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Analysis of Sandwich Structures with 3D-Printed Kresling Origami Cores

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Lightweight structures with bioinspired metamaterials, with their uniquely engineered properties not found in naturally occurring materials, have garnered significant attention for their potential in various engineering applications. This study explores the mechanical behavior of sandwich plate structures utilizing the Kresling origami pattern, fabricated through a straightforward 3D printing process. By conducting 3-point bending and compression tests, as well as simulations with Abaqus software, the research investigates the distinctive mechanical properties and performance enhancements these origami-inspired structures offer under mechanical loading. This study is noteworthy for being the first to investigate the bending characteristics of sandwich structures utilizing the two cell Kresling pattern or double Kresling, an area that has not been previously explored. Utilizing the Kresling structure in sandwich panels poses a challenge due to its rotational behavior. To address this, we employ a double Kresling pattern, which confines the rotation to the middle layer. This approach ensures that the outer layers remain stable, maintaining the overall integrity of the sandwich panel structure during deformation under mechanical loading. The findings reveal that the 3D-printed Kresling origami core significantly reduces weight while maintaining structural integrity, making it especially beneficial for aerospace engineering, where lightweight yet strong materials are crucial. This research highlights the potential of Kresling-patterned sandwich plates to improve efficiency and performance in supersonic vehicles, providing valuable insights into their structural efficiency and applicability in advanced engineering fields.

Keywords: Metamaterial, Mechanical behavior, Kresling structure, Lightweight Structure

I. Introduction

In recent years, engineers have focused their interest on origami structures and their intriguing characteristics. Features such as lightweight and portability, reduction in the number of manufacturing components, reduced assembly time, and deployability make these structures particularly valuable in various fields, including aerospace engineering. In aerospace, the deployability, lightweight, and portability of origami structures, combined with adequate stability, play a crucial role in the design of mechanisms and products. To date, several aerospace products utilizing origami structures have been developed and deployed, such as deployable solar panel arrays and innovative telescopes, demonstrating the practical application of these materials [1–3]. In addition, origami's historical origins in the art of skillfully folding paper, recognized since the 18th century due to Japan's cultural influence, have evolved significantly beyond its traditional boundaries. The folding and compression behavior, often observed in nature, can also be found in the spontaneous folds

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of origami [4]. Currently, origami inspires the design of deployable structures, such as the ingenious sunshield used on the James Webb Telescope, and has captured the interest of researchers in various disciplines, leading to developments in origami core sandwich panels [5], foldable robotics [6], and the synthesis of DNA nanoparticles [7]. Figure 1 (a) and (b) illustrate natural and bioinspired structures that resemble origami.

In sandwich structures are composite structures comprising two face sheets known as skins, with a core material sandwiched between them. An adhesive bonding layer secures each skin to the core material, ensuring that the components cohere and function as a unified element. Fig. 1 (e) illustrates a sandwich structure that we used in our study. Generally, skins are made from a composite metal that is both strong and stiff, while the core materials are chosen to minimize weight while still providing the necessary stiffness. Lightweight core materials, such as foam blocks, are used when weight reduction is a primary concern, whereas metal honeycomb structures are selected for their superior compression and shear strength. Sandwich structures are widely used in aircraft bodies and wings of aircraft to reduce weight, leading to benefits such as increased fuel efficiency, greater payload capacity, and enhanced structural integrity [8–10]. Research into alternative core materials is driven by the extensive use of sandwich structures in aerospace. The origami architecture represents one of the most promising advances in this area. The properties of origami structures can be customized through the manipulation of joint properties and folding patterns, making them inherently lightweight with substantial voids that can accommodate fluids, cooling systems, storage, and aerospace-specific sensors and actuators. However, the application of origami as the core in sandwich structures poses significant challenges due to the current lack of understanding of mechanical instabilities and the relationship between architectural design and material properties under quasi-static loads [11, 12].

Various origami cores for sandwich structures have been studied in the engineering field. Origami structures are lightweight, and all properties can be entirely tuned using joint properties and fold patterns. However, employing origami as the core for sandwich structures poses challenges due to a lack of understanding of the mechanical instabilities, failure modes, and complex architecture-property correlations under quasi-static and transient loads in such settings. The past decade has seen an increased interest in origami-inspired engineering. It has been demonstrated that foldable and spatially expandable structures with unconventional Poisson's ratios, which have rich kinematics and tunable kinetics, can be created using origami patterns [16]. One leading origami pattern in engineering research is the Miura-ori, which has been applied in metamaterials [17], solar cells [18], artificial muscles [19], and soft robotics [20]. Other popular folds include the Ron Resch [21], origami based square waterbomb [22], and Kresling patterns [23].

