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Folding Simulation of Flat Arrays Using Refined Beam Finite Elements

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Abstract. The shift toward smaller satellites has sparked growing interest in deployable booms that can stow compactly and extend to full length once on-orbit [1]. These booms are typically rolled into a coil and, when released, unroll into slender rods made of thin-walled composite shells, releasing stored strain energy in the process; such mechanisms are common in spaceborne telescopes and other large-aperture payloads [2,3]. Tape springs, thin elastic strips, remain the most prevalent deployable boom. The introduction of carbon-fibre-reinforced-plastic (CFRP) tape springs has further improved stiffness-to-mass ratios [4]. A related concept, the Triangular Rollable and Collapsible (TRAC) boom, links two tape-spring "flanges" along a common "web," forming a triangular cross-section that offers markedly higher bending stiffness. First developed at the Air Force Research Laboratory by Murphey and Banik [5], metallic TRAC booms flew on NASA's NanoSail-D solar sail [6]; more recent work has shifted to composite TRAC designs to mitigate temperature-gradient problems seen in metal versions. One high-profile application is Caltech's Space Solar Power Project (SSPP), which envisions a modular lattice of TRAC longerons and rectangular CFRP battens that supports arrays of multifunctional tiles. These tiles harvest solar energy, convert it to RF power, and beam it to Earth [7]. The SSPP structure consists of bending-stiff trapezoidal strips, arranged in four identical quadrants. The two edges of each strip are formed by composite TRAC longerons, connected by carbon fiber rectangular battens. Accurate simulation is vital for sensitivity studies and for minimizing costly hardware tests. Conventional finite-element analysis often relies on 2-D shell elements to model slender booms, a choice that struggles to capture out-of-plane responses and local effects, especially critical in composite laminates [8]. To overcome these shortcomings, this work employs a Carrera Unified Formulation (CUF)–based finite-element model [9]. CUF enriches one-dimensional beam elements with high-order cross-sectional expansions, allowing three-dimensional and localized behaviours to appear within a low-degree-of-freedom framework. The method has already proven effective for buckling and post-buckling studies of deployable booms [10]; here, it is extended to simulate the full folding and deployment sequence of the SSPP flat-array module.

Refined one-dimensional finite element

For the numerical model, a Cartesian reference system is used, so that the y direction is placed in the length direction, and the x,z identify the cross-sectional domain as shown in Fig. 1.

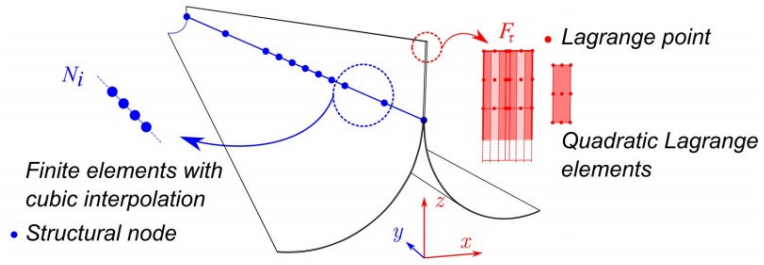


Figure 1 - Model of the TRAC longeron based on the Carrera unified formulation.

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Materials Research Proceedings 69 (2026) 1387-1390 https://doi.org/10.21741/9781644904251-242

According to the Carrera Unified Formulation (CUF), the three-dimensional displacement field can be written in the following unified manner:

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

where $\boldsymbol{u}(x,y,z)$ is the displacement vector, whose components are expressed in the general reference system (x,y,z), $F_\tau(x,z)$ represent the cross-sectional functions depending on the x,z coordinate, τ is the sum index and M is the number of terms of the expansion in the cross-section plane assumed for the displacements. The proposed work adopts quadratic Lagrange polynomials (L9) as $F_\tau(x,z)$ to approximate the kinematics of the theory.
To approximate the displacement field over the beam axis, the Finite Element Method (FEM) is adopted. The generalized displacement vector $\boldsymbol{u}_\tau(y)$ is expressed as follows:

$$\boldsymbol{u}_\tau(y) = N_i(y)\boldsymbol{u}_{\tau i} \qquad \tau = 1,2,\dots,N_n \tag{2}$$

where N_i stands for the i-th one-dimensional shape function, i indicates summation and N_n is the number of the FEs nodes per element. Finally, $\boldsymbol{u}_{\tau i}$ is the following vector of the FE nodal parameters:

$$\boldsymbol{u}_{\tau i} = \{\boldsymbol{u}_{x_{\tau i}}, \boldsymbol{u}_{y_{\tau i}}, \boldsymbol{u}_{z_{\tau i}}\}^T \tag{3}$$

Here, 1D finite Lagrangian elements are used along the y-axis.

Methodology

The deployable structure analyzed in this study is a complex structure made of longerons, transverse battens, and hinges. A simple version is shown in Fig. 2(a), and it is referred to as a double-strip due to its composition of two sub-structures connected by two hinges.

