

Design and Numerical Study of Origami-Inspired Structures for Axial Compression and Energy Absorption in Crashworthiness Applications

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Abstract—Recently origami inspired structures have become of great interest because of their potential to provide lightweight, deployable, energy absorbing structures for impact mitigation in the automotive and aerospace industries. This study illustrates a numeric computational framework utilizing Rhino with Grasshopper for parametric origami CAD modeling, and Ansys Workbench to perform finite element analysis of origami structures in axial compression. Origami patterns, including Miura-ori and Kresling patterns, were modeled and tested using axial compression to characterize load bearing capabilities, deformation mechanisms, and energy absorption efficiencies. Simulation results show that both Miuraori and Kresling patterns are able to resist peak loads and dissipate energy more effectively than structures of greater simplicity due to their stable concertina deformation modes. The study suggests that origami geometries can be calibrated to improve crashworthiness performance and demonstrates their applicability for lightweight crashworthy components. This study contributes significant insight for the optimization and future fabrication of origami-based energy absorbers for use in impact zones.

Keywords— Origami Structures, Miura-ori, Folded TPU, Flat TPU, Stress, Deformation, Flexibility, Stiffness, Energy absorption, ANSYS simulation.

I INTRODUCTION

A variety of origami-based engineering systems have been discussed or studied because they can provide high strength-to-weight ratio, have

foldability, and are energy absorbers for applications in automotive crash safety and aerospace structures. These systems use geometric design principles that are found in origami of the past to develop novel, lightweight, and collapsible components that have

an inherent ability to be resilient when compressed axially. Origami designs, specifically the Miura-ori and Kresling, have again been noted for their unique mechanical properties and their ability to be incorporated into systems designed for impact mitigation or crashworthiness. This project will assess the mechanical properties of a few different origami geometries under an axial compression load through experimentation. Focus will be placed on the load-displacement response, deformations modes, and energy absorption performance of the various geometries. The research will lead to the design of next generation crashworthy structures that have low density with high performance energy absorption capacity.

II LITERATURE REVIEW

There are numerous studies outlined in volume suggesting the mechanical versatility that can be achieved with origami-based geometries. Jiayao Ma et al. [1] have proposed structures with graded stiffness based on the origami to assure that origami enables a tailorable stiffness response, along the axis of compression. Xiang, Lu, and You [2] provided evidence of the substantial energy absorption that several origami inspired materials provided when compared to traditional materials when subjected to axial and impact loading. The performance of Kresling origami structures

physical principles where Moshtaghzadeh and Mardanpour reported that multi-story origami formats can dissipate energy and provide scalable crash protection. Continuing the work, Leanza et al. reported functional origami utilizing smart materials to achieve adaptive deployment and response [3].

Gattas and You [4] parameterized curved-crease origami geometries, allowing for exact precision to fold and deform. Liu et al. [5] connected the areas of materials science and origami by demonstrating how the material properties and folding patterns play critical roles in the overall stiffness and mechanical response of the origami structure. Origami engineering has also been collaborating with the biomedical field, as highlighted in Johnson et al.'s review, and with programmable and shape changing materials via active materials [6].

Comprehensive overviews by Fonseca et al. and Mou et al. discussed how pattern geometry, scaling, and material selection affect global deformation and energy absorption in origami systems [7,8]. Miuraori, Kresling, and Miura-derivative folded patterns have been dosed as mechanical metamaterials and performance for energy absorption [9,10].

Chen et al. and Zhou et al. [11,12] have compared the design of the geometric and kinematic mechanisms through which such foldable patterns have been used for effective engineering performance. Foundational work of Lu and Yu and more recently by Song et al. and Ma and You makes it clear that a few origami pre-folds can greatly enhance the energy dissipation profile of thin-walled and square tube structures under axial crushing type loading [13],[14],[15].

Collectively, these works provide significant evidence supporting origami-based systems for energy absorption, protection, and recognition of fabrication and scale-up as continuing obstacles to our realworld use of these systems.

III METHODOLOGY

The research approach used in this research can be generalized into two key stages:

1) Computation design of origami-inspired structures, and

2) Numerical evaluation of the crashworthiness and energy absorption characteristics of the origami-inspired structures.

1. Computational Origami Design with Rhino + Grasshopper

In order to create accurate and parametric models of the origami patterns selected, Rhino 3D software was used together with the Grasshopper visual programming plug-in. The origami geometries for the Miura-ori were modeled by defining the fold lines (mountain and valley folds) as curves and manipulating the mesh geometry within Grasshopper. Using custom scripts and available plug-ins (Crane to run simulation of folding kinematics) allowed for accurate construction, modification, and visualization capabilities into the design capabilities of foldable structures Figure 1.

