2019

AP® CollegeBoard

AP® Research Academic Paper

Sample Student Responses and Scoring Commentary

Inside:

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- ☑ Scoring Guideline
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AP® RESEARCH — ACADEMIC PAPER
2019 SCORING GUIDELINES

The Response…				
Score of 1 **Report on Existing Knowledge**	**Score of 2** **Report on Existing Knowledge with Simplistic Use of a Research Method**	**Score of 3** **Ineffectual Argument for a New Understanding**	**Score of 4** **Well-Supported, Articulate Argument Conveying a New Understanding**	**Score of 5** **Rich Analysis of a New Understanding Addressing a Gap in the Research Base**
Presents an overly broad topic of inquiry.	Presents a topic of inquiry with narrowing scope or focus, that is NOT carried through either in the method or in the overall line of reasoning.	Carries the focus or scope of a topic of inquiry through the method **AND** overall line of reasoning, even though the focus or scope might still be narrowing.	Focuses a topic of inquiry with clear and narrow parameters, which are addressed through the method and the conclusion.	Focuses a topic of inquiry with clear and narrow parameters, which are addressed through the method and the conclusion.
Situates a topic of inquiry within a single perspective derived from scholarly works **OR** through a variety of perspectives derived from mostly non-scholarly works.	Situates a topic of inquiry within a single perspective derived from scholarly works **OR** through a variety of perspectives derived from mostly non-scholarly works.	Situates a topic of inquiry within relevant scholarly works of varying perspectives, although connections to some works may be unclear.	Explicitly connects a topic of inquiry to relevant scholarly works of varying perspectives **AND** logically explains how the topic of inquiry addresses a gap.	Explicitly connects a topic of inquiry to relevant scholarly works of varying perspectives **AND** logically explains how the topic of inquiry addresses a gap.
Describes a search and report process.	Describes a nonreplicable research method **OR** provides an oversimplified description of a method, with questionable alignment to the purpose of the inquiry.	Describes a reasonably replicable research method, with questionable alignment to the purpose of the inquiry.	Logically defends the alignment of a detailed, replicable research method to the purpose of the inquiry.	Logically defends the alignment of a detailed, replicable research method to the purpose of the inquiry.
Summarizes or reports existing knowledge in the field of understanding pertaining to the topic of inquiry.	Summarizes or reports existing knowledge in the field of understanding pertaining to the topic of inquiry.	Conveys a new understanding or conclusion, with an underdeveloped line of reasoning **OR** insufficient evidence.	Supports a new understanding or conclusion through a logically organized line of reasoning **AND** sufficient evidence. The limitations and/or implications, if present, of the new understanding or conclusion are oversimplified.	Justifies a new understanding or conclusion through a logical progression of inquiry choices, sufficient evidence, explanation of the limitations of the conclusion, and an explanation of the implications to the community of practice.
Generally communicates the student's ideas, although errors in grammar, discipline-specific style, and organization distract or confuse the reader.	Generally communicates the student's ideas, although errors in grammar, discipline-specific style, and organization distract or confuse the reader.	Competently communicates the student's ideas, although there may be some errors in grammar, discipline-specific style, and organization.	Competently communicates the student's ideas, although there may be some errors in grammar, discipline-specific style, and organization.	Enhances the communication of the student's ideas through organization, use of design elements, conventions of grammar, style, mechanics, and word precision, with few to no errors.
Cites **AND/OR** attributes sources (in bibliography/ works cited and/or in-text), with multiple errors and/or an inconsistent use of a discipline-specific style.	Cites **AND/OR** attributes sources (in bibliography/ works cited and/or in-text), with multiple errors and/or an inconsistent use of a discipline-specific style.	Cites **AND** attributes sources, using a discipline-specific style (in both bibliography/works cited **AND** in-text), with few errors or inconsistencies.	Cites **AND** attributes sources, with a consistent use of an appropriate discipline-specific style (in both bibliography/works cited **AND** in-text), with few to no errors.	Cites **AND** attributes sources, with a consistent use of an appropriate discipline-specific style (in both bibliography/works cited **AND** in-text), with few to no errors.

