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Reduced-order modelling of the deployment of a modified flasher origami for aerospace applications

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Abstract. In this paper, we simulate the nonlinear deployment mechanics of a modified flasher origami structure designed to be a deployable solar panel. We compare reduced-order bar-and-hinge simulations, where panels are modelled as bar assemblies connected by joints and torsional springs, with results obtained from commercial finite element software. Through this comparison, we demonstrate the ability of the bar-and-hinge approach to capture key features of the origami behaviour at a fraction of the time needed to perform regular finite-element simulations. We also provide details on how to properly tune the bar properties to simulate panels made bonding printed circuit boards to textile, and the joint properties to mimic folds that are made of fabric and flexible circuit interconnects.

Introduction

In the past few decades, origami structures have attracted significant attention in the field of science and engineering, due to their unique mechanical properties and reconfigurable and tuneable attributes. These properties make origami designs suitable for applications in fields such as robotics, medicine, and especially aerospace.

The task of modelling origami structures for space applications presents several challenges. First, modelling origami requires accounting for significant geometric nonlinearity due to the large rotations that the panels undergo during deployment and stowage. Additionally, real-life origami structures do not deploy following rigid body motions and are instead characterized by panel bending. Additional challenges appear when the origami systems to be modelled are made of multi-layer materials such as rigid-flex printed circuit boards (PCB). These materials are typically used in CubeSat applications, in which origami techniques are applied to deployable solar panels, communication devices and solar sails. Finally, origami simulations must yield information on the forces exerted by the deployment on the spacecraft.

Research investigations on the deployment of origami structures have been conducted utilizing a variety of finite element software and techniques, including ABAQUS 5, formulations based on Hamilton's equations to capture the dynamics of deployment with validation using ADAMS multibody dynamics [2], and quasi-static bar and hinge methods [3]. The fundamental principle of the bar-and-hinge approach, elucidated by Schenk and Guest [4] as well as Filipov et al. [5], centers on the simplification of the mechanics in origami, by replacing panels with assemblies of bars, hinges and torsional springs that limit out-of-plane rotations. This approach leverages the inherent limitations of permissible deformations within origami structures: in-plane stretching, out-of-plane folding along creases, and out-of-plane bending of panels. Bars are strategically positioned along straight fold lines and across panels to ensure in-plane stiffness. Rotational hinges are incorporated along the bars connecting panels to simulate crease folding, as well as along the bars traversing panels to replicate panel bending. The method solves the equilibrium equations iteratively, using a displacement-controlled algorithm. Despite having a limited number of degrees of freedom, the reduced-order bar-and-hinge model accurately predicts the overall mechanical behaviour of origami structures [6].

Here, we use the bar-and-hinge method to simulate the deployment of a modified flasher origami for space applications and compare the results to shell FEM results from ANSYS Motion.

Model generation workflow

The selected folding pattern is a modified Flasher origami, which is renowned for its radial deployment mechanism and has been notably utilized in the design of the NASA Starshade prototype, for which the modification amounts to an octagonal variation of the folding technique. The geometry is initially designed in 2D and saved as .svg. A specific color convention is used to distinguish between mountain folds and valley folds, as illustrated in Figure 1 (left): mountain folds are red, valleys are blue and boundary edges are black.

To simulate the deployment process, we need a closed version of this origami structure. This closed configuration is obtained using the interactive origami software (*Origami simulator*) by Ghassaei et al. [7]. The structure before and at a stage of partial folding are shown in Figure 1 (center and right).

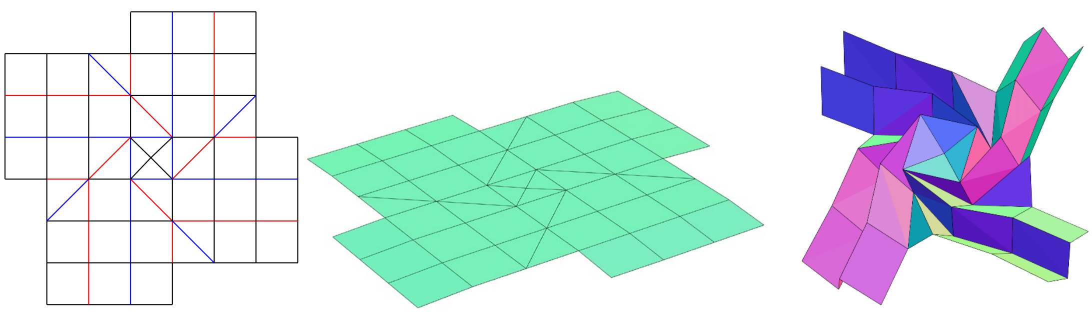

Figure 1 – Origami pattern in .svg file (left), 3D open configuration (center) and 3D partially closed (right). The image in the center and the one on the right have been rendered from the code in [7].

After obtaining the closed version of the origami structure, we export it as .obj file and import it in Merlin 2 (written in MATLAB) [2]. Prior to using it, the nodal coordinates from the .obj file are modified to better fit the desired geometry. The geometry of the origami structure is a 10x10x10 centimeters cube.

