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Folding simulation of TRAC longerons via unified one-dimensional finite elements

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Abstract. This paper proposes a simulation of the folding phase of TRAC deployable booms using refined one-dimensional finite elements in the framework of the Carrera Unified Formulation. The mathematical model involves standard beam finite elements placed along the length of the longeron, and Lagrange polynomials as expansion functions for the cross-sectional domain. The nonlinear governing equations are written recalling the principle of virtual work, and they are linearized using the Newton-Raphson scheme. The contact between the two flanges is simulated with linear spring which activate when pre-defined node pairs approach under a fixed tolerance. Two simulations are carried out, including or not the contact behavior, respectively. The results highlight the capability of the proposed model to deal with large displacements and contact between the ultra-thin flanges of the structure.

Introduction

Over the years, deployable structures have become increasingly popular in space engineering, since they make it possible to obtain a consistent reduction of mass, volume, and consequently, the cost of a satellite. Deployable booms found a large number of applications such as for telescopes [1] and antennas [2].

The most common type of deployable booms is tape springs, which can be described as thin-walled elastic strips. A combination of those can be used to generate other types of booms, such as the Triangular Rollable And Collapsible (TRAC). Originally invented by Murphey and Banik [3] and developed by the Air Force Research Laboratory, it consists of two circular domains (flanges) made of tape-spring that are attached along the common edge (web). The resultant cross-section gives TRAC longerons larger bending stiffness than other popular options (such as the Collapsible Tubular Mast (CTM) [4], the Storable Tubular Extendable Member (STEM) [5] and bi-STEM [6]).

The present work deals with the simulation of the folding phase of TRAC booms. By employing the Carrera Unified Formulation [7], the ultra-thin boom can be modeled using refined one-dimensional beam finite elements. The nonlinear governing equations are solved using a Newton-Raphson linearization scheme along with a displacement control.

One dimensional model of the TRAC longeron

The deployable mechanism analyzed in this work is shown in Fig. 1, and it consists of a foldable TRAC longeron. The geometric properties are $L = 400$ mm, $h = 8$ mm, $r = 12.8$ mm, $\vartheta = 105°$ and $t = 80$ µm.

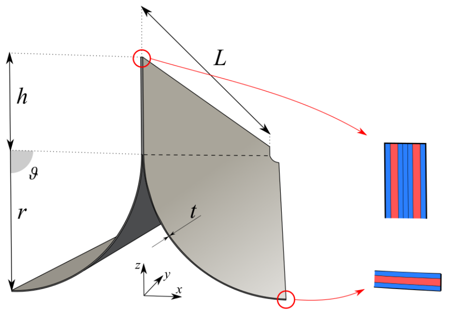


Figure 1 - Geometry of the considered TRAC longeron

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 that in the web region is [±45 GFPW/ 0 CF/ $\pm45_3$ GFPW/ 0 CF/ ±45 GFPW], where CF represents a thin ply with unidirectional carbon fibers. GFPW represents plain weave scrim glass. Both plies are impregnated with resin, as described in [8].

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

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

where $\boldsymbol{u}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ is the displacement vector, whose components are expressed in the general reference system $(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ of Fig. 1, $\boldsymbol{F_\tau}$ represent the cross-sectional functions depending on the *x*, *z* coordinate, $\boldsymbol{\tau}$ is the sum index and *M* is the number of terms of the expansion in the cross-section plane assumed for the displacements. $\boldsymbol{N_i}$ stands for the $\boldsymbol{i}$th one-dimensional shape function, $\boldsymbol{u_{\tau i}}$ is the vector of the FE nodal parameters, $\boldsymbol{i}$ indicates summation and *Nn* is the number of the FEs nodes per element. In this work, a cubic interpolation for the axis direction is assumed. Figure 2 shows the resultant one-dimensional model of the TRAC longeron.

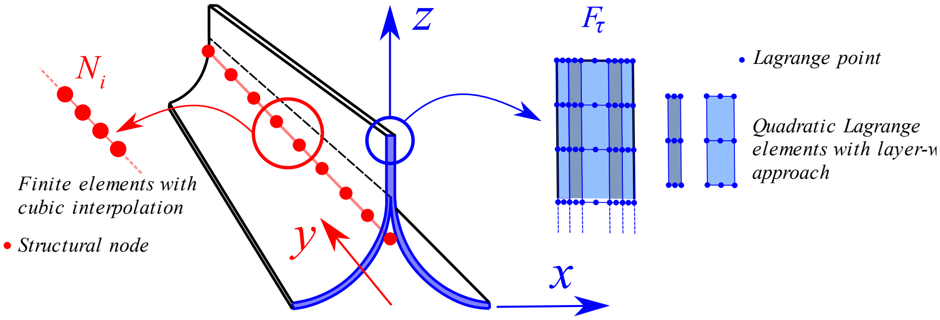


Figure 2 - Modeling of the TRAC longeron

Boundary conditions

The considered boundary conditions are reported in Fig. 3. Basically, one side of the TRAC can rotate around the *z* axis, whereas the other can rotate around the *z* axis and move along the *y* axis.