AP® RESEARCH
2019 SCORING COMMENTARY

Academic Paper

Overview

This performance task was intended to assess students' ability to conduct scholarly and responsible research and articulate an evidence-based argument that clearly communicates the conclusion, solution, or answer to their stated research question. More specifically, this performance task was intended to assess students' ability to:

- Generate a focused research question that is situated within or connected to a larger scholarly context or community;
- Explore relationships between and among multiple works representing multiple perspectives within the scholarly literature related to the topic of inquiry;
- Articulate what approach, method, or process they have chosen to use to address their research question, why they have chosen that approach to answering their question, and how they employed it;
- Develop and present their own argument, conclusion, or new understanding while acknowledging its limitations and discussing implications;
- Support their conclusion through the compilation, use, and synthesis of relevant and significant evidence generated by their research;
- Use organizational and design elements to effectively convey the paper's message;
- Consistently and accurately cite, attribute, and integrate the knowledge and work of others, while distinguishing between the student's voice and that of others;
- Generate a paper in which word choice and syntax enhance communication by adhering to established conventions of grammar, usage, and mechanics.

Folding Under Pressure

Exploring the Properties of Nonstandard Origami Tessellations as Folded Cores in Sandwich Structures

AP Research

Word Count: 5170

INTRODUCTION

Structural, mechanical, and materials engineers have recently found inspiration in the unlikeliest of places: origami– the ancient Japanese art of folding paper. In particular, the implementation of tessellated crease patterns on folded sheets has given rise to new metamaterials[1] and structures with unprecedented applications, bringing impact to fields as diverse as optics, space structures, antenna design, storage, and even biomedical engineering [1]. Specifically, these structures have gathered interest as cores in sandwich plates, which consist of a folded tessellation between two rigid surfaces acting as a truss-like support. The merits of folded cores arise not only from their structural capacities but also as a result of the ability to be ventilated, which is not easily achieved in conventional cores [1,2]. Despite the enormous potential of these materials, however, the vast majority of research centers on a very narrow range of origami tessellations [3, 4]. Most prevalent in the literature of this field is the Miura-Ori pattern, shown in Figure 1, which has unique characteristics that spur a plethora of practical uses [1-4]. However, many other folded tessellations exist, such as the waterbomb, Yoshimura, and Resch patterns, and more than 100 designed by the same mathematician, each pattern with its own variations. Few studies appear to have conducted more than cursory investigations into the particular mechanical properties of such less-commonly explored folded tessellations [3-5].

Being a relatively new field of study, there remains much to be learned to take full advantage of the potential of origami tessellations. Considering the recent surge in the relevance of frequently-used tessellated crease patterns, investigating those that are less-commonly studied promises to unlock the even greater potential of these metamaterials. Exploring these patterns as folded cores in sandwich structures will give information pertinent to mechanical properties, ultimately leading to new applications of origami design. It is hoped that the results of this research will be a step toward new, better, and more efficient applications in the previously mentioned areas and in others as of yet unimagined.

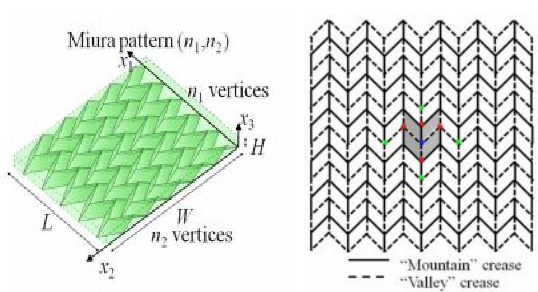


Figure 1 | Miura-ori. (left) diagram showing a basic Miura-ori folded tessellation. (right) Crease pattern of the Miura-ori tessellation, showing the folds of a Miura pattern on an unfolded surface [4].

