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Effect of Geometric Parameters on the Failure Index of Composite Deployable Booms / Augello, R., Carrera, E., Latini, F., Petrolo, M.. - ELETTRONICO. - 73:(2026), pp. 195-199. (V International Conference on Mechanics of Advanced Materials and Structures (ICMAMS) Toulouse, France 1-3 July 2026) [10.21741/9781644904459-38].

Availability:
This version is available at: 11583/3012649 since: 2026-11-07T13:08:46Z

Publisher:
Materials Research Forum

Published
DOI:10.21741/9781644904459-38

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13 November 2026

Materials Research Proceedings 73 (2026) 195-199 https://doi.org/10.21741/9781644904459-38

Effect of Geometric Parameters on the Failure Index of Composite Deployable Booms

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Keywords: Deployable Composite Booms, Geometric Parameters, Failure Index, Carrera Unified Formulation, Nonlinear Structural Analysis

Abstract. This study investigates how geometric parameters (particularly the length) influence the failure index of thin-walled composite deployable booms. The analysis is performed using a 1D refined finite-element model based on the Finite Element Method (FEM) and the Carrera Unified Formulation (CUF). In this model, the 3D displacement field is expanded across the cross-section with quadratic Lagrange polynomials (L9) and along the boom axis with cubic (B4) finite elements. Hashin's failure criteria are used at each equilibrium state to compute Failure Index (FI), assuming a pristine linear-elastic material. Numerical results show that longer booms achieve larger tip rotations before activating FI, and that the first failure mode is consistently matrix compression (MC). The findings confirm that increasing boom length significantly alters the moment–rotation response, maximum achievable rotation, and damage initiation pattern, underlining the critical role of geometry. A progressive damage model is recommended for future work to capture post-initiation behavior.

Introduction

Lightweight deployable composite booms are key enabling components for space structures (antennas, solar arrays, telescopes, etc.) because they deliver high stiffness-to-mass ratio and can be stowed compactly. Common designs include tape-spring elements and TRAC (triangular rollable and collapsible) booms. However, their extreme slenderness and material anisotropy pose challenges: classical 3D finite-element models are accurate but computationally expensive for such thin-walled beams. Refined one-dimensional models using the Carrera Unified Formulation (CUF) [1,2] have proven effective for composite structures [3,4]. CUF allows arbitrary-order expansions of the displacement field across the cross-section, enabling high-order 1D elements that capture 3D stress states. For example, a global/local CUF approach for deployable booms achieved accurate local stress fields with reduced cost [5].

Geometric design parameters strongly affect the mechanical response of composite beams. Prior studies [5] highlight that variations in thickness, length, or cross-sectional shape significantly change load transmission and failure behavior in composite components. In the context of deployable booms, boom length and boundary conditions markedly influence bending stiffness and failure onset [6]. Here, the effect of length on the Failure Index (FI) of booms under bending is examined. The failure index is computed using the three-dimensional Hashin failure criteria for composites, and the influence of geometric variations on the point at which the FI exceeds 1 is identified. The adopted refined 1D CUF model provides a balance between accuracy and efficiency.

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Methodology

According to the CUF, the 3D displacement field can be expressed in the following unified form:

$$\boldsymbol{u}(x,y,z) = F_\tau(x,z)\boldsymbol{u}_\tau(y), \tau = 1,2,\ldots,M$$

where $\boldsymbol{u}$ is the displacement vector, whose components are defined with respect to the global reference system (x,y,z). The functions $F_\tau(x,z)$ are the cross-sectional expansion functions defined over the in-plane coordinates (x,z), τ is the summation index, and M is the number of terms adopted in the cross-sectional displacement expansion. In the present work, quadratic Lagrange polynomials (L9) are used to approximate the kinematic field over the cross-section.

The displacement field along the beam axis is discretized by means of the Finite Element Method (FEM). Accordingly, the generalized displacement vector $\boldsymbol{u}_\tau(y)$ can be interpolated along the beam axis as:

$$\boldsymbol{u}(x,y,z) = N_i(y)F_\tau(x,z)\boldsymbol{u}_{\tau i}, i = 1,2,\ldots,N_n$$

where $N_i(y)$ is the i-th one-dimensional shape function, i is the summation index, N_n is the number of finite-element nodes per element, whereas $\boldsymbol{u}_{\tau i}$ is the vector of nodal unknowns associated with the cross-sectional expansion term F_τ.