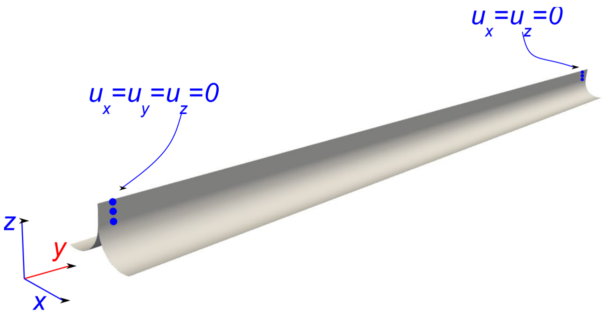
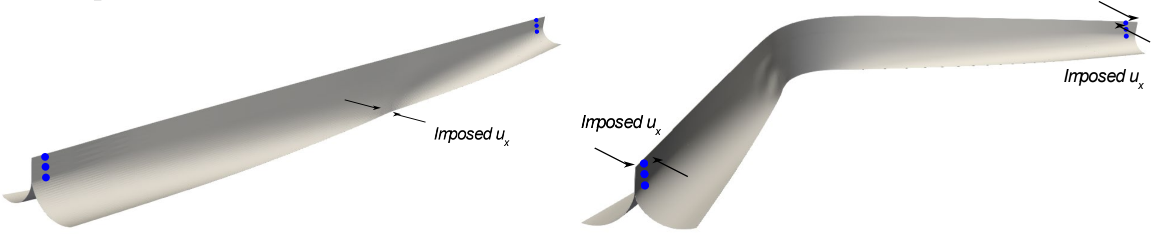


Figure 3 - Boundary conditions

Subsequently, the structure is subjected to a pinching in the middle, by imposed displacements, as depicted in Fig. 4(a). Figure 4(b) reports the folding process, where the rotations are ensured by pairs of displacements at the sides of the structure.



(a) (b)

Figure 4 - Pinching and folding of the TRAC longeron

Nonlinear governing equations

The set of the nonlinear governing equations, which full derivation is described in [10], is expressed in the following:

$$\boldsymbol{K_S q - p = 0} \tag{2}$$

where K_S, q and p are the global, assembled FE stiffness, displacement and external force arrays of the final structure. Equation (2) represents a nonlinear algebraic system of equation for which an iterative method is needed. We employ here the same procedure detailed in [11], where a Newton–Raphson scheme is used by making use of a path following constraint. This procedure demands for the linearization of the nonlinear governing equations. As a result, we need to introduce the so-called tangent stiffness matrix $K_T = \frac{d(K_S \boldsymbol{q} - p)}{d\boldsymbol{q}}$: The explicit form of K_T is not given here, but it is derived in a unified form in [12]. Finally, in this work, a displacement control algorithm is introduced.

Contact mechanics

In the present work, contact between the flanges of the TRAC longeron is simulated. A node-to-node contact approach is employed, recalling the penalty technique. Basically, a linear spring is simulated between the nodes of the two flanges, as depicted in Fig. 5.

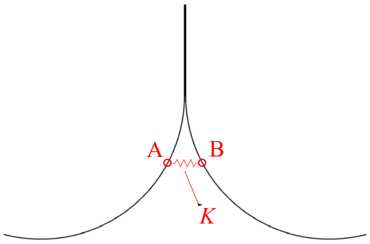


Figure 5 - Node-to-note contact simulation

The nodes are paired as input of the analysis, so the mesh coincidence between the inner surfaces of the two flanges must be ensured. The springs activate under a particular tolerance, which is set as 1 µm, and produces two opposite forces on the nodes. Thus, the force vector $\boldsymbol{p}$ and the stiffness matrix K_T are updated at each iteration step of the previously described Newton-Raphson algorithm.

Numerical results

The numerical results regard two simulation, including or not the contact between the two flanges. The developed mathematical model involves 20 cubic FEs for the axis discretization and 64 quadratic Lagrange polynomials for the cross-sectional domain (30 for each flange and 4 for the web). The total number of degrees of freedom is 74871.

As far as the simulation without contact is concerned, the pinching phase is reported in Fig. 6.