[1] Materials with properties which are not generally found in nature.

LITERATURE REVIEW

Thanks to modern developments in computer science, computational geometry, and number theory, the ancient art of folding paper now appears in revolutionary ways throughout engineering and the sciences. For instance, origami design allows for the packaging and deployment of large membranes, including solar panels and telescope lenses [4,6]. Similar applications have resulted in the realization of adjustable and collapsible antennas [1,7]. Flexible heart stents and minimally invasive surgical tools have been proposed and modeled [1,8], and engineers at Brigham Young University have even prototyped a lightweight, deployable bulletproof shield to protect law enforcement officers [9]. To elaborate on every such captivating implementation of origami design would be beyond the scope of this literature review, but packaging, optics, medicine, and space structures are just a few areas to which origami design has brought, or will soon bring, tremendous impact [1]. All of this is to say that this relatively new field of research fosters abundant and diverse applications that promise to help many people. Thus, the ultimate goal of research in this area is to glean knowledge that will lead to similar innovations aimed at improving the human condition.

Unique to origami-based structures and materials are several properties from which their versatility arises. According to Arthur Lebée [2], a structural engineer who has done research pertaining to engineering applications of origami, the transformation of a flat plane by means of folding creates a unique, complex mechanism that begs analysis from multiple perspectives. Folded surfaces, he explains, may be conceptualized as shells, membranes, trusses, or assemblies of rigid faces, each with their own analytical merits. Regardless of how they are considered, origami structures exhibit distinct characteristics that are exploited in their real-world uses. Much of literature surrounding this field investigates these characteristics with mathematical and material-scientific approaches. The property of flat-foldability, for example, is of particular interest as it allows for the compact packaging of expansive membranes and surfaces [1,6]. On the other hand, Beatini and Koray [10], structural design experts associated with the Izmir Institute of Technology in Turkey, study the property of mobility, exploring the freedom to vary the geometry of origami designs while preserving the number of degrees of freedom[2]. The property of mobility has also been studied in the context of systems with multiple or hidden DOF and bistability, which lends itself to numerous applications such as mechanical switches [11-13]. Other researchers consider wealth of additional such properties, including pattern variability, rigid foldability, load bearing capacity, deployability, and many more [2,4,14-16].

Recently, the study of origami tessellations has gained significant traction in this field. These form structures and materials by implementing a repeated pattern of creases over a surface and collapsing it partially or completely

[2] In the context of this field, the terms "degrees of freedom" (DOF) and "mobility" refer to the number of parameters that must be altered to place an origami structure in a specified configuration [14].

[1,2,15]. Tessellation essentially consist of a unit cell that is tiled in multiple directions according to one of seventeen mathematically predetermined plane symmetry groups to form a periodically-repeating pattern [5,14]. Tessellations have properties even more specific and accessible than those of other origami-based designs; notably, many have unique Poisson's ratios[3]. So profound is this trait that it is largely responsible for classifying these folded patterns as metamaterials. A fair amount of literature in this field primarily focuses on the Poisson's ratios of origami tessellations [4,18]. The Poisson's ratio of the Miura-ori pattern, the more widely-known origami tessellation depicted in figure 1, has been shown to take on both negative and positive values[4] under various conditions [4], and the ratios for some Miura-ori inspired patterns have been derived [18].