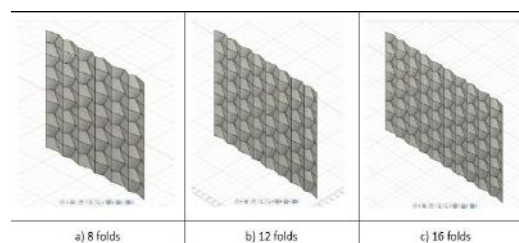


Fig. 1: Origami CAD

2. Finite Element Analysis Using Ansys Workbench

The digital models which had been created in Rhino + Grasshopper were transferred from an appropriate format (e.g., STEP or IGES) and transferred to Ansys Workbench for simulation. In Ansys, the origami geometries were each meshed appropriate to thin-walled structures, thus creating an accurate representation of fold lines, and facets. The axial compression tests were simulated by applying boundary conditions and displacement-controlled loading to the models, where material properties were assigned based on actual test materials (e.g., small sheets of thin aluminum or TPU). The results were then analyzed flexibly to extract metrics such as peak load, deformation patterns, energy absorbed during compression. Ultimately, the analysis provided a systematic way to quantitatively compare different origami geometries to determine performance, such as suitability for impact reduction, based on loadbearing and energy absorption performance.

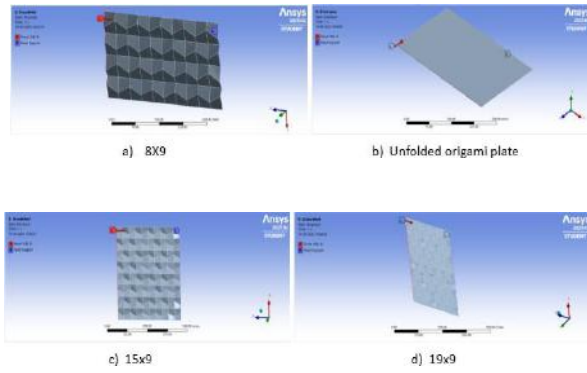


Fig. 2: Force Applied and fixed support for miura origami and flat plate

Figure 2. represents the simulation setup for the Miura-ori structure within a different folding pattern and unfolded configuration, modeled and analyzed in ANSYS. The upper images are basic geometric configurations of the origami sheet, where alternating

mountain and valley folds are repetitively arranged in a periodic tiling pattern. This structures the fundamental symmetrical and flexible aspects of the Miura-ori designs. The lower images are boundary conditions applied for running the simulation. One edge of the sheet is fixed to represent a stationary support, while a force is applied on the opposite edge, representing loading and monitoring structural response. This configuration can mimic actual mechanical surroundings like stretching, compression, and deployment. As discerned from the deformation configurations, the Miura-ori structure would largely deform along its fold lines, keeping the structure high in rigidity while accommodating high flexibility.

IV RESULTS

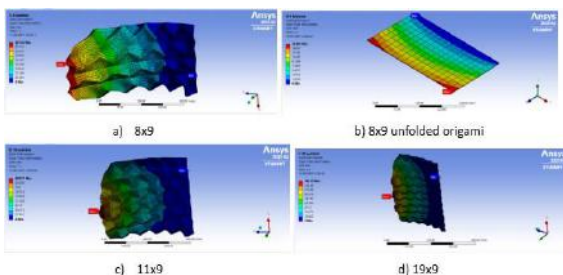


Fig. 3: Total deformation for fold origami

The Figure. 3 shows the overall deformation response of the fold origami framework subjected to various loading conditions through ANSYS analysis. Each of the four subfigures shows deformation behavior that is different because they detail a different perspective or load condition. The origami folds in each subfigure demonstrate how they will behave in response to applied, loading forcing. The color indicating the distance of deformation, represents semiconductor analysis results, in which blue is the lowest distance of deformation, and red is the highest distance of deformation. From the images, it is apparent that deformation next to the highest loading, or around stress potential concentrations, deforms the most while the rest of the structure will deform less. This visual analysis will help to conceptualize the overall mechanical behavior of origami-inspired structures. Understanding the mechanical response is critical in discerning where structure may require additional reinforcement or have opportunity for optimization to provide structural integrity when it is loaded.