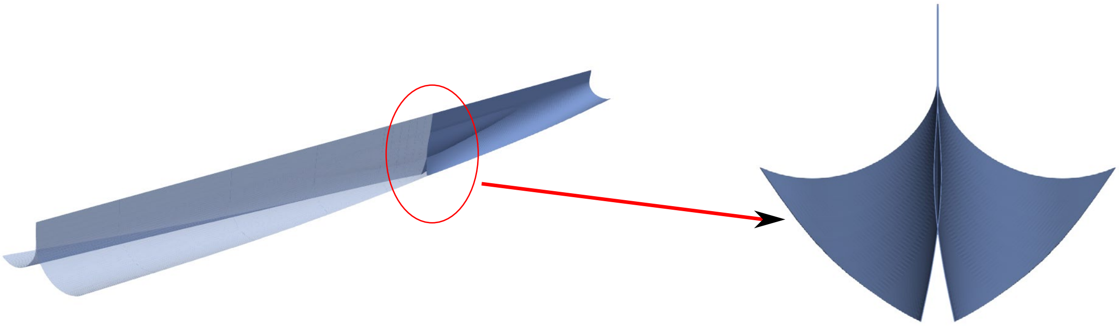


Figure 6 - Pinching simulation of the TRAC longeron without contact mechanics

As can be seen from Fig. 6, the penetration between the two flanges arises in a large domain of the boom. The complete folding simulation is reported in Fig. 7.

Figure 7 - Folding simulation of the TRAC longeron without contact mechanics

The folding of the TRAC boom can be simulated, although, the penetration between the two flanges persists during the overall simulation..

The same simulation is conducted including the contact between the two flanges. The results for the pinching simulation are reported in Fig. 8.

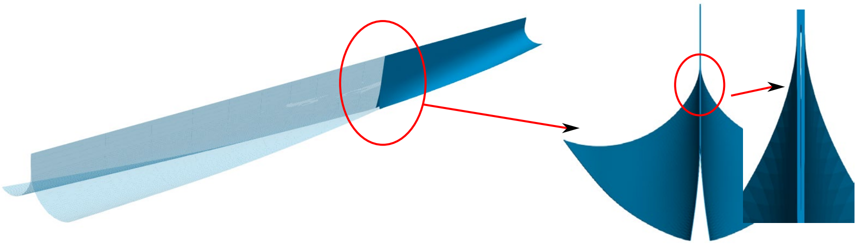


Figure 8 - Pinching simulation of the TRAC longeron including contact mechanics

In contrast to the case without contact, no penetration is observed between the two flanges. Moreover, since the web has one additional layer that the two flanges (see Fig. 1), the two flanges do not contact each other in the proximity of the web (see the enlargement in Fig. 8). The full folding simulation is reported in Fig. 10.

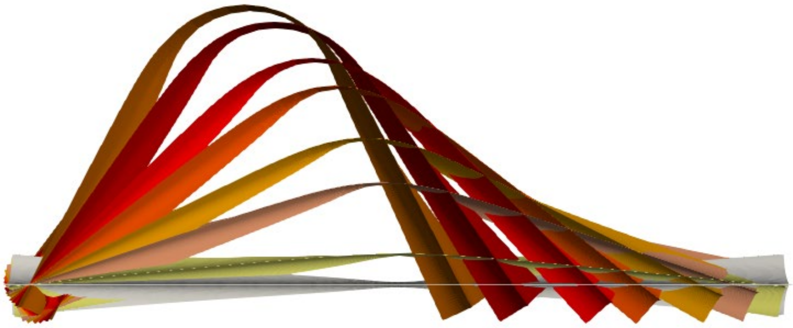


Figure 10 - Folding simulation of the TRAC longeron including contact mechanics

Finally, Fig. 10 reports the contact between the two flanges in one of the equilibrium state.

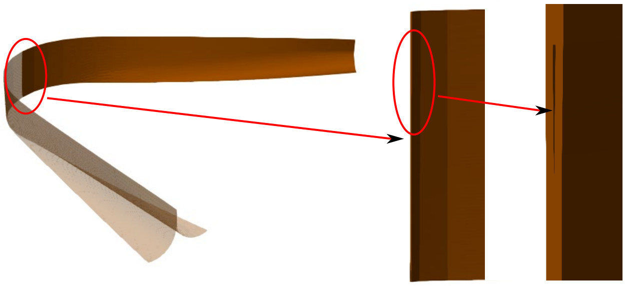


Figure 10 - Particular of the folding simulation of the TRAC longeron including contact mechanics

Conclusions

The present work focussed on the simulation of the folding phase of a deployable boom, namely the TRAC longeron. This composite ultra-thin structure was modelled with the Carrera unified formulation, thanks to which refined one-dimensional finite elements can be built, accounting for any cross-sectional deformation. The nonlinear governing equations were derived in terms of the fundamental nuclei, which represent the basic building block of the overall stiffness matrix. Then, a Newton-Raphson scheme was employed, and a consistent linearization of the governing equation was performed. The contact between the two flanges of the TRAC longeron is simulated with node-to-node linear springs, which are updated at every iteration of the nonlinear procedure. Two simulations with and without the contact were carried out. The results show the robustness of the present approach to deal with far nonlinear regimes and contact nonlinearities. Future works will deal with the introduction of nonlinear springs to improve the convergence rate of the nonlinear solution and for the dynamic nonlinear simulation of the deployment of the TRAC longerons.

Acknowledgment

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