A particularly powerful engineering application of origami is attributable to folded tessellations: sandwich structures, which consist of a tessellation fixed between two rigid panels, as depicted in figure 2. The assembly as a whole serves as a structural element that makes use of the truss and membrane conceptualizations of origami described by Lebée [1,2]. Sandwich panels have a broad range of uses in the aerospace, marine, and, recently, automotive industries in cases where there is a risk of bending or deformation if only a single material sheet were to be used [19]. The benefits of structures containing folded cores exceed those with conventional honeycomb cores in that they possess open channels that allow for ventilation. The widely used honeycomb tessellation creates individual pockets of air that accumulate condensation with changes in temperature, degrading the structure over time. Folded cores circumvent these problems as their structures allow air circulation [2,3,20]. European countries and research institutions have taken a vested interest in developing these structures and have launched the transnational project CELPACT (Cellular Structures for Impact Performance) to do so [20]. The energy absorption capabilities and optimal strength to weight ratios of origami tessellations make them especially suited to the role of a core in a sandwich panel. Compression, shear, bending moment, and energy absorption tests[5] have been performed or simulated for Miura-based foldcores, and results have shown their mechanical properties to be comparable with, their honeycomb counterparts [1-4,20]. Studying origami tessellations as folded cores in sandwich panels gives insight into their mechanical properties more generally.

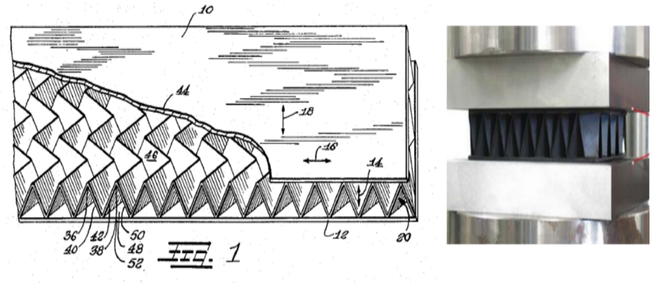


Figure 2 | Sandwich Panel. (left) Illustration of a sandwich panel with a Miura-ori folded core [21]. (right) Compression testing of a composite core structure [20].

Considering the research into the applications and mechanical and mathematical properties of origami structures, one begins to get a sense of the state of this relatively new field of study. An undeniable trend emerges– that most research, theoretical or pragmatic in scope, focuses on a disproportionately narrow range of tessellations. The Miura-ori pattern specifically enjoys most of the limelight in this field due to its distinct characteristics [1-4,10,14,15,18,20], but the waterbomb pattern also appears throughout relevant literature with some frequency [1,12,13,15]. Some authors acknowledge this discrepancy, but rarely go into more depth than a simple recognition, perhaps they briefly stating that this is due to difficulty in mathematical modelling [3,4]. On the other hand a vast assortment of origami tessellations have been documented or shown to exist. For example, the Yoshimura, diagonal, and Resch patterns are noted in multiple sources, but their specific properties are rarely explored in as much depth as the Miura-ori and waterbomb patterns [1,4]. Renowned computer scientist and mathematician David Huffman reportedly designed and folded more than one hundred origami tessellations in his lifetime [5]. The incomprehensibly wide array of possible origami tessellations creates an undeniable dissonance when pitted against the very few patterns that are prevalently considered by most of the research in this field.

The fact that the majority of research on origami tessellations focuses on such a small a range of patterns is the inconsistency from which the question driving this study emerges: How do the mechanical properties of less-frequently explored origami tessellations compare to those of the Miura-ori pattern and other recognized standards? This study attempts to patch over this observed discrepancy in what is known about origami tessellations and will be different from other related literature as it will consider *less common* origami patterns as folded cores in sandwich structures implementing a numerical method. Some have made attempts to broaden the spectrum of patterns in their research. For example, Fathers and You, affiliates of the Department of Engineering Science at the University of Oxford, and Gattas, an affiliate of the School of Civil Engineering at the University of Queensland [22], explore the energy-absorbing capacities of the cube and

[3] Defined as the ratio of transverse contraction strain (a measure of deformation) to axial extension strain in the direction of applied force [17].

[4] Most materials demonstrate a positive Poisson's ratio. A classic example is a rubber band, narrowing in one direction when stretched in another. certain origami tessellations, however, can demonstrate a negative Poisson's ratio, expanding simultaneously in two in-plane directions (while contracting in a third, out-of-plane direction) [4].