The Kresling origami fold has shown great promise from current research and development on it. It is generated by the twisting and buckling of a cylinder to make it compressible and expandable [24]. Researchers have examined the Kresling pattern in various studies, including load displacement testing [25], equilibrium and spring behavior analysis [1], and its application in cryogenic technology [26]. The Kresling origami fold is comprised of a series of adjacent triangles. Notably, the Kresling fold is of particular interest due to its non-rigidly foldable nature, necessitating the bending and stretching of facets for compression of the structure [26]. Fig. 1 displays the geometry of the Kresling fold employed in this paper [27]. The Kresling can be folded based on side length s, number of sides n, and angles α and β. Research has provided evidence of bi- and tri-stability in Kresling paper structures, as well as advancements in 3D printer and polymer fabrication techniques [26] and their restoring load behavior [1]. It is crucial to note that the behavior of the Kresling depends on the folds of the structures [16].

Previous studies on the Kresling structure are essential for validating our fabrication process and comparing the Kresling behavior with previously fabricated polymer samples. In a recent study, the Kresling pattern was utilized to design springs with nonlinear and tunable behavior, termed Kresling Origami Springs (KOSs) [28]. When axial loads or torque are applied, the KOS stores energy through deformation and releases it when unloaded, making it useful in various engineering structures. Many research applications have employed the KOS, such as in vibration isolators [29], tunable truss structures [30], and modular robotics [31]. A popular method for fabricating Kresling origami structures involves using additive manufacturing (3D printing). Overall, significant research has been conducted on various origami patterns for their application as structures in engineering. This study aims to contribute to research in fabricating and testing origami structures, focusing particularly on the compression behavior and three-point bending response of the Kresling pattern. Utilizing TPU-based single material manufactured through a low-cost printing technique using fused filament fabrication (FFF), the research explores the feasibility of using the Kresling pattern as a core in sandwich structures. This investigation not only provides inspiration for further testing and research into sandwich structures but also addresses the unique design challenges associated with the Kresling pattern. Additionally, this research seeks to enhance our understanding of the mechanical behavior of the Kresling pattern with potential applications in aerospace, particularly in the development of products for hypersonic vehicles. Through a comprehensive examination, we aim to contribute valuable insights into the potential use of these structures in advanced engineering applications.