After importing the geometry, we set boundary conditions and loads. The only boundary condition imposed on the model is a complete translational block along the three axes to the central node of the horizontal panel. The loads are represented by four displacement constraints of 385 millimeters imposed on the top four vertices of the outermost panels.

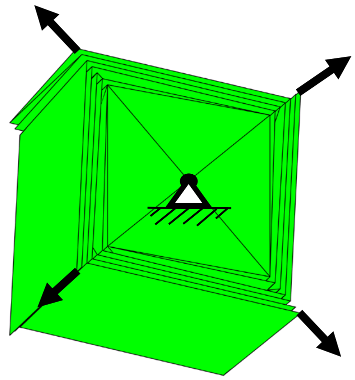

Figure 2 – Closed geometry of the flasher with graphical representation of boundary conditions and loads

In Merlin 2, the most important modelling parameters are the type of discretization of each panel, the material properties and the thickness of the geometry elements. The discretization alternatives for the analysis are called N4B5, which includes four nodes and five bars for every square panel and N5B8, including five nodes and eight bars for every square panel; here, we choose the latter.

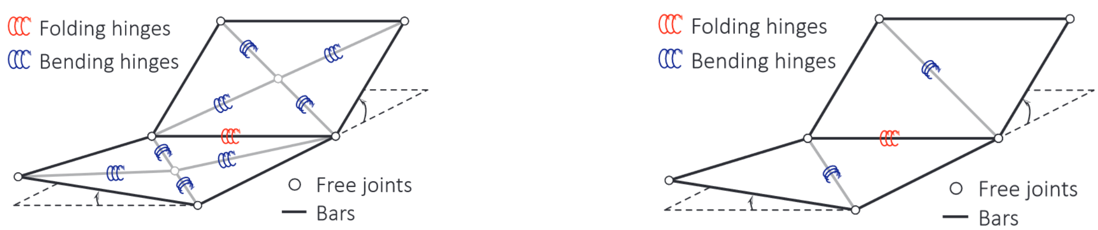

Figure 3 –N5B8 (left) and N4B5 (right) discretization, images from [2]

The parameters imposed for the material properties come from experimental data on a specific textile-based electronics substrate [8], used for the realization of the physical prototype that will be subjected to experimental tests to validate the data coming from both models.

The code allows to obtain a load-displacement curve for any node from the simulation, together with information concerning the stored energy of the bending and folding hinges in the geometry. The result of our analysis is shown in Figure 4. At large displacements, the load increases asymptotically since the deployment is complete at 360 millimeters and any further loading engages the high axial stiffness of the panels. The detail of the load-displacement curve, shown on the right, shows a gradual increase of the force from zero to 350 millimeters.

It can also be noticed that the first part of the plot shows a zero load, due to an initial free rotation given by the imperfect alignment of the forces in the model.

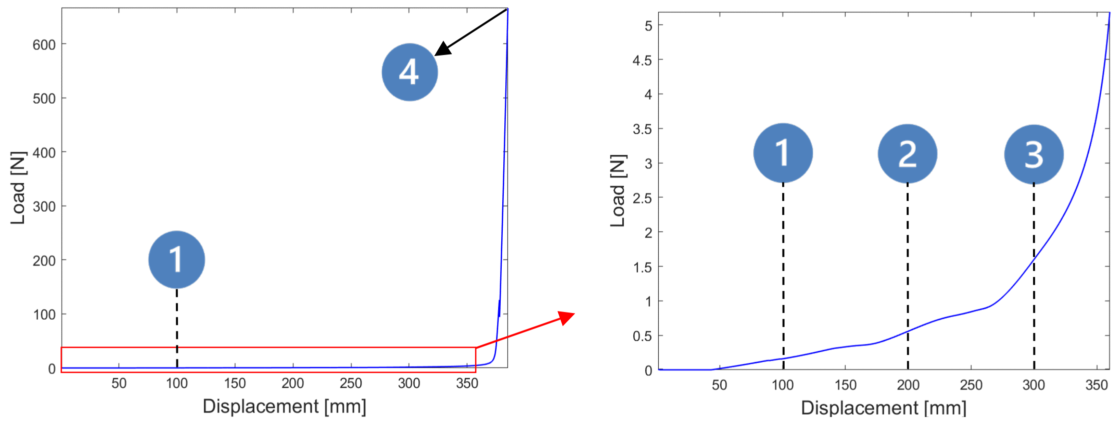

Figure 4 – Full load-displacement curve (left) and partial graph from 0 to 360 mm

