Composite Structures 194 (2018) 119–125

Contents lists available at ScienceDirect

Composite Structures

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

Design of filament-wound composite structures with arch-shaped cross sections considering fiber tension simulation

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ARTICLE INFO

Keywords:
Composite materials
Filament winding
Arch-shaped cross section
Fiber tension
Pretension stress

ABSTRACT

The binding effect of fiber materials due to the winding tension during the filament winding process of arch-shaped cross sections was successfully evaluated using the Finite Element Method (FEM). The use of FEM was validated by comparing results obtained with the results from the numerical analysis of a classic cylindrical mandrel winding model. In this study, four methods were combined in the commercial finite element code ANSYS to predict the change trend of the residual stress of the layer and explore the relationship between the winding layer thickness and the winding relaxation effect. These methods include the element birth and death option, which was used to simulate the step-by-step winding process, the thermal parameter method, which produced the equivalent filament winding tension, contact analysis, which was used to carry out the transmission of radial pressure and deformation, and the restart method, which was used to simulate the procuring process. Compared with the mathematical algorithm and test of variable thickness, the results of FEM were in the range of allowable error. Therefore, these results provide a useful reference in designing the filament wound composite structures with considerably high fiber tensions.

1. Introduction

In the composite materials industry, filament winding technology has evolved to become an effective and automatic method to manufacture composite cylinders. In this process, composite layers are continuously wound around a rotating mandrel. The fibers are passed through a resin bath and wound onto the mandrel while the resin is cured at high temperatures then cooled to room temperature. Studies on filament wound composite materials have focused mostly on the stress or strain in their production under a variety of load conditions, with only few studies conducting simulation analyses for the winding process.

A number of investigations have previously focused on design and manufacture of filament-wound composite structures. Vasiliev et al. [1] derived the optimality conditions for a filament-wound pressure vessel by maximizing the stress invariant, and outlined the optimal dome profiles for various anisotropic characters. Liang et al. [2] presented the optimal dome contours based on the maximum shape factor and evaluated the effect of the dome depth on the filament-wound structural performance. Zu et al. [3–10] developed several design and optimization methods for filament-wound isotensoid pressure vessels with unequal polar openings, articulated pressure vessels comprising various dome cells, toroidal pressure vessels, elbows, square tubes and continuum-based non-geodesic domes. Teng et al. [11] studied the effect of the roving band width on the stability of the winding patterns and carried out the optimal design for an ellipsoid dome. Vafaeesefat et al. [12] presented a multi-level strategy for the optimization of composite pressure vessels with geodesic and ellipsoidal heads, by using a combined FEM/genetic algorithm. De Jong [13] compared the dome profiles that are respectively determined by the netting and continuum theory and indicated that the geometry and performance of the dome are dependent on the elastic properties of the materials used. Blachut [14] investigated the optimal meridian shape and thickness distributions in a filament wound dome closure, in order to increase shell buckling resistance under static external pressure. Mitkevich [15] determined the equilibrium dome shapes, the fiber tension and the interlaminar shear stress. Hojjati et al. [16] evaluated the effect of mechanical properties of composite materials on the dome profiles and proved that the matrix properties have a major role in the dome design. Fukunaga et al. [17] obtained optimal meridian shapes using several failure criteria and outlined an analytic approach for the design of dome structures.

Processing conditions, which include winding tension, lay-up pattern, temperature, winding, and holding time, can affect the quality of the filament wound composite structures [18]. These variables must be designed accurately to meet a variety of mechanical and physical

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https://doi.org/10.1016/j.compstruct.2018.04.018
Received 3 March 2018; Accepted 2 April 2018
Available online 03 April 2018

requirements of the filament wound cylinder. Studies have reported on the influence of primary processing parameters on secondary processing parameters [19]. Cohen [20] used the design of experiment method to identify the applied tow tension during winding (winding tension) as the most significant manufacturing parameter for the resulting mechanical part properties. Cohen et al. [18] demonstrated the relationship between the fiber volume fraction in hoop-dominated laminae and the failure strength of filament wound pressure vessels. The curing process is the other key problem that requires models of fiber consolidation and thermochemical behavior during the process [21,22]. Lee and Springer [23] developed a fiber motion model, namely sequential compaction, in which consolidation is assumed to begin with the outermost layer. Dave et al. [24] and Gutowski et al. [25] developed a squeezed-sponge model in which the compaction is not sequential and applied pressure is shared by both the fiber bed and resin. The study by Cai et al. [26] combined Darcy's flow and nonlinear spring compaction and then developed a fiber motion model.

However, the majority of previous research has merely considered the structure-dictated design based on continuum lamination theory, and overlooked the influence of winding tension and resulting pretension fiber stress on the structural performance of filament-wound composite structures. In addition, very few studies have been devoted to the design of filament-wound structures with arch-shaped cross sections.