The stress $\boldsymbol{\sigma}$ components are given in vectorial form as follows.

$$\boldsymbol{\sigma} = \{\sigma_{xx}\ \sigma_{yy}\ \sigma_{zz}\ \sigma_{yz}\ \sigma_{xz}\ \sigma_{xy}\}^T$$

To assess material failure, the 3D Hashin failure criterion [7] is adopted. This criterion allows the identification of the dominant failure mode at the ply level on the basis of the local stress state. Four different failure indices are considered, namely Fiber Tension (FT), Fiber Compression (FC), Matrix Tension (MT), and Matrix Compression (MC):

FT: $\left(\frac{\sigma_{11}}{X_T}\right)^2 + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} \geq 1$

FC: $\left(\frac{\sigma_{11}}{X_C}\right)^2 \geq 1$

MT: $\frac{(\sigma_{22}+\sigma_{23})^2}{Y_T^2} + \frac{\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_{23}^2} + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} \geq 1$

MC: $\left[\left(\frac{Y_C}{2S_{23}}\right)-1\right]\left(\frac{\sigma_{22}+\sigma_{33}}{Y_C}\right) + \frac{(\sigma_{22}+\sigma_{13})^2}{4S_{23}^2} + \frac{\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_{23}^2} + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} \geq 1$

where X represents the material strength in the fiber direction, and Y represents that of the transverse direction, with the subscripts T and C denoting tensile and compressive loading, respectively. S_{ij} denotes the material shear strengths.

Numerical Results

The first numerical result regards the tape spring of Fig. 1, with t = 80 μm, r = 11.25 mm, and α = 90°.

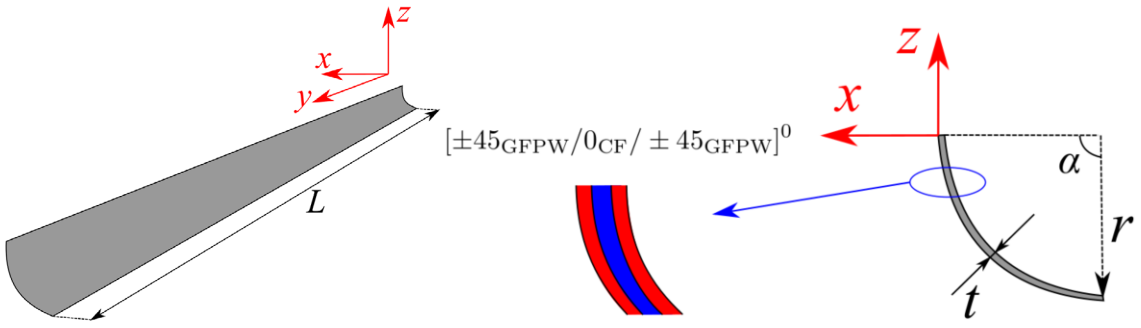


Figure 1 – Considered tape spring.

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The structure is simply supported at its edges and subjected to opposite moments to induce bending. Figure 1 shows the nonlinear static curves considering various lengths of the deployable.

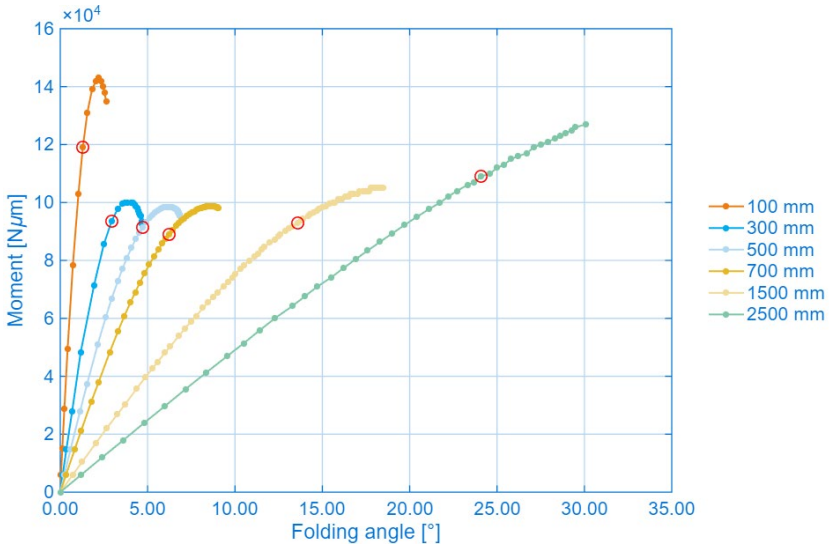


Figure 2 – Nonlinear curves varying the length of the analyzed tape spring. Circles indicate the point of first FI > 1.

