Composite Structures 132 (2015) 226–238

Contents lists available at ScienceDirect

Composite Structures

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

Nonlinear buckling and folding analysis of a storable tubular ultrathin boom for nanosatellites

Daniele Barbera [a], Susanna Laurenzi [b,*]

[a] Department of Mechanical and Aerospace Engineering, University of Strathclyde, 75 Montrose Street, Glasgow G1 1XJ, UK
[b] Department of Astronautic Electrical and Energy Engineering, Sapienza University of Rome, Via Salaria 851-881, 00138 Rome, Italy

ARTICLE INFO

Article history:
Available online 14 May 2015

Keywords:
Deployable structures
Ultrathin composite
Buckling analysis
Finite element method

ABSTRACT

In this work we investigated the stability behavior and the folding capability of an ultrathin tubular composite boom with C-cross section to be used in nanosatellites applications. A nonlinear buckling analysis was performed using the Riks method, adopting a perturbed finite element model to study the influence of the unavoidable geometrical variations of the boom thickness, arising from the composite manufacturing processes, on the stability behavior of the tubular structure. The effect of several levels of geometrical imperfection on the buckling behavior was analyzed. The minimum coil radius that can be used for a safe storage the boom was determined by quasi-static explicit analysis. The boom folding process was considered as formed by two sequential steps, the flattening and the coiling. The stress fields associated with both steps were investigated.

1. Introduction

Storable tubular extensible members (STEMs) have been widely investigated for many years as technological solution for numerous space applications [1–5]. STEMs are considered for stabilization systems via gravity gradient in low orbit spacecrafts [6,7], self-deployable antennas [8], and deployable booms for solar sails [9,10]. Their peculiarity is the capability to change the configuration from a packed arrangement, which is suitable for the launch phase, to a large-scale deployable configuration once in orbit.

Cylindrical composite booms are the simplest deployable structures among STEMs, using the strain energy stored during the folding process to provide the motive force for deployment. In these cylindrical systems, the folding and deployment mechanisms have low complexity, and the presence of external energy sources such as motors is not necessary. The lack of these additional elements leads to a significant weight saving and a smaller required volume for the structure. These advantages can be exploited in the design of micro- and nanosatellites, allowing them to be equipped with tip payloads. For example, cylindrical booms may be used to position sensitive instruments far from the interferences caused by the satellite subsystems. On the other hand, despite their potential uses, the knowledge of the real structural behavior of deployable composite booms is not sufficiently established. In fact, Schenk et al. recently highlighted that the large research efforts on deployable structures are not compensated by an appropriate technology readiness level [11]. An accurate *ad hoc* design of the deployable structure is necessary to avoid its failure during folding, stowage, deployment and operative life.

Cylindrical composite booms suffer from bending and torsional stiffness, as well as buckling instability. Moreover, these structures are realized using ultrathin laminates to make them foldable. The use of ultrathin composites jeopardizes the application of traditional failure criteria, as they lack the accuracy for bending and axial-bending interactions [12]. In addition, in cylindrical composite booms, the cross-sectional shape plays an important role in the definition of the loading limits. Different types of cross-sections were studied in the literature, including Y-shape, single STEM, interlocked bi-STEM omega shape [10], and double omega cross-section [3,9,13,14].

In this work, we investigate the buckling behavior and the structural integrity under folding process of a boom with C-open cross-section, having radius of 10 mm and a 2-mm-wide opening [15–17]. The C-open cross-section offers several advantages with respect to the above mentioned cross-sectional shapes. First, it has a cost-efficient manufacturing due to its geometry of low complexity. In addition, the simplicity of the shape allows to reduce the formation of areas with high stress concentrations due to the packaging. We use a nonlinear analysis with the Riks method to estimate the critical load of the composite boom and the effects of random geometry imperfections on the boom stability behavior.

* Corresponding author. Tel.: +39 06 49 919 756; fax: +39 06 49 919 757.
E-mail address: susanna.laurenzi@uniroma1.it (S. Laurenzi).

http://dx.doi.org/10.1016/j.compstruct.2015.05.024

In particular, we study how the geometry imperfections, inherently related to the manufacturing, throughout the structure thickness influence the boom stability behavior with respect to the critical load. In addition, we study the structural integrity of the boom during the folding process using quasi-static explicit analysis. We determine the minimum coil radius that can be achieved during the rolling process without failure of the laminate, and the stress fields related to the flattening and coiling steps.

2. Finite element modeling

2.1. FEM models

Numerical analyses were performed in double precision using the finite element method (FEM) by the commercial code ABAQUS 6.12. Two different FEM models were realized to perform the buckling and folding analyses, respectively. In both cases, the boom geometry was discretized by implicit/explicit shell reduced-integration elements (S4R). This class of elements allows considering only the linear part of the nodal incremental displacement, thus reducing widely the computational cost. The nonlinear part is represented by hourglass modes, which can produce an excessive mesh deformation during the computational simulation [18]. In order to avoid this problem, the hourglass control method is in general adopted.

