TEXAS A&M UNIVERSITY USES ABAQUS TO SIMULATE SELF-FOLDING STRUCTURES

The Shape Memory Alloy Research Team (SMART) analyses Shape memory alloy (SMA)-based self-folding structures

Figure 1. Examples of paper models created via origami principles.

Origami has inspired the design of engineering structures for decades. The endless variety of shapes that can be obtained by folding a planar sheet makes origami of great interest to engineers and scientists. For instance, Figure 1 shows a small spectrum of the countless shapes obtained by folding a piece of paper.

The fundamental principles of origami are universal, which has led to applications ranging from nano-scale devices to large deployable space structures. In recent years, engineers have become interested in the use of active materials, those that transform various forms of energy into mechanical work, to exert the folds in these structures. Active materials allow engineers to make self-folding structures, which are capable of executing folding and unfolding processes without being manipulated by external loads. This is valuable for many applications including remotely-operated systems (space and underwater), small scale devices, and self-assembling systems.

In this work, the focus is on the simulation of shape memory alloy (SMA)-based self-folding structures. SMAs are active materials that undergo solid-to-solid phase transformations induced by appropriate temperature and/or stress changes during which they can generate or recover seemingly permanent strains. These characteristics allow them to have several existing and potential applications in diverse fields such as aerospace, biomedical, and others. SMAs can provide a significant amount of strain (up to 10%) under large stress (hundreds of MPa), a characteristic of great utility in morphing structures.

The ***Shape Memory Alloy Research Team*** (SMART) at Texas A&M University (http://smart.tamu.edu/), led by Drs. Dimitris Lagoudas and Darren Hartl, has years of expertise in constitutive modeling of SMAs and structural analysis of SMA-based structures. An Abaqus user-material subroutine (UMAT) developed by the SMART team members of the world-renowned Texas A&M SMA constitutive model, which has evolved over the years, provides for the state-of-the-art simulation of SMA structures in finite element analysis.

Two challenges arise in the modeling of SMA-based morphing structures: the account for large rotations that arise during morphing (e.g., folding from one configuration to another), and the numerical implementation of evolution equations of variables that account for the inelastic phenomena in SMAs (e.g., martensite volume fraction and transformation strain). To account for large rotations, Abaqus provides the NLGEOM option for most types of analysis steps which provides for proper rotation of variables such as stress and strain and allows for accurate simulation of structures experiencing large rotations. Such a rotation is applied automatically for stress and strain once NLGEOM is active in the considered analysis step; however, non-scalar quantities stored as solution dependent variables in the UMAT (e.g., transformation strain tensor) have to be rotated in the UMAT code itself. To this end, Abaqus provides the rigid body rotation increment matrix DROT as an available input in the UMAT and the built-in utility subroutine ROTSIG that allows for rotation of a tensor. For shell elements where the coordinate system of the material point rotates with the structure, it is not necessary to rotate variables inside the UMAT (DROT is simply an identity matrix) and just activating NLGEOM in the analysis step suffices for the consideration of large rotations.

For the evaluation of the non-linear thermomechanically-coupled SMA constitutive equations in the UMAT, an elastic predictor/ transformation corrector framework is used. The first step in the UMAT is to rotate the non-scalar solution dependent variables using the ROTSIG utility subroutine. Then, the martensite volume fraction and transformation strain are assumed to be unchanged from the previous global iteration and the elastic prediction is performed. Analogous to classical rate-independent plasticity, a transformation surface (dependent on stress, temperature, and martensite volume fraction) is evaluated to determine if the SMA is transforming. Unlike classical plasticity, however, the SMA model has two transformation surfaces that need to be checked; one for transformation from austenite to martensite (transformation strain may be generated during this transformation) and from martensite to austenite (existing transformation strain is recovered during this transformation). If transformation is found to not occur (transformation surfaces having non-positive values), the current value of stress is provided as output. When transformation is found to occur, a return mapping algorithm is used to correct stress, transformation strain, and martensite volume fraction to ensure that the transformation surface value goes to zero (or in practice close to zero within a given tolerance). Proper tangent matrices of stress with respect to strain and temperature (DDSDDE and DDSDDT in the UMAT, respectively) have been derived and are implemented in the UMAT to ensure fast global convergence of the solution. For more information about the SMA constitutive model and its numerical implementation, the reader is referred to: Lagoudas, D., et al. (2012). Constitutive model for the numerical analysis of phase transformation in polycrystalline shape memory alloys. International Journal of Plasticity, 32, 155-183.