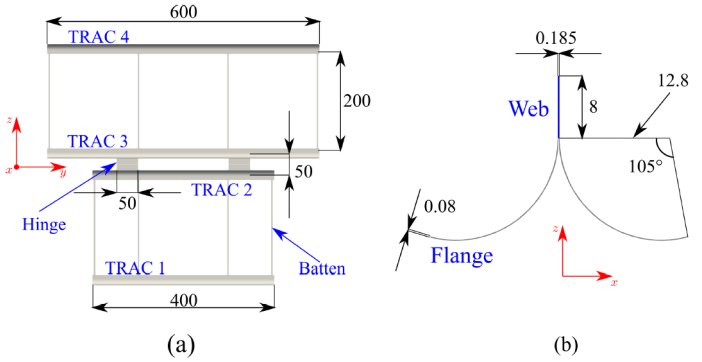


Fig. 2 (a) double-strip structure (b) one TRAC longeron cross-section. The dimensions are given in mm.

Each strip consists of two TRAC longerons and four battens. The cross-section of the longerons is shown in Fig. 2(b), with all dimensions provided in millimeters. As far as the material properties are concerned, the composite layup in the flanges of the longeron is [± 45 GFPW/ 0 CF/ ± 45 GFPW]°, and the layup of the web region is [± 45 GFPW/ 0 CF/ ± 45 GFPW/ 0 CF/ ± 45 GFPW]°, where CF represents a thin ply with unidirectional carbon fibers and GFPW stands for plain weave scrim glass. Both plies are impregnated with resin. In this case, six different cross-sections are utilized, as illustrated in Fig. 3(b).

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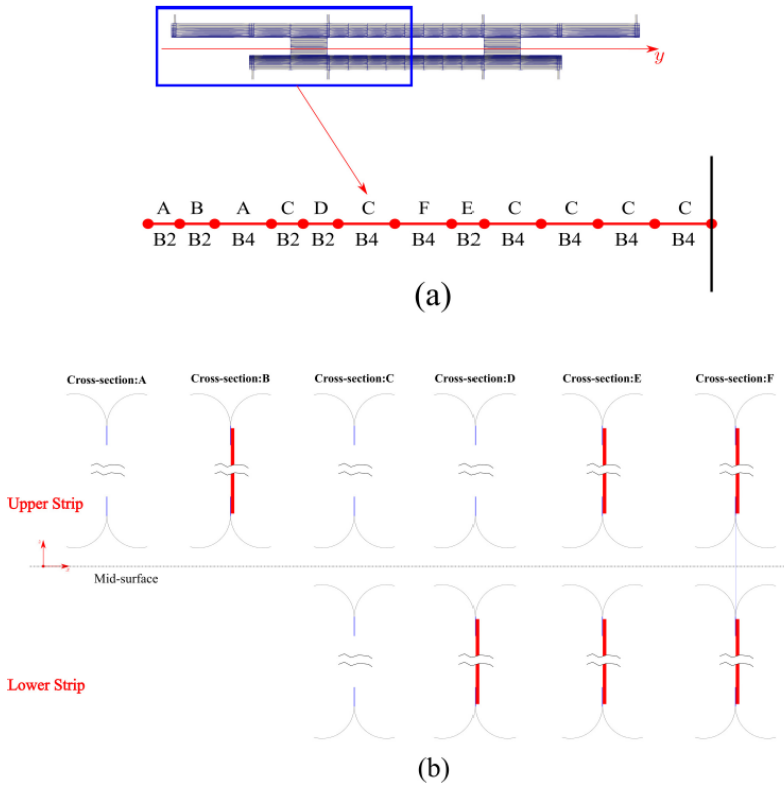


Fig. 3 Mesh discretization for the double-strip structure. (a) Beam finite element used along y-axis. (b) Representation of the six cross-sections.

Finally, Fig. 4 shows a four-strip structure that the will be also analysed in the full paper. It involves four strips joined together with hinges and both transverse and diagonal battens. The structure is modeled using a single axis refined beam, using the same approach described above.

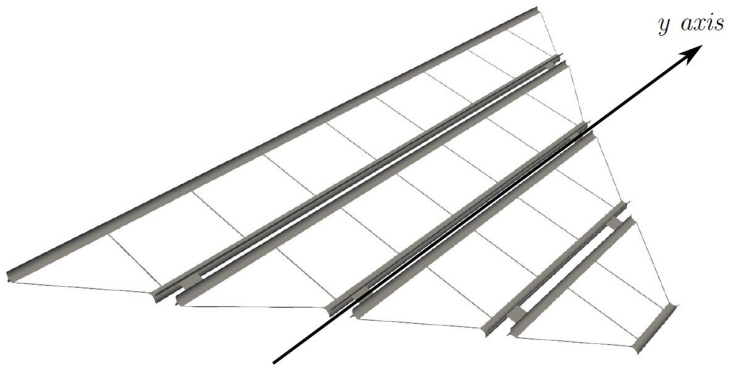


Fig. 4 Model of the elastically foldable flat array.

The full paper will deal with the folding of the elastically foldable flat array.

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