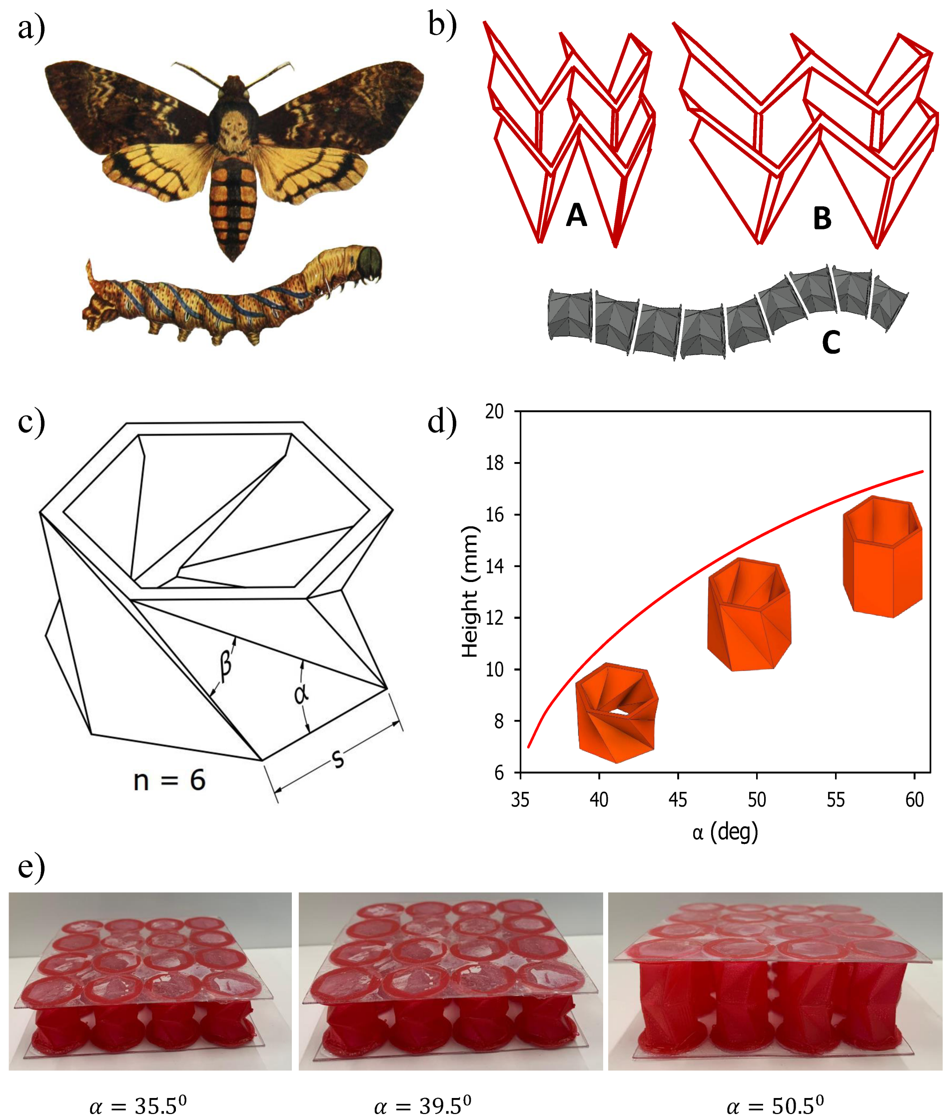

Fig. 1 a) Hawk moth (top) and caterpillar (bottom) [13] b) intima of abdominal ait sac in hawkmoth (A & B) [14] and bioinspired origami structure [15] (C) c) schematic of Kresling, d) change of height with the variation of Kresling internal angle α and c) three different experimental Kresling sandwich samples with different angle α with side lenght $s = 10mm$ and $\beta = 29.5°$.

II. Methodology

This research focuses on the design and fabrication of sandwich structures incorporating Kresling origami cores, which are known for their unique mechanical properties and potential for high strength-to-weight ratios. The study involves a comprehensive experimental approach that includes the fabrication of double Kresling origami cores using by single step with 3D printing techniques with Thermoplastic Polyurethane (TPU), one of the low cost fabrication techniques. The fabricated samples exhibit desirable flexibility, enabling the origami to fold without fracturing. These Kresling cores are then integrated into sandwich structures with PET plastic sheets used as the outer panels. We fabricated three different sandwich structures with varying angles α, while keeping all other geometric parameters constant. In Fig. 1, part (a) illustrates the schematic of the Kresling geometry, while part (b) demonstrates how the height of the Kresling structure changes with the changes of α. This study primarily focuses on the effect of changes in angle α on the bending and compression behavior of these three sandwich panel structures. Mechanical testing, compression and three-point bending tests, is conducted using an MTS machine to evaluate the performance of these sandwich structures. The focus of the mechanical testing is to analyze the bending behavior of the Kresling origami cores under load, identifying characteristics such as linear spring (LS), non-linear spring (NLS) and quasi-zero stiffness (QZS) behaviors. These tests provide critical data on how the origami cores respond to bending forces and their potential advantages in practical applications.

A. Preparation of Test Samples

For the preparation of these Kresling origami samples, we initially developed a 3D CAD model using a CAD modeling tool. This CAD drawing was then converted into an STL file format, which is suitable for 3D printing. After 3D printing the samples, each single Kresling structure was reinforced with PET plastic at the top and bottom to prepare it for tensile testing. This single Kresling unit was primarily used to determine the material properties using FE simulation software (ABAQUS). To create the sandwich panel structure, we glued the Kresling unit onto a PET plastic plate. Finally, it was left overnight to ensure the glue set properly, preparing it for subsequent compression and three-point bending tests. For our sample, we exclusively utilized TPU as the material for 3D printing. The geometry of the sample was designed with a side length ($s = 10$ mm) and configured into a regular hexagonal shape. Additionally, we set the angle β to 29.5°. For three different samples, the values of α were 35.5°, 39.5°, and 50.5° respectively. The height of the sample varied according to the specified equation and as illustrated in Figure 1(b).

B. Experimental Procedures

For the experimental tests, we used the MTS criterion with a sample rate of 0.5 mm/s for both the compression and three-point bending tests. In the three-point bending test, the rollers were spaced 72 mm apart, with force applied through the top roller. A 250 N load cell was used for all tests, and total displacement was applied up to approximately 25 mm for each sample. The undeformed and deformed states of the samples for three pint bending are shown in Fig. 2: (a) for $\alpha = 35.5°$, (b) for $\alpha = 39.5°$, and (c) for $\alpha = 50.5°$, respectively.