The team exploring origami-inspired SMA structures at Texas A&M is led by professors Darren Hartl (Aerospace), Dimitris Lagoudas (Aerospace), Richard Malak (Mechanical), Ergun Akleman (Visualization Architecture), Nancy Amato (Computer Science), and Daniel McAdams (Mechanical). They consider a self-folding composite laminate that has three layers. The two outer layers are composed of pre-strained thermally activated SMA wires in an orthogonal mesh pattern while the inner layer of the laminate is composed of a thermally insulating and compliant elastomer. When either side of the laminate is heated in a line-like region up to a certain SMA transformation temperature, the SMA wires begin recovering the pre-strains and contract, generating a fold at the heated line in the direction of the side being heated.

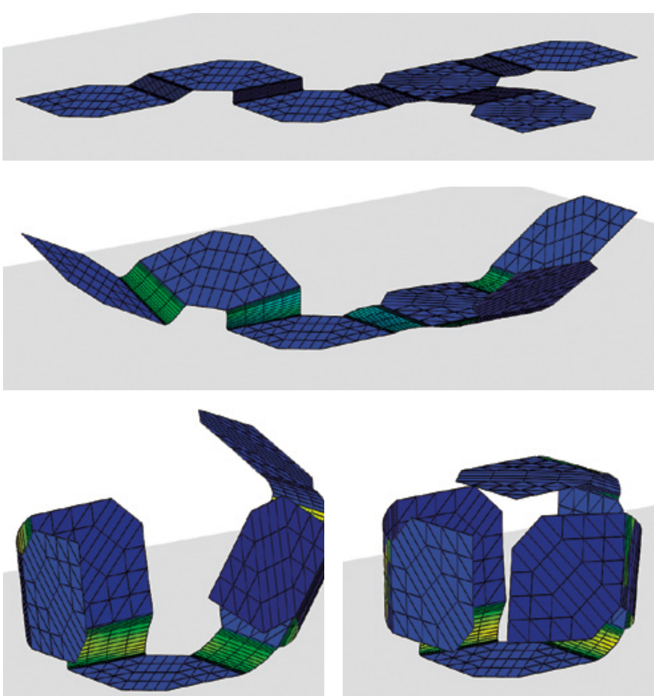

Figure 2. Finite element analysis results considering the thermally induced morphing of an SMA-based laminate sheet shaped to self-fold into a cube. The contour plot indicates local phase transformation progress, a state variable provided by the SMA UMAT.

"Without the capabilities provided by Abaqus, I cannot imagine tackling such a complex structural analysis problem. From the underlying hysteretic material behavior to local instabilities to self-contact, we truly aim to test the limits of the software as we explore this exciting new area."

– Darren Hartl, Ph.D. , Texas A&M University

The generation of the sheet geometry and fold patterns is a challenge that involves multiple disciplines. Such a challenge has been addressed by the collaboration between engineering and architecture/visualization. Dr. Ergun Akleman, professor in the Visualization department at Texas A&M University, is part of the team that works on the study of SMA-based self-folding sheets.

Dr. Akleman and his research group have developed several algorithms and programs to provide engineers with appropriate geometries and fold patterns for origami design. In addition of generating the sheet geometry and fold patterns, Drs. Akleman, Hartl, Lagoudas and their students have developed Python scripts and .inp files to import such sheets into Abaqus for analysis. The .inp files contain the information of the mesh, which can be subsequently refined or modified in Abaqus if desired, as well as element and node sets corresponding to the fold heating regions for convenient element and node selections during the application of boundary conditions.

One of the works includes an algorithm for unfolding and folding of polyhedra. Figure 2 shows an Abaqus finite element simulation of a self-folding cube which geometry was generated using such algorithm (the sheet is modeled with Abaqus S4, S4R, and S3 elements, a composite section is used). The contour plot shows martensite volume fraction (a state variable in the aforementioned SMA UMAT) which ranges from 1 (100% pre-strained martensite) to 0 (100% austenite, a phase in which all the transformation strain in the SMA has been recovered).

The non-linear hysteretic behavior of SMAs as well as structural instabilities such as local buckling at certain regions of the self-folding sheets during the folding/unfolding maneuvers add more difficulty to the execution of these studies. Abaqus