In this paper, a new finite element model was developed to highlight the compaction effect during the winding process of composite structures with arch-shaped cross sections. Several finite element approaches were incorporated into the system to reduce the error in the simulation. This study attempted to determine a method of finite element analysis that effectively simulates the pretension stress of a composite structure during the winding process. Such a method would make it possible to predict the radial pressure and deformation in the surface of the mandrel and the fiber binding constraint under the internal pressure load. The proposed analytical solution provides an efficient tool able to design and optimize the filament-wound structures with arch-shaped cross sections.

2. Modeling approach

The Finite Element Method (FEM), which is used to simulate the filament winding structure, shell element and solid element, proved to be effective in calculating the laminated plates or pressure vessels under a variety of loading conditions. However, this modeling method had difficulty simulating the complex stresses during the filament winding process.

2.1. Thermal parameter method

Simulating the process of a filament winding structure with inner lining can be a very difficult process. Other studies typically convert the hoop stress in the fiber layer into an equivalent external pressure and load it on the mandrel, or use other simplified calculation methods. However, because such methods produce inevitable errors in structure stress analysis, we introduced the thermal parameter method to avoid these errors.

The thermal parameter method, combined with the real-fictitious finite element analysis strategy, was used to simulate the auto-balance stress fields induced by pre-stressed fiber winding. If material was added to (or removed from) a system, certain elements in the model may become "existent" or "nonexistent". The element birth and death options can be used to deactivate or reactivate selected elements in such cases. This feature can be useful for analyzing excavations (as in mining and tunneling), staged construction (as in shored bridge erection), sequential assembly (as in fabrication of layered computer chips), and many other applications in which one can easily identify activated or deactivated elements based on their known locations. The birth and death feature is only available in the ANSYS/Multiphysics, ANSYS/Mechanical, and ANSYS/Structural products.

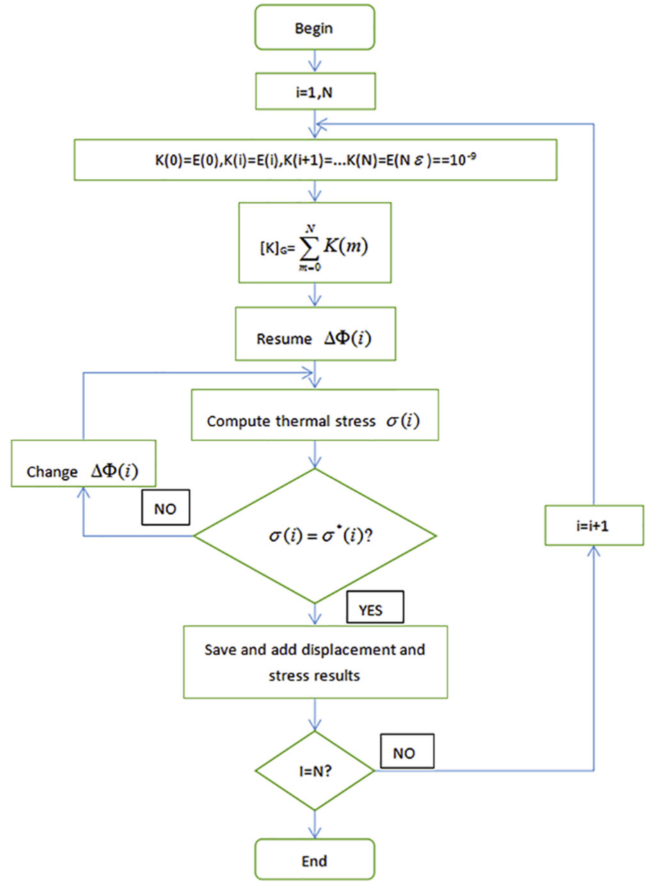

Fig. 1. The flow chart of the thermal parameter method.

A finite element analysis strategy for simulating the winding process of band wound vessels with metal lining was proposed according to the characteristics of the winding process and FEM. The finite elements were classified into two types: "real elements" and "fictitious elements". Real material constants were used for "real element", whereas for the fictitious elements, a fictitious stiffness that was small enough not to affect the computation results was used. When a new layer was wound, all the elements in the winding layer were "realized" by replacing the small fictitious stiffness with the real one. The temperature parameter of the elements was employed to limit the winding tension to respected values. The proposed method is simple, flexible, and suitable for vessels with complex shapes. Several typical cylinders were analyzed. The flow chart of the thermal parameter method is in Fig. 1.

2.2. Contact element

The radial pressure transmission from the outer layer to inner layer led to the reduction of hoop stress in the inner layer. Even the inner layer may be compressed and wrinkled when the filament winding layers were excessive. The finite element analysis software ANSYS used Section and Real Constants to calculate the stress in the filament winding composite structure, while the APDL command/ESHAPE showed the fictitious laminated structure. However, this element cannot simulate the effects of pressure transmission between the layers. In this study, the contact element had the following advantages:

(1) Contact elements do not interpenetrate each other;
(2) Normal stress and tangential friction force can be transmitted correctly;