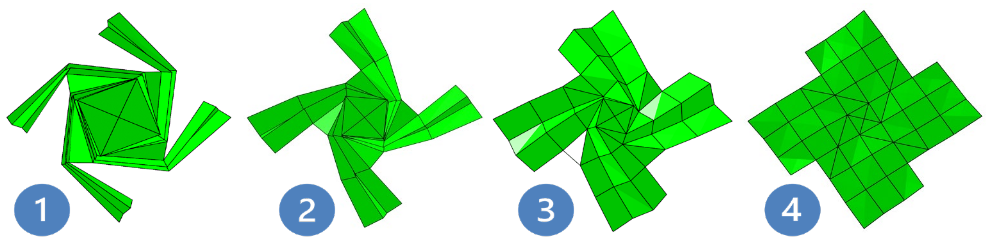

Figure 5 – Four configurations of flasher origami pattern during different phases of deployment, the numbers next to each configuration are related to the Load-Displacement curve in Figure 4

Ansys Motion

The same geometry is imported in the finite element software ANSYS Motion, with the objective of obtaining a comparison between the reduced order model and the finite-element one for validation purposes. To import a .obj geometry in ANSYS, we first import it in Solidworks, export it as a 2D geometry to the Ansys Workbench environment and successively modify it using SpaceClaim.

The material properties imposed to the ANSYS model are the same utilized for the reduced order model, with the approximation of elastic isotropic material, which is suitable for the expected large deformations and small strains. The contact constraint has been created for every panel to accurately model the interaction between the geometric elements.

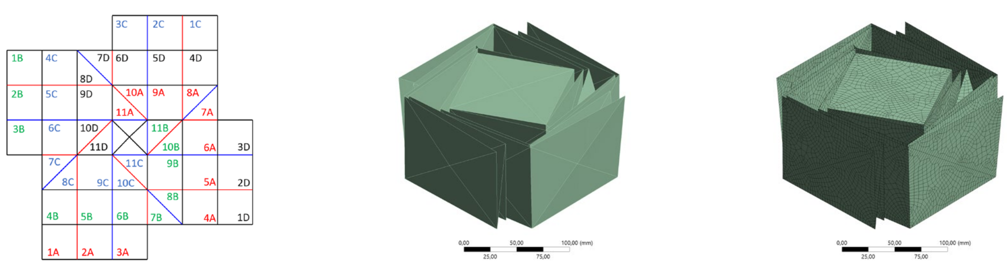

Figure 6 – From left to right: schematics used for constraints enumeration in ANSYS, geometry imported in ANSYS Workbench and geometry discretized using shell elements

The geometry in the closed configuration is renamed according to Figure 6 (left) to make the constraint-imposition process more efficient. The discretization is carried out using shell elements. All the boundary conditions and loads have been set up to create a simulation identical to the bar-and-hinge one. The main difference between the two models is the absence of folding springs in the ANSYS one, which causes zero resistance during deployment and therefore does not allow to validate load-displacement curves. As we can see, both models capture the same kinematics of deployment.

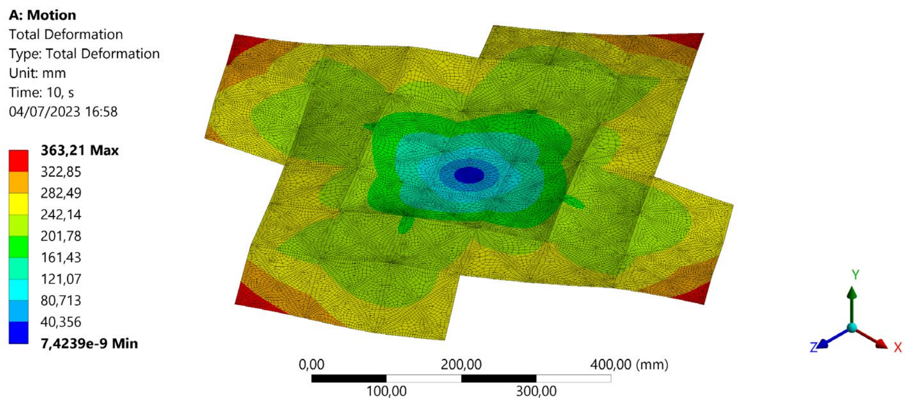

Figure 7 - Diagram of deformation in the final configuration

Conclusions and future developments

The finite element model and the bar and hinge one capture different aspects of the behaviour of the structure. FEM pursues this task through the utilization of higher-order elements, such as plates/shells or volumetric elements, with the same amount of information for the material properties under the approximation of linear isotropic behaviour. Bar-and-hinge models are an efficient tool for approximating the mechanical behaviour of origami structures. Despite their simplicity, these models can be used to capture out-of-plane bending and in-plane shearing, allowing to obtain a conspicuous amount of information with a reduced computational expense compared to the finite element models.

As a next step, we plan an in-depth analysis of the results of the two models (introducing torsional springs in the FEM as well), with a campaign of experimental tests on a physical prototype of the origami structure. This will allow a complete validation of the results, as well as the opportunity to refine the models and the material properties.

Up to now, deployment is simulated as outward radial applied displacements. To accurately capture the forces exerted on the spacecraft during deployment, we will implement a follower load in both models and change the boundary conditions by blocking rotations along the structure's axis; this should allow us to extract the moment produced on the structure during deployment – which will be useful to design the actuation device for deployment.

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