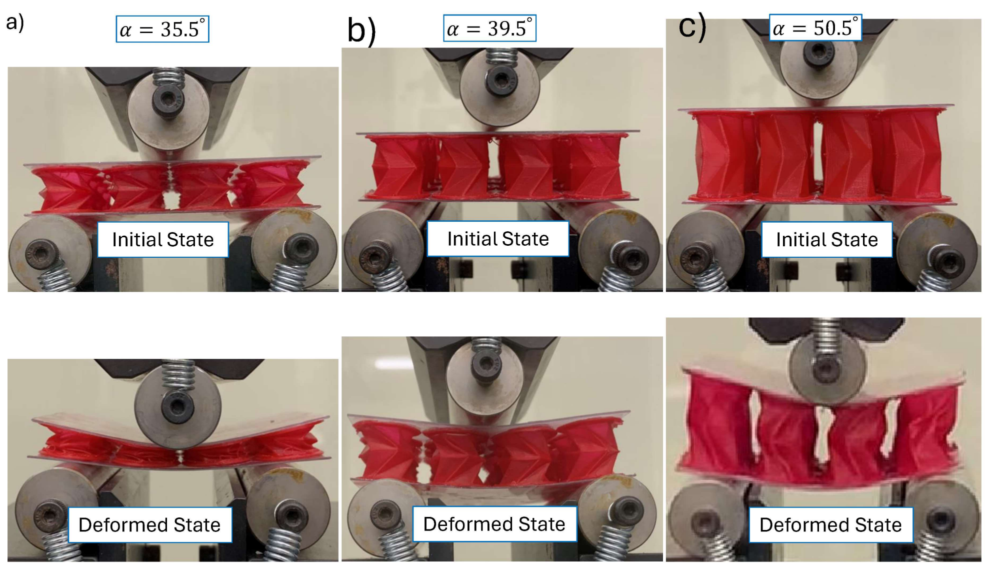

Fig. 2 Initial and deformed shapes of the Kresling sandwich sample for the bending test for three different angles: (a) $\alpha = 35.5°$**, (b)** $\alpha = 39.5°$**, (c)** $\alpha = 50.5°$**.**

C. FE Simulation Approach

We use the commercial finite element (FE) software Abaqus/CAE 2021 (Dassault Systèmes) for validation. This FE model is developed to compare the experimental results with those obtained from the three-point bending experiment. The FE simulations are carried out in Abaqus/CAE (Dassault Systèmes), maintaining all the dimensions and loading conditions of the scale-covered plate identical to the experimental tests for all three test samples.

Initially, we conducted a mesh convergence study to determine an appropriate mesh size for the simulation. A

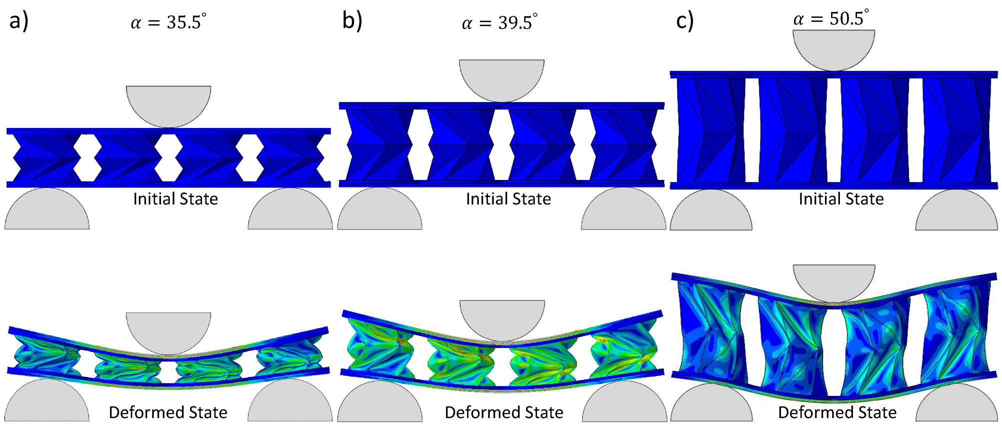

Fig. 3 Initial and deformed shapes of the Kresling sandwich sample for the 3-point bending FE simulation in three different angles: (a) $\alpha = 35.5°$**, (b)** $\alpha = 39.5°$**, (c)** $\alpha = 50.5°$**.**

sample with $\alpha = 50.5°$ was used for this study. The simulations were performed with a fixed modulus of elasticity and Poisson's ratio, while varying the mesh sizes. The mesh sizes tested were 1.5, 1, 0.75, 0.6, and 0.5, with the results shown in Fig. 4.

After evaluating the time efficiency and accuracy of each mesh size, we found that a mesh size of 0.75 provided the optimal balance between accuracy and computational time. This mesh size was therefore used in all subsequent simulations. With the optimal mesh size determined, we conducted numerical simulations to identify the material properties of the Kresling structure. These simulations were set up for $\alpha = 50.5°$ with a mesh size of 0.75. Subsequently, we varied the material properties in the simulations to accurately characterize the structure's material behavior. Ultimately, we determined the material properties of the Kresling structure, identifying the modulus of elasticity as $E = 32$ and the Poisson's ratio as $\nu = 0.35$. The resulting plot is shown in Fig. 4.