Several considerations can be made:

- The longer the structure, the higher are the reached angle before any failure occurs;
- The peak moment is around 145 Nmm for the 100 mm-long TAPE deployable boom. It then decreases as the boom length increases, reaching about 100 Nmm for lengths between 300 and 700 mm. For longer booms, the peak moment increases again, almost reaching the same value as the 100 mm case in the 2500 mm case.

In Fig. 2, red circles correspond to the first FI greater than 1. In all cases, the first active failure mode is MC (Matrix Compression). Figure 3 shows the deformed configuration of 1500 and 2500 mm tape springs in correspondence of MC > 1.

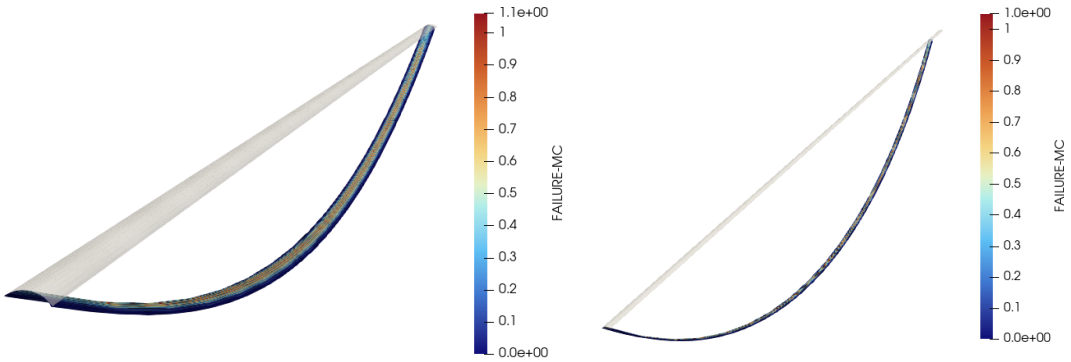


Figure 3 – Deformed configuration of MC > 1 for the tape spring study case. 1500mm left, 2500mm right.

The second study case is about the TRAC boom. The geometry of the cross-section is reported in Fig. 4, and w=8mm, r=12.7mm, θ= 90°, t = 0.08mm. The stacking sequence is the same as for the tape spring.

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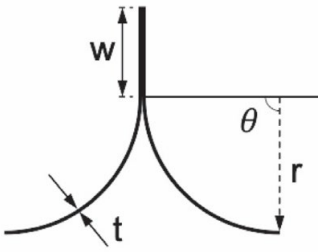


Figure 4 – Geometry of the cross-section of the TRAC.

The boundary and loading conditions are the same as in the previous analysis and the results are reported in Fig. 5, along with circles indicating the first FI > 0.

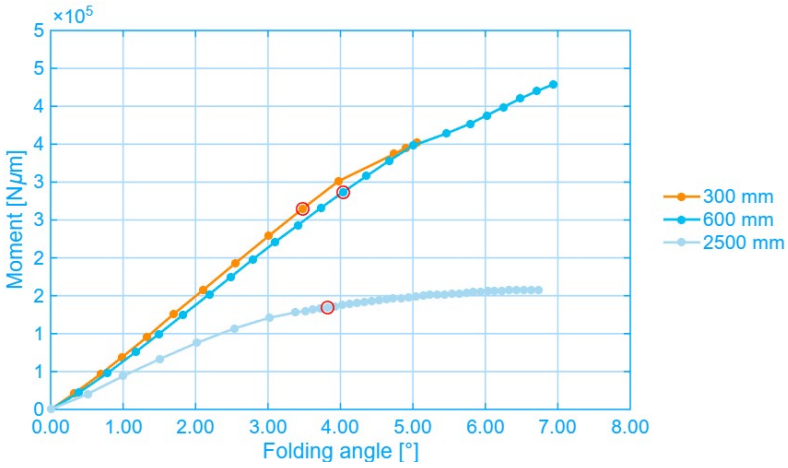


Figure 5 – Nonlinear curves varying the length of the analyzed TRAC. Circles indicate the point of first FI > 1.