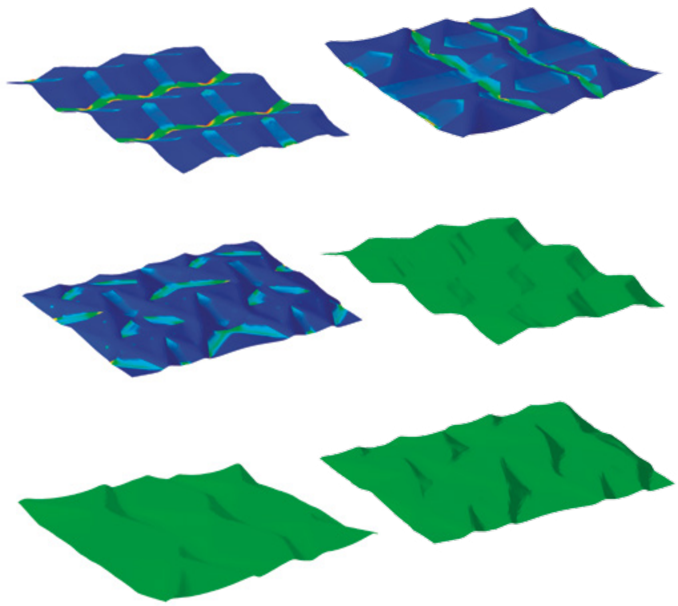

Figure 3. Martensite volume fraction contour plots and shaded shape deformation plots from Abaqus after analysis are presented.

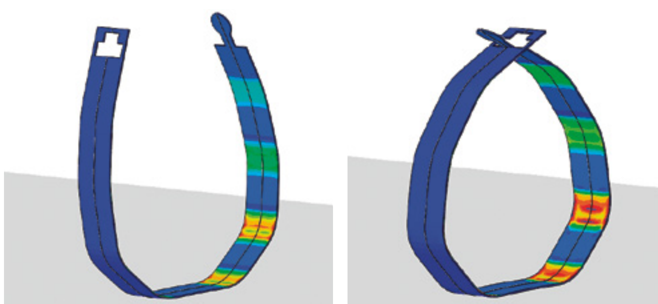

Figure 4. Maneuver towards folding a ring-shaped structure with a tab and slot connector. When the sheet is cooled the tab slides into the thin slot region and the two ring ends connect. Contour plot indicates local phase transformation progress.

features such as geometrically non-linear simulation, contact, and implicit dynamic analysis procedures, along the with UMATs developed by Texas A&M researchers, made this kind of simulations possible. Most of the Abaqus finite element simulations of SMA origami structures at Texas A&M have been performed by Edwin Peraza Hernandez, a Ph.D. student in Aerospace Engineering.

In addition to the use of in-house tools, the team has also explored freely available origami design tools, such a Tomohiro Tachi's Freeform Origami (http://www.tsg.ne.jp/TT/software/). A Python-based script for the importation of Freeform Origami crease patterns into Abaqus has been developed. First, the folding pattern is exported from Freeform Origami as a Drawing Exchange Format (.dxf) file. It contains the considered folding pattern in the form of a line drawing. The .dxf file is then imported into Abaqus as a line sketch. Afterwards, the sketch is oriented, scaled, and positioned into a sheet which dimensions are defined by the user. Next, the folding lines are thickened to create heating areas at the location of the folds. Subsequently, the heating areas are classified as mountain or valley folds. The final step entails the discretization of the sheet into finite elements. Material properties and boundary conditions are added after the importation process is finalized. Examples of fold patterns generated by Freeform Origami and imported and analyzed in Abaqus are shown in Figure 3. It should be noted that although the SMA cannot provide sharp folds (as in creased paper) due to stress constraints, it provides significant curvature at the folds such that the obtained foldcore approximates the desired shape as shown in Freeform Origami.

For self-folding structures created with the SMA laminate, it is inefficient to hold permanent heating at the actuated SMA regions to preserve the shape of the folded structure. Connectivity systems have also been proposed to prevent this permanent heating. Various designs for connectivity systems have been explored via finite element analysis in Abaqus. An example is shown in Figure 4 where the connecting maneuver of a self-folding ring with a tab and slot connector is explored. This problem entails non-linear boundary conditions involving normal contact and tangential friction in the interaction at the tab and slot connection. Abaqus and its multiple options for simulation of contact were essential for these simulations.

The experimental validation of the finite element simulations is essential. To this end, Aaron Powledge, Darren Hartl, and Richard Malak used Digital Image Correlation (DIC) techniques to explore the deformation of experimental samples of the SMA-based self-folding sheet. Finite element models have been created in Abaqus for comparison with experimental data and validation of the finite element approach.

For experimental samples, the overall curvature is found by averaging the curvature of multiple points on the sheet, either on the entire sheet or in local sheet regions (to avoid including regions where sheet defects affect the local radius of curvature). Table 1 shows that the radius of curvature predicted by the finite element model is in good agreement with experimental data that was obtained using different approaches.

There are multiple other efforts in the simulation of SMA-based self-folding systems, for more information visit http://origami.tamu.edu/. This work is supported by the National Science Foundation and the Air Force Office of Scientific Research under grant EFRI-1240483 and the finite element analysis was performed using a research license granted by Simulia to Texas A&M University.

For More Information

http://smart.tamu.edu