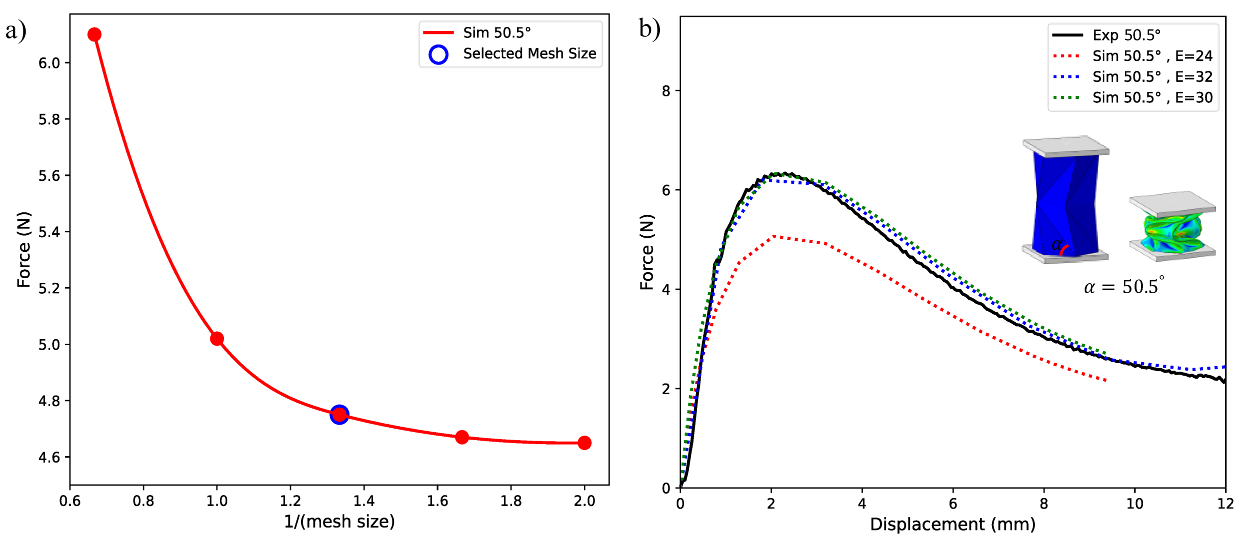

Fig. 4 Determination of material properties: (a) Mesh convergence study for the sample with $\alpha = 50.5°$ **showing the selected mesh size used for all numerical results; (b) Numerical and experimental force-displacement plot for the compression test of a single Kresling with** $\alpha = 50.5°$**, evaluated with varying Young's modulus values.**

III. Results and Discussion

Fig. 5 illustrates the impact of wall thickness on the force-displacement behavior of the Kresling structure. As observed, the mechanical behavior is almost consistent across the three measured thicknesses, with the distinction that increasing thickness results in enhanced stiffness of the sandwich panel. Initially, as the force increases, the displacement rises significantly and almost linearly until the structure reaches a point where it begins to exhibit spring-like, soft behavior. As displacement continues to increase, the load remains nearly constant, after which the structure begins to show renewed resistance, causing the load to increase again and displaying linear spring-like behavior. However, with increased thickness, a degree of nonlinearity emerges, likely due to shear effects in the thicker double Kresling structure. This behavior is highly dependent on the angle $\alpha = 39.5°$ used in the Kresling design.

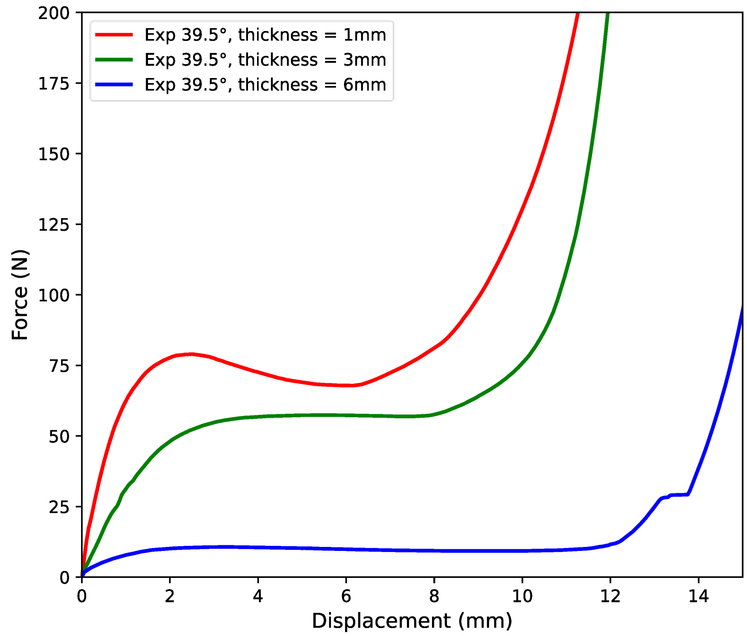

Fig. 5 Effect of thickness in compression load for Kresling sandwich structure for one unit double Kresling with angle $\alpha = 39.5°$.