[5] These tests ultimately explore different load-bearing situations that can be handled by these patterns. See methods section for more detail.

eggbox patterns as folded cores. However, these are *kirigami*-based structures, which involve cutting in the manufacturing process whereas traditional origami allows folding alone. This study will constrain its focus to origami-based structures since cutting in the manufacturing process introduces imperfections that have been shown to have a substantial bearing on core performance that must be handled accordingly in computer simulations [20,22,23]. In addition, the Ron Resch pattern was briefly studied by Lv et al. [4], but not as a folded core in a sandwich structure. The very little research that has been conducted on non-conventional origami patterns fails to shed light on the properties of the much larger assortment of tessellations at the disposal of engineers seeking to reap the benefits of their applications.

The answers to the question this study will investigate are of paramount real-world significance. As Lebée [2] states, "Because any application of a folded shape will endure some mechanical loadings, the question of the relation between folds and structures needs to be addressed." By investigating folded tessellations in sandwich structures, this research hopes not just to gain knowledge about these patterns in the context of a specific application, but also to gain insight into their mechanical properties more generally. The understanding of new patterns that this study will produce aims to inspire novel engineering applications of origami, more fully unleashing the potential of this exciting new field.

METHODOLOGY

To gauge the effectiveness of the sandwich structures, and, by implication, the mechanical properties of the core comprising its interior, its performance under the various conditions experienced in application must be considered. Such conditions, or loading cases, include compression (movement of the rigid plates toward each other), shear (relative translational movement of the plates parallel to each other), and torsion (relative rotation of the plates). In most studies, this is done through direct experimentation and/or computer simulation [3,20,22]. Since imperfections that would be present in any physical model have been shown to have a significant bearing on the core's effectiveness [20,22,23], an experimental design making use of computer simulation was employed to quantitatively evaluate each core. This was done so that the cores could be studied purely from a structural standpoint, eliminating any sensitivities due to minute imperfections. The independent variable was the core geometry while the dependent variable was the stress (calculated from the measured force as the plate was given a prescribed displacement). The software used in this experiment falls into the broad category of Finite Element Analysis (FEA) software, a useful engineering tool. In the case of a quasi-static mechanical analysis[6] such as this, FEA curtails the complexities involved in considering the structure as a continuum by treating it as collection of many discrete elements on which it subsequently performs numerical operations. Cheng Lv, a mechanical engineer affiliated with Arizona State University who has studied origami structures extensively with this approach, explains the finite element method (FEM) nicely:

> "[The FEM] introduces the equilibrium on an integral level, not on a pointwise one. By introducing this assumption, the continuum in the real world is discretized into a finite number of smaller pieces, called elements in FEM, so that complex structures can be analyzed" [23].

This theoretical simplification enables the researcher to study sandwich structures efficiently and in great depth, thus making it the optimal method to approach the question driving this study.

Four cores were considered in this study. The honeycomb core, due to its current widespread use in the aerospace industry [2], and the Miura-ori core, due to the volume of literature in which it appears, were considered standards of comparison against which the other cores were evaluated. Constraints of time and computational capacity limited the amount of non-traditional patterns studied to two: the zigzag base and square twist tessellations. The zigzag base pattern was adapted from a study conducted by Eidini and Paulino [18], who studied its geometry and Poisson's ratio, but did not consider it as a folded core inside a sandwich structure. The square twist pattern makes very few appearances in relevant literature and was adapted from a study by a group affiliated with the Department of Physics at Cornell University [25]. These patterns were selected due to their flat curvature, allowing the patterns to fit between two rigid plates without placing them under an initial stress. Additionally, their relatively simple geometries eased the process of modelling them in the computer-aided design (CAD) program. To ensure comparability of results, the patterns each included four unit cells in a 2 x 2 array configuration and were designed with a height of 10 mm and a unified core density of $0.05\,\rho_m$. Core density (ρ_c) is given by the equation:

$$\rho_c = \frac{t_m S_m}{S_u H c} \rho_m \ , \qquad (1)$$

where t_m, S_m, and ρ_m represent, respectively, thickness, total area, and density of the sheet of material from which the pattern's unit cell was made. S_u and H_c denote the base area of the unit cell and the core height (10 mm). This system of ensuring consistency among the patterns was adopted from the methods of Zhou et al. [3], who studied cores consisting of variations of the Miura-ori fold, and was adopted to ensure that no core had any inherent advantage over the others.