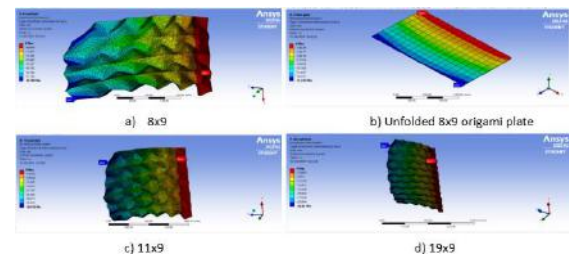


Fig. 4: Directional deformation for miura origami

This figure.4 shows four simulation outputs from ANSYS representing the structural analysis of a geometrically complex surface under varying forms of loading or boundary conditions. Each subplot contains a color contour showing the von-Mises-stress distribution, which can be important for determining yielding of material under load. The stress values are color coded from very low (blue/green) to very high (red) and indicate the deformation or how stress is taken up over the surface of the structure. The first two images seem to show the deformation from the front and rear, while the bottom two images show a side or angled view; together they provide a full view of spatially how stress is distributed on the structure. The usage of software from an ANSYS Student version seems to suggest this was performed as an academic

project. The figure gives a good overall picture of how geometry and loading affect stress distribution in the structure, which is valuable for evaluating mechanical performance.

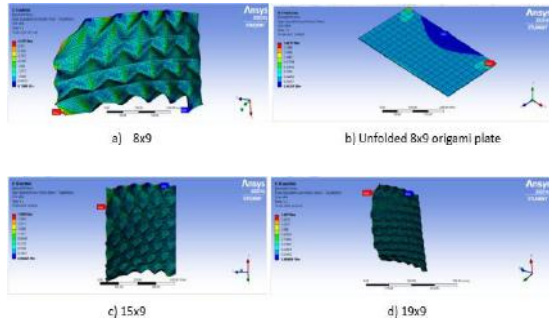


Fig. 5: Equivalent stress for miura origami

Figure 5. shows four perspective views of a finite element analysis (FEA) completed in ANSYS on an origami structure of Miura-ori with an 8x9 tessellation pattern. The information displayed is the equivalent (von Mises) stress that the structure is showing under some applied loading or deformation case, which allows the engineer to see how the structure

mechanically behaves overall. The Miura origami is a lightweight, t-foldable origami type, and its uniquely folded geometry results in more interesting areas of concentration related to stress levels. The figures use color contours from blue to red (low stress/ high stress) to indicate the level of concentration in areas of interest that could potentially fail under stress. The four subplots likely demonstrate different perspectives (front/front, top side) or loading cases to allow for a complete understanding of loading and stress distribution throughout the structure. Overall, this schematic demonstrates very clearly the stress response of a Miura-ori pattern, which could potentially be beneficial to applications related to deployable structures, aerospace, and mechanical metamaterials. Similarly, simulations were performed for plates of varying dimensions to represent different sizes of the origami structures. Finite Element Analysis (FEA) was carried out in ANSYS Workbench to evaluate multiple Miura-ori origami geometries under diverse structural configurations and loading conditions. These simulations aimed to investigate how geometric scaling and folding patterns influence mechanical

behavior, particularly in terms of deformation response, stress distribution, and energy dissipation. The results demonstrated that variations in the plate dimensions and fold angles significantly affected the crashworthiness and energy absorption efficiency of the structures. Larger geometries tended to exhibit higher deformation capacities, while optimized fold patterns enhanced the stiffness-to-weight ratio, providing better impact resistance. Overall, the analysis confirmed that the Miura-ori design parameters play a crucial role in determining the performance characteristics of origami-inspired energy absorbers.

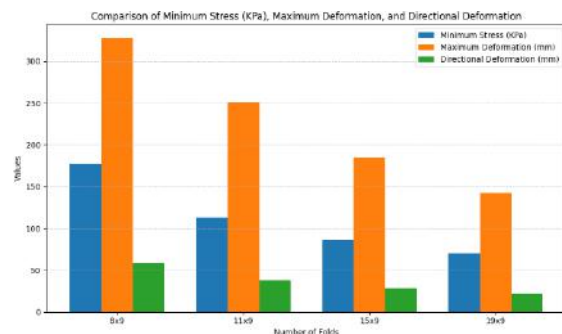


Fig. 6: Miura origami

In Figure 6, the minimum stress (KPa), maximum deformation (mm), and directional deformation (mm) of four separate fold configurations of a TPU material, specifically 8x9, 11x9, 15x9, and 19x9, are displayed at a constant applied force of 500 N. It is evident from the results witnessed that with each fold configuration, all three parameters decrease with each configuration. The 8x9 configuration has the best minimum stress whilst this value declines for configurations with increasing folds. The better stress is clearly visible in the first couple of folds, supporting the idea that structures with fold configurations distribute stress better when increasing fold counts. Furthermore, the maximum deformation and directional deformation both decrease for each increasing fold count which illustrates better stiffness and resistance to deformation with folds. To summarize, the bar chart provides evidence that by increasing folds will improve your structural performance due to having lower stress concentrations and less overall deformation.