Figure 6 depicts the impact of varying the internal angle, , on the force-displacement response during compression and three-point bending tests. It can be seen that changes in have a significant influence on the mechanical behavior of the structure. For smaller angles, the structure initially exhibits compliance, but as the load increases, it becomes stiffer, leading to limited displacement. In contrast, at larger angles, the structure initially shows higher stiffness, which then decreases, followed by a compliant phase before transitioning into a linear spring behavior, resulting in substantial displacement without a significant increase in load. Under compression, the TPU-based double Kresling structure does not demonstrate bi-stability but instead displays quasi-zero stiffness (QZS) at specific displacement points for all tested angles. The angle that exhibits the most pronounced QZS behavior resembles the performance of an ideal cushioning material. Overall, in this structure, all parameters remain constant except the Kresling internal angle . From these plots, it is also evident that the energy absorption of the Kresling structure is highly dependent on Kresling internal angle α. The observed non-linear response indicates that the mechanical behavior of the Kresling structure evolves as it deforms, with the rate of change being most significant at higher angles.

Fig. 7 illustrates the effect of varying the angle alpha on the force-displacement curve during three-point bending tests. In Fig. 7, the behavior is similar to the nonlinear spring across all three conditions even though the amplitude of nonlinearity is highly dependent on the Kresling internal angle α shown in this case; however, with angle $\alpha = 50.5°$, the bending rigidity initially increases rapidly and subsequently follows a decreasing trend. From Fig. 7 we can observe that when α is lower the Kresling mostly works as a linear and nonlinear spring the QZS hardly can be seen. On the other hand, when α is higher, we can see that QZS is more visible with the increase of cross-head displacement. The same CAD model used for 3D printing the experimental samples was employed as an input in Abaqus. We found that the simulation plots in Abaqus closely follow the experimental results, demonstrating good agreement between the

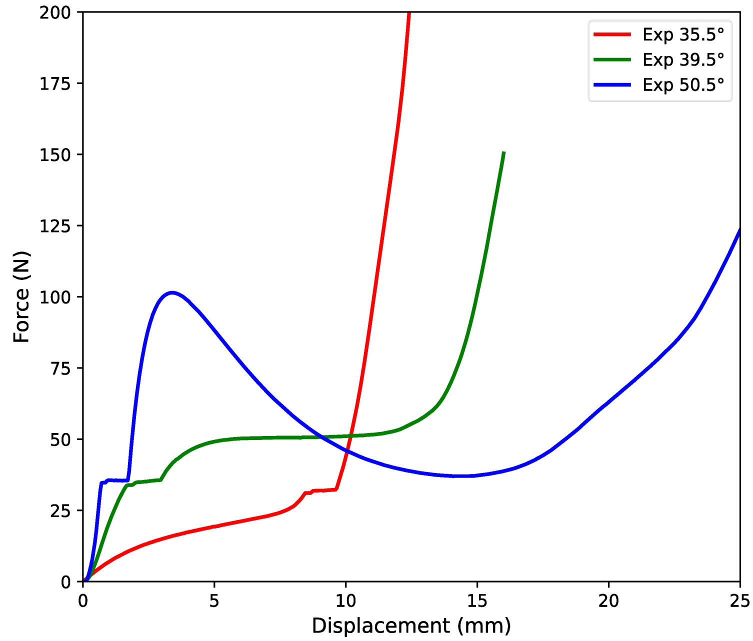

Fig. 6 Effect of α angle in compression load for three different Kresling sandwich samples

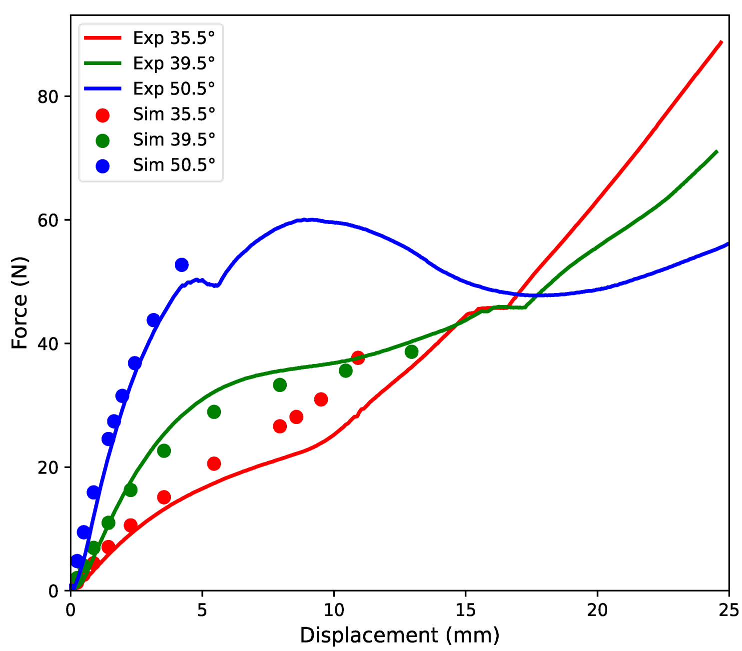

Fig. 7 3-point bending test and FE simulation results for Kresling sandwich structure in three different samples

experiment and the simulation, which is shown in Fig. 7.

