were calculated by finite element method using the measured in-plane shear deformation of each fabric layer. Finally it was found that the new simple method predicted well the residual stresses without requiring material properties.

2. Fabrication of cylinder specimens

Thick carbon fabric phenolic composite cylinder specimens similar to the nozzle parts of solid rocket motors were fabricated to measure residual stresses. The composite specimens were made of either a polyacrylonitrile (PAN)-based carbon fabric phenolic prepreg (CF3336, Hankuk Fiber Glass Co., Korea) or a rayon-based carbon fabric phenolic prepreg (RCP2003, Hankuk Fiber Glass Co., Korea). Specifications of the prepregs are shown in Table 1 and the elastic properties and CTE's of $[\pm 45]_{ns}$ laminates made of the prepregs are shown in Table 2. The insufficient compaction of fabric laminates results in large through-thicknesss CTE and high void content [19], which may induce not only high residual stresses, but also deteriorate inter-laminar strength and ablative property. Therefore, the through-thickness

Table 1
Specifications of the carbon fabric phenolic prepregs

	PAN-based carbon fabric phenolic prepreg	Rayon-based carbon fabric phenolic prepreg
Woven pattern	8-harness satin	Twill weave
Yarn width	2.2 mm	0.6 mm
Uncompacted ply thickness	0.62 mm	0.71 mm