Steven R. Woodruff

A Multi-Physical Analytical Framework for Curved Crease Deployable Structures

Keywords: *curved origami, structural analysis, deployable structures, computational mechanics*

Introduction: The goal of this proposed project is to establish efficient methods for multi-physical analysis, evaluation, and application of curved crease origami structures. These three-dimensional deployables can be created by folding thin sheets about geometrically arbitrary creases. Enabling designers to implement curved folding at multiple scales could lead to new systems from reconfigurable micro-robotics, to deployable space structures, and transformative architecture. To enable this technology, an analytical framework and better understanding of their physical behavior must be developed. Thus, I will focus on three investigations: (1) creating reduced-order methods for approximating multi-physical behaviors, (2) model verification, validation, and calibration, and (3) conducting a parametric study of curved crease structures to establish a library of versatile solutions to different structural and multi-physical problems. By creating a general process for analyzing and applying curved crease structures, engineers could incorporate these elements to create reconfigurable and functional designs while maintaining *safety, efficiency, and reliability.*

Background: In the past decade, researchers have investigated how origami, the ancient Japanese art form, could be used to solve technological problems in structural engineering. For example, deployable structures following these principles can create stowable members (pertinent to the aerospace industry) and infrastructure with adaptable stiffness (useful for reducing acoustic amplification and structural vibrations). However, research has been focused on sheets with straight creases with little investigation into the multi-physical properties of curved crease origami. Traditional straight crease origami structures deploy without incurring stresses while curved crease origami inherently generates bending stresses with folding. This bending can be used to store potential energy in the structure that can subsequently be used to facilitate deployment and has the potential to greatly increase the load bearing capacity of thin sheets[1]. My ongoing research at the University of Michigan (UMich) has used finite element models to evaluate how the curved creasing of thin sheets can capture these stiffening effect[2]. The proposed work will extend the investigation to multi-physical analysis by combining structural reconfiguration with heat transfer and acoustic control.

1. Create Efficient Multi-Physical Modeling Techniques: The first aim of this proposal is to create methods for reduced-order modeling of static stress-strain, dynamics, acoustics, and heat transfer problems that can be compiled into a holistic program which can be disseminated to researchers and designers. Although finite element models of curved crease structures offer solutions to a wide range of physical problems, as these models become more complex, computational run times exceed practical limits. Thus, in order for numerical simulation of the multi-physical properties of curved crease structures to be viable, the methods must be efficient. This work will create reduced-order modeling where piecewise developable approximations[3] are used along with bar and hinge models[4]. This approach would simulate the three-dimensional geometry of the curved crease origami and would provide approximations of the multi-physical characteristics. Reduced-order modeling will make simulations efficient and accessible for a variety of multi-physical Dirichlet and Neumann boundary conditions. This analysis envelope will be compared against finite element solutions in order to optimize computation time within an appropriate margin of error.

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[1] Pini et al., *How 2D Bending Extraordinarily Stiffens Thin Sheets*, Sci. Rep., vol. 6, 2016. [2] Woodruff & Filipov, *Struc. Analysis of Curved Fold. Deploy.*, ASCE Earth & Space Conf., 2018. [Submitted]. [3] Kilian et al., *Curved Folding*, ACM SIGGRAPH, 2008 [4] Liu & Paulino, *Nonlin. mechanics non-rigid origami...*, Proc. R. Soc. A, 2017

2. Validate, Verify, and Calibrate Analysis with Physical Testing: The second aim of this proposal is to perform multi-physical tests on simple, small-scale models. The resources offered by UMich's 3D printing and visualization lab will be useful to manufacture and evaluate the deformed shapes of models. Stress-strain properties will be tested using small-force load cells already available in my research team's lab. Thermal and acoustic properties could be explored in collaboration with labs in the Mechanical Engineering and Naval Architecture departments at UMich. Results from these tests will be compared to finite element model results, and the reduced-order models will be calibrated and improved. The codes will be improved to keep computational costs low, while maintaining accuracy verified by physical and finite element models.

3. Optimize Multi-Physical Properties through HPC Parametric Studies: The third aim of this proposal will take advantage of the XSEDE supercomputer network available through the NSF to create a library of practical curved crease cases for a variety of geometric, material, and boundary condition parameters. By using high-powered computing (HPC), a sufficiently large amount of data can be collected within a realistic timespan. The data generated by the XSEDE computers will be analyzed for trends in order to generalize how different parameters affect the multi-physical behavior of curved crease structures. These generalizations will be useful to address specific problems relevant to engineers. In particular, the work will optimize stiffness for a deployable curved arch structure, find the curved crease geometry for a reconfigurable acoustic focusing device, and create an adaptive radiative heat exchanger that saves space, but deploys when needed.

Intellectual Merit: Although origami-inspired structures have been built, including those with curved creases, the full potential of deployability, energy storage, and tailorable stiffness cannot yet be realized in these designs. To enable future investigations and practical implementations that are safe, serviceable, and cost effective, *this proposal will create the necessary analytical framework for understanding the multi-physical behavior of curved crease deployables*. Efficient models validated by physical testing would further explain the behavior of these poorly understood structures. Combined with HPC, these models would be processed into a versatile library in a timely manner. The library will allow for the discovery of generalized trends which provide optimal curved crease geometries for practical application. This proposed research is one part of a concerted effort to introduce designers in the fields of aerospace, civil structures, and mechanical systems to curved crease deployables to inspire further inquiry that leads to innovative designs and pushes on the limits of structural engineering.

Broader Impacts: Curved crease origami structures are unique in their ability to be deployed automatically with adjustable multi-physical properties. The proposed analytical framework could lead to *critical technology* such as self-deploying floodgates for tunnel entrances, dynamic vibration control in motion sensitive buildings such as hospitals, or shading facades activated by heat from sunlight to cut energy consumption. I will present the results from these studies in journals and conferences so that engineers can begin to *incorporate informed design of curved crease structures* into their work. To make the results of my work broadly accessible, I will compose publications and workshops designed to *expose younger students in underrepresented groups to engineering* through artistic origami – commonly taught in elementary schools. Next summer, I plan to implement one of these workshops on curved crease origami at the GISE program at UMich, a week long program exposing middle school girls to science and engineering. During my PhD, I will continue to *mentor undergraduate researchers* with my advisor through UMich's SURE/SROP programs, exposing younger engineers to 3D printing, physical testing, and modeling of scaled origami specimens.