The program Onshape, an internet browser-based computer-aided design software, was used to model the cores.

[6] According to the Simscale documentation, a static mechanical analysis, as opposed to a dynamic analysis, ignores inertial and dampening effects and determines time-independent stresses and displacements under steady loads [24].

First, the planar structure of each was modeled using calculated dihedral angles. Each face was then given a calculated thickness determined by Equation (1) using the "extrude" or "thicken" tool. The "split" and "delete part" tools were employed to eliminate the extra material near the corners that resulted from overlapping extrusions and to flatten the top and bottom edges, ensuring a surface for contact between the core and the rigid plates. The constituent parts of the core were fused into a single solid using the software's "boolean" function. In assembly, the core was fastened to two equivalent rigid plates, each 10cm x 10cm with the same thickness as the respective core, and the coordinate system was manipulated such that the z-axis was normal to both plates and the x and y axes were aligned with the orthogonal shear directions. See Appendix A for detailed geometries and other details regarding the construction of the cores.

The core geometries were then imported into Simscale, a free, browser-based FEA software. Multiple reasons were responsible for the choice of Onshape and Simscale over competing programs, particularly their mutual compatibility, user-friendliness, cost effectiveness, and ease of accessibility. Once imported, the geometries were used to generate a second-order mesh[7], with the sizing set to automatic and the fineness set to moderate. A mesh refinement was applied on the rigid plates to render them undeformable. To ensure a reasonable computational time, contacts between the cores and plates were represented as bonded contacts with the interior faces of the rigid plate assigned as master surfaces and the denser faces of the core as slave surfaces. Following the model of Zhou et al., the parts were assumed to be made out of aluminum, and a linear elastic material model was employed since only pre-buckling behavior will be considered. Three types of tests were done on each model: one compressive test and one shear test in each of two orthogonal directions. The torsional loading case was avoided due to limitations in computational time, but understanding the behavior of the plates in these other situations will still provide deep insight into the strengths and shortcomings of each core. The simulations were conducted under quasi-static conditions with nonlinear analysis enabled.

The boundary conditions were set as follows. For all tests, the bottom rigid plate was set to be a fixed support. The top plate was given a time-dependent displacement of $5 \times 10^{-5} * t$ m in the appropriate direction with its motion constrained in all others. The initial time step was set to be 0.1 s over a simulation length of 1 s. The reaction force was measured on the surface of the top plate. After the run was complete, the data was exported to Microsoft Excel and used to plot an effective stress-strain curve[8]. Similarly, for the shear tests, the top plate was displaced in the positive x or y direction with the reaction force again calculated on the surface of the top plate. From this data, graphs of effective shear stress vs. shear strain were generated. See Appendix B for the full simulation parameters.

The criteria used to evaluate each core were the slopes of the compressive and shear stress-strain curves. A stronger core responds to large stresses with minimum deformation (strain) or, in other words, resists strain with more reactionary force. This relationship appears graphically as a line with a greater slope. The greater the slope of the graph, therefore, the better the performance of the core and the more potentially valuable it would be in engineering applications. Consistency between the shear directions and buckling behavior were also considered in assessing each pattern. See the Discussion section for more information about what these factors indicated about core performance.