Figure 7 presents the three-point bending test and finite element (FE) simulation results for the Kresling sandwich structure at three different internal angles. Similar to the compression tests, higher internal angles result in greater stiffness during the bending of the sandwich beam. From different mechanical models, it can be observed that more strain energy is developed from the compression and rotation of the Kresling structure. A similar characteristic is observed during the bending of the sandwich beam. The key difference between the loading modes is that the deformation of a specific unit depends on its location within the sandwich beam, which is influenced by the applied load. The deformation is most significant at the center of the beam, with lower deformation towards the sides. Thus, the total energy that can be absorbed due to indentation during three-point bending is influenced by the Kresling internal angle , while keeping all other parameters constant. The experimental and simulation curves in Figure 3 show good agreement, with similar trends for different internal angles, demonstrating the validity of the model. The deformation patterns from the experiment and simulation, indicate that the internal Kresling angle α plays a crucial role in the structural response, especially during bending.

IV. Conclusion

This study explores the innovative use of the Kresling origami pattern in sandwich plate structures using a 3D-printed double structure, focusing on their bending and compression characteristics. Implementing both 3-point bending and compression tests from the experimental analysis, alongside finite element (FE) simulations in ABAQUS for 3-point bending analysis, we highlight the unique mechanical properties and potential performance benefits of these sandwiched Kresling origami structures. The investigation into the bending behavior of Kresling-patterned sandwich structures reveals that tailored nonlinear bending rigidity can be achieved by varying the internal angle α, making these structures suitable for applications requiring significant weight reduction while maintaining structural integrity.

Our findings indicate that Kresling-patterned sandwich plates exhibit beneficial mechanical behaviors, such as nonlinear spring responses and quasi-zero stiffness. By determining material properties from both experimental data and FE simulations, we achieved close agreement between the simulated and experimental results. This research provides valuable insights into the structural efficiency and applicability of Kresling origami patterns, especially for aerospace and other engineering fields where lightweight, high-strength materials are essential.

Acknowledgments

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References

[1] Dalaq, A. S., Khazaaleh, S., and Daqaq, M. F., "An origami-inspired design of highly efficient cellular cushion materials," *Applied Materials Today*, Vol. 32, 2023, p. 101835.

[2] Masana, R., Dalaq, A. S., Khazaaleh, S., and Daqaq, M., "The Kresling origami spring: a review and assessment," *Smart Materials and Structures*, 2024.

[3] Kidambi, N., and Wang, K., "Dynamics of Kresling origami deployment," *Physical Review E*, Vol. 101, No. 6, 2020, p. 063003.

[4] Kresling, B., "Origami-structures in nature: lessons in designing "smart" materials," *MRS Online Proceedings Library (OPL)*, Vol. 1420, 2012.

[5] Zhang, J., Lu, G., Zhang, Y., and You, Z., "A study on ballistic performance of origami sandwich panels," *International Journal of Impact Engineering*, Vol. 156, 2021, p. 103925.

[6] Yan, W., Li, S., Deguchi, M., et al., "Origami-based integration of robots that sense, decide, and respond," *Nat Commun*, Vol. 14, 2023, p. 1553.

[7] Bush, J., Singh, S., Vargas, M., Oktay, E., Hu, C., and Veneziano, R., "Synthesis of dna origami scaffolds: Current and emerging strategies," *Molecules*, Vol. 25, 2020, p. 3386.

[8] Castanie, B., Bouvet, C., and Ginot, M., "Review of composite sandwich structure in aeronautic applications," *Composites Part C: Open Access*, Vol. 1, 2020, p. 100004.

[9] Choudhari, C. J., Thakare, P. S., and Sahu, S. K., "3D printing of composite sandwich structures for aerospace applications," *High-performance composite structures: additive manufacturing and processing*, Springer, 2021, pp. 45–73.

[10] Birman, V., and Kardomateas, G. A., "Review of current trends in research and applications of sandwich structures," *Composites Part B: Engineering*, Vol. 142, 2018, pp. 221–240.

[11] Tarlochan, F., "Sandwich structures for energy absorption applications: A review," *Materials*, Vol. 14, No. 16, 2021, p. 4731.