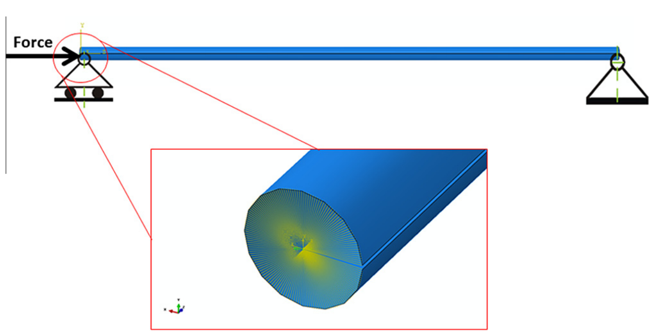

Fig. 1. Schematic of boundary conditions for the buckling analysis with detailed view of MPC constraints for the axial loading.

Table 1
Characteristics of the meshes studied for the finite element model.

Model name	Mesh 1	Mesh 2	Mesh 3	Mesh 4
Number of elements	10,000	20,000	25,000	30,000
Critical load [N]	55.51	55.68	55.68	55.68
Computational time [s]	1160	2250	2780	3480

Fig. 1 shows a schematic of the constraints used for the linear and nonlinear buckling analysis: one extremity of the boom was constrained in the x–y plane translations and z rotation, whereas the other extremity had also the z translation fixed. The axial load was transferred to the structure using a master node positioned in the center of the section and connected to the slave nodes located around the contour of the C-section, as shown in the detailed view in Fig. 1. The number of elements was set using a mesh sensitivity analysis. The analysis was based on the results of the linear buckling, in particular, comparing the critical loads determined with different number of elements. The results of this analysis are summarized in Table 1, where it can be observed that mesh 2 is the discretization that carries out a stable result with the smallest number of elements, and therefore could be selected for the numerical analyses. However, we noted that, in order to guarantee the stability of the Riks analysis, a mesh with the element aspect ratio approaching the unity was necessary. For this reason, we used mesh 3 for the analyses, which presents a square elements and the computational time is still acceptable. Fig. 2 illustrates the meshes used for the sensitivity analysis, showing that mesh 3 is a good compromise between the number of elements and the element aspect ratio.

Folding of cylindrical composite booms consists of flatting the structure and then rolling it on itself. To investigate the structural behavior associated with these configuration changes, we built two different models. The first model for the study of minimum coil radius was formed by a composite laminate representing the flatten boom, which rolled around a rigid cylinder standing for the hub where the boom coiled (Fig. 3). The coiling radius was set as a parameter and, starting from the value of 15 mm, it was gradually decreased at every analysis. Fig. 3 shows the boundary conditions used in this model. The node set A (on the two edges of the lamina) was free to move in the x-axis and to rotate around the z-axis. The cylinder had a fixed negative displacement u on the z-axis simulating the lamina bending during the rolling process around the cylinder.

The second finite element model was set to investigate the stress fields induced by the flattening process, and consisted of a boom portion of length 20 cm positioned on a rigid plate (Fig. 4). The boom was discretized by 5320 shell elements S4R with reduced-integration scheme. The plate was modeled with 2080 four-node rigid elements, R3D4, which formed a single rigid body connected to a fixed reference node. The simulation of the flattening process consisted of two steps: during the first one, a low pressure was applied on the internal surface of the boom, preventing the rotation of the node sets A and B (Fig. 4) around the x-axis. The second step consisted in the rotation of the node set A around the x-axis, whilst the node set B was fixed and the node set C was prevented from rotating around the z-axis.

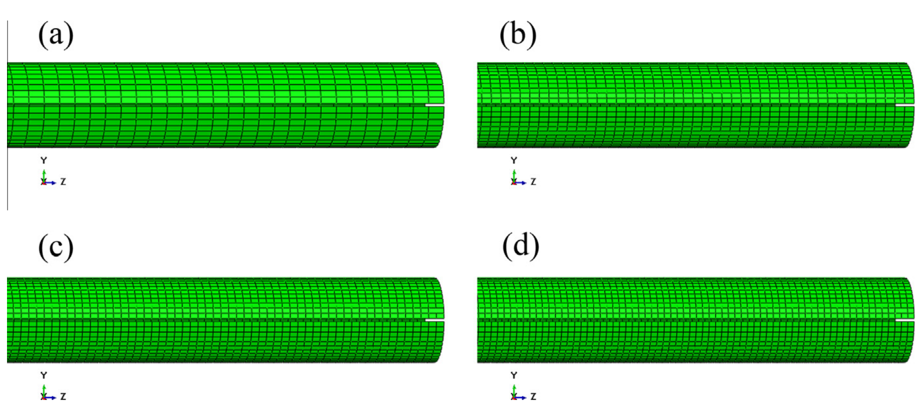

Fig. 2. View of the mesh used to establish the number of elements. (a) Mesh 1 with 10,000 S4R elements, (b) Mesh 2 with 20,000 S4R elements (c) Mesh 3 with 25,000 S4R elements, (d) Mesh 4 with 30,000 S4R elements.