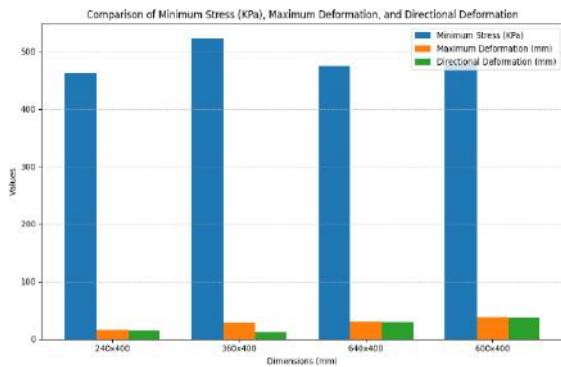


Fig. 7: Flat origami

Figure 7. illustrates the structural performance of different plate sizes (240x400, 360x400, 640x400, and 600x400 mm) in terms of the three engineering parameters: minimum stress (KPa), maximum deformation (mm), and directional deformation (mm). Notably, it is interesting to observe that the 360x400 mm plate demonstrates the greatest minimum stress at approximately 520 KPa, while all the plates show comparable low (under 40 mm) maximum and directional deformation. These results demonstrate that even though stress is significantly different with respect to different plate sizes (with the 360x400 mm the most according to the results) the deformation values were consistently low with respect to all plate sizes indicating good structural stiffness for each of the tested plate sizes.

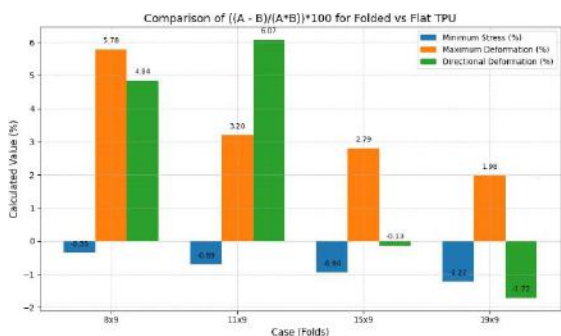


Fig. 8: folded vs flat origami

Figure 8. demonstrates the percentage difference of each of the measured minimum stress, maximum deformation, and directional deformation for Folded and Flat TPU samples in investigation of four different folding cases (8x9, 11x9, 15x9 and 19x9) comparison. Folded TPU acts with a lower minimum stress (negative values) than Flat TPU exhibiting improved distribution of stress. The Folded TPU sample has increased maximum deformation and directional deformation with the

first two fold cases (8x9 and 11x9), suggesting the sample has great amounts of flexibility. However, observation of these deformation behaviors decreased for larger fold count (15x9 and 19x9). Subsequently, the deformation values changed to either less positive or negative suggesting less deformability and an increased stiffness. In the overall view, the greatest and optimal differences were within the tests that were moderately folded (8x9–11x9), while the extreme folded cases had extra folding that tapered off any benefits associated with folding, while contributing to less deformation.

V CONCLUSION

The simulation outcomes from ANSYS validate that structures having rotatable origami forms, and especially Miura-ori and functionally graded fold patterns, show excellent crashworthiness and energy absorption when subjected to axial compression. The load-bearing response capability or energy absorption characteristics can be tailored through changes in geometric parameters or to modify the structural configuration to meet a given design requirement.

The evaluations conducted under axial compression show that origami-based multifold structures deform significantly greater, and thus exhibit greater energy absorption than flat plates of the same base dimensions and constituent materials.

For example, the 8-fold origami deformed on average to 89.8 mm, which is nearly 12 times greater than the 8-face flat plate that only produced 7.4 mm of deformation, with maximum deformation (peak readouts) being nearly 20 times greater. The 12-fold origami deformed, on average, to 60.6 mm, which is roughly 4.4 times greater than the deformation measured for the corresponding flat plate at 13.7

mm. The 16-fold origami deformed to 45.8 mm, which is 2.5 times greater than the deformed length measured for the flat counterpart that only produced 18.5 mm.

These results clearly demonstrate that superior compliance and energy absorption characteristics, based on the load response, have been delivered via the use of origami geometries when under axial loading. The lower density of folds (in this case, the 8-fold designs) leads to significantly greater deformation and absorption potential. When higher

density folds are used (whether it be the 12 or 16-fold origami designs) the resulting imposition causes the structural assembly to stiffen, leading to lower resultant deformation over the same distance. By contrast, flat plates remain comparatively rigid, with displacements limited to under 40 mm in all cases.

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