[12] Qi, J., Li, C., Tie, Y., Zheng, Y., and Duan, Y., "Energy absorption characteristics of origami-inspired honeycomb sandwich structures under low-velocity impact loading," *Materials & Design*, Vol. 207, 2021, p. 109837.

[13] Library, B. H., "Butterflies and moths," , 2013 (accessed Nov 25, 2024). Online Image, Flickr, `https://www.flickr.com/photos/biodivlibrary/9261753403`.

[14] Wasserthal, L., "The open hemolymph system of Holometabola and its relation to the tracheal space," *Microscopic anatomy of invertebrates*, Vol. 11, 1998, pp. 583–620.

[15] Wu, S., Zhao, T., Zhu, Y., and Paulino, G. H., "Modular multi-degree-of-freedom soft origami robots with reprogrammable electrothermal actuation," *Proceedings of the National Academy of Sciences*, Vol. 121, No. 20, 2024, p. e2322625121.

[16] Grey, S., Scarpa, F., and Schenk, M., "Mechanics of paper-folded origami: A cautionary tale," *Mech. Res. Commun.*, Vol. 107, 2020, p. 103540.

[17] Sengupta, S., and Li, S., "Harnessing the anisotropic multistability of stacked-origami mechanical metamaterials for effective modulus programming," *J. Intell. Mater. Syst. Struct.*, Vol. 29, No. 14, 2018, pp. 2933–2945.

[18] Tang, R., Huang, H., Tu, H., Liang, H., Liang, M., Song, Z., Xu, Y., Jiang, H., and Yu, H., "Origami-enabled deformable silicon solar cells," *Appl. Phys. Lett.*, Vol. 104, 2014, p. 083501.

[19] Li, S., Vogt, D., Rus, D., and Wood, R., "Fluid-driven origami-inspired artificial muscles," *PNAS*, Vol. 114, No. 50, 2017, pp. 13132–13137.

[20] Zhang, Z., Fan, W., Chen, G., Luo, J., Lu, Q., and Wang, H., "3D Printable Origami Vacuum Pneumatic Artificial Muscle with Fast and Powerful Motion," *2021 IEEE 4th International Conference on Soft Robotics (RoboSoft)*, 2021, pp. 551–554.

[21] Chen, Z., Wu, T., Nian, G., Shan, Y., Liang, X., Jiang, H., and Qu, S., "Ron Resch Origami Pattern Inspired Energy Absorption Structures," *J. Appl. Mech.*, Vol. 86, No. 1, 2018.

[22] Hanna, B. H., Magleby, S. P., Lang, R. J., and Howell, L. L., "Force–deflection modeling for generalized origami waterbomb-base mechanisms," *Journal of Applied Mechanics*, Vol. 82, No. 8, 2015, p. 081001.

[23] Masana, R., and Daqaq, M., "Equilibria and bifurcations of a foldable paper-based spring inspired by Kresling-pattern origami," *Phys. Rev. E*, Vol. 100, No. 6, 2019, p. 063001.

[24] Hunt, G., and Ario, I., "Twist buckling and the foldable cylinder: an exercise in origami," *Int. J. Non Linear Mech.*, Vol. 40, No. 6, 2005, pp. 833–843.

[25] Dalaq, A., and Daqaq, M., "Experimentally-validated computational modeling and characterization of the quasi-static behavior of functional 3d-printed origami-inspired springs," 2022.

[26] Westra, K., Dunne, F., Kulsa, S., Hunt, M., and Leachman, J., "Compliant polymer origami bellows in cryogenics," *Cryogenics*, Vol. 114, 2021, p. 103226.

[27] Wang, X., Qu, H., and Guo, S., "Tristable property and the high stiffness analysis of Kresling pattern origami," *International Journal of Mechanical Sciences*, Vol. 256, 2023, p. 108515.

[28] Khazaaleh, S., Masana, R., and Daqaq, M., "Functional, Durable, and Scalable Origami-Inspired Springs," *arXiv*, 2021.

[29] Ishida, S., Suzuki, K., and Shimosaka, H., "Design and Experimental Analysis of Origami-Inspired Vibration Isolator With Quasi-Zero-Stiffness Characteristic," *J. Vib. Acoust.*, Vol. 139, No. 5, 2017.

[30] Yasuda, H., Tachi, T., Lee, M., and Yang, J., "Origami-based tunable truss structures for non-volatile mechanical memory operation," *Nat. Commun.*, Vol. 8, No. 1, 2017, p. 962.

[31] Mena, L., Muñoz, J., Monje, C., and Balaguer, C., "Modular and Self-Scalable Origami Robot: A First Approach," *Mathematics*, Vol. 9, No. 12, 2021, p. 1324.