Clearly, similar values for 300 and 500-mm-cases arise and convergence is met and the curves align with those available in the literature [8]. As the previous cases, the first FI to exceed the value of 1 is MC.

Finally, Fig. 6 reports deformed the failing deformed configurations. The 2500 m buckles.

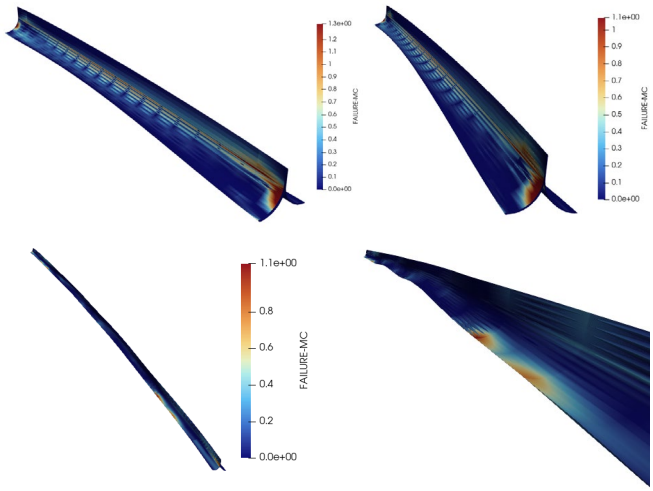


Figure 6 – Deformed configuration of MC > 1 for the TRAC study case. 300mm top left, 500mm top right and 2500mm bottom.

Conclusions

This parametric study highlights the significant role of geometry in deployable composite boom response. Boom length strongly influences the load–deflection behavior and failure onset. Longer booms exhibit greater flexibility and delay the onset of failure under the same end moments. Across all cases, matrix-compression was the first failure mode. The results confirm that careful geometric design (length, cross-section) is crucial for ensuring structural integrity of deployable booms. The CUF-based 1D modelling strategy proved effective for capturing these effects. Future work will implement progressive damage models to simulate post-initiation behavior under even larger loads.

Acknowledgments

This study was carried out within the DISPCOMP funded by the Italian Space Agency, ASI, under contract n. 2024-38.I.0.

References

[1] E. Carrera, G. Augello, and R. Augello, Implementation of Beam-Type Finite Elements Based on Carrera Unified Formulation. Cham, Switzerland: Springer, 2026. https://doi.org/10.1007/978-3-031-95856-4

[2] E. Carrera, M. Cinefra, M. Petrolo, and E. Zappino, Finite Element Analysis of Structures Through Unified Formulation. Hoboken, NJ, USA: Wiley, 2014. https://doi.org/10.1002/9781118536643

[3] I. Kaleel, M. Petrolo, and E. Carrera, "Elastoplastic and progressive failure analysis of fiber-reinforced composites via an efficient nonlinear microscale model," Aerotecnica Missili & Spazio, vol. 97, no. 2, pp. 103–110, 2018. https://doi.org/10.1007/BF03405805

[4] D. Scano, E. Carrera, and M. Petrolo, "Use of the 3D equilibrium equations in the free-edge analyses for laminated structures with the variable kinematics approach," Aerotecnica Missili & Spazio, vol. 103, pp. 179–195, 2024. https://doi.org/10.1007/s42496-023-00177-2

[5] R. Augello, A. Pagani, E. Carrera, and D. A. Iannotta, "Stress and failure onset analysis of thin composite deployables by global/local approach," AIAA Journal, vol. 60, no. 10, pp. 5954–5966, 2022. https://doi.org/10.2514/1.J061899

[6] A. Pagani, R. Augello, and E. Carrera, "Numerical simulation of deployable ultra-thin composite shell structures for space applications and comparison with experiments," Mechanics of Advanced Materials and Structures, vol. 30, no. 8, pp. 1591–1603, 2023. https://doi.org/10.1080/15376494.2022.2037173

[7] Z. Hashin, "Failure criteria for unidirectional fiber composites," Journal of Applied Mechanics, vol. 47, no. 2, pp. 329–334, 1980. https://doi.org/10.1115/1.3153664

[8] C. Leclerc and S. Pellegrino, "Nonlinear elastic buckling of ultra-thin coilable booms," International Journal of Solids and Structures, vol. 203, pp. 46–56, 2020. https://doi.org/10.1016/j.ijsolstr.2020.06.042