RESULTS

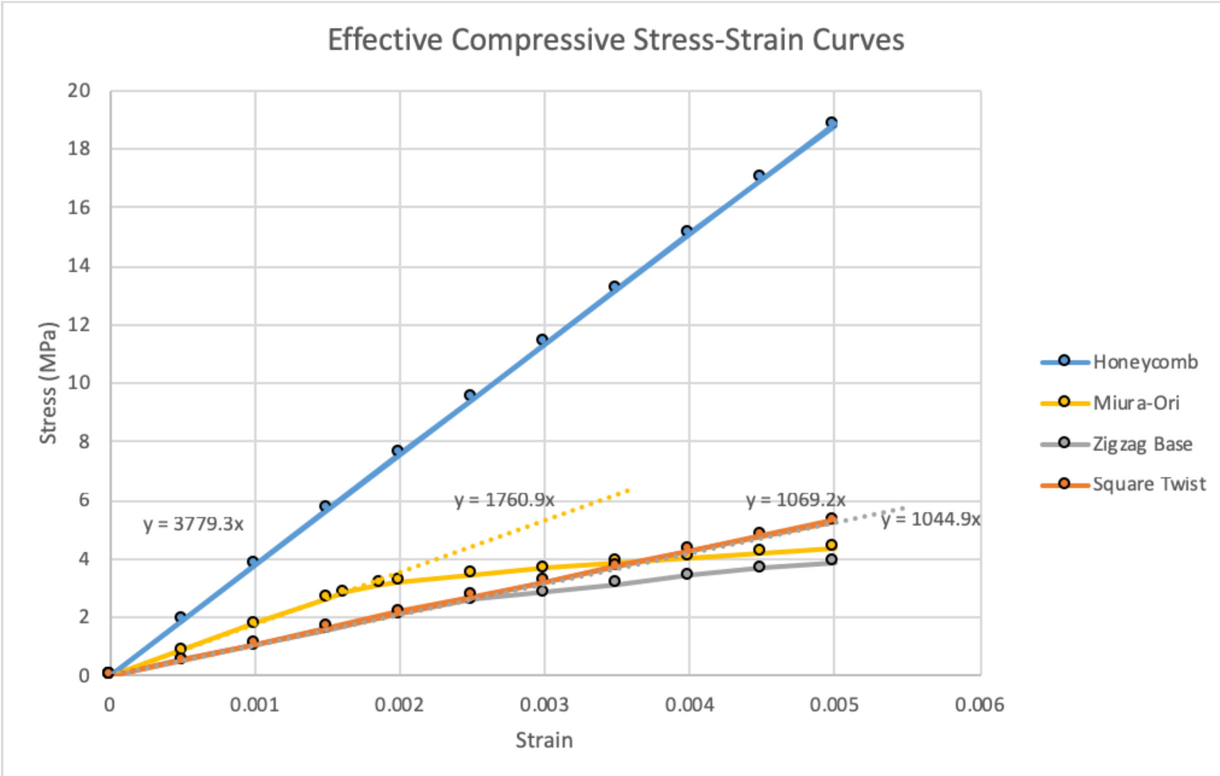
Simulation data was used to generate the effective stress-strain curves shown below for the compression loading case and two shear loading cases in perpendicular directions. The horizontal axis of each graph represents strain (dimensionless), calculated by dividing the prescribed displacement at the time-step of the simulation by the original core height of 10 mm. The vertical axis represents stress (in MPa), calculated by dividing the reaction force on the displaced plate in the respective direction by the projected area of the core. A linear regression with a set intercept at the origin was used to generated a formula of the form y = kx that is displayed next to each curve.

For ease of comparison, the curves for each case are plotted on the same set of axes. The honeycomb core is represented by the blue line, the Miura-ori by the yellow line, the zigzag base by the gray line, and the square twist by the orange line. In instances where buckling behavior was exhibited, the linear portion of the stress-strain curve is extended by a trendline (see the compression results for the Miura-ori and zigzag base cores). The slopes are assembled into a table for quick reference. For example, if one was evaluating the performance of the zigzag base core, they could reference the graph, which had a prebuckling slope of 1044.9 MPa with a buckling point at nearly 3 MPa. It demonstrated a slope of 604.97 MPa in the first shear direction and 215.88 MPa in the other. Of course, these values are also readily accessible in the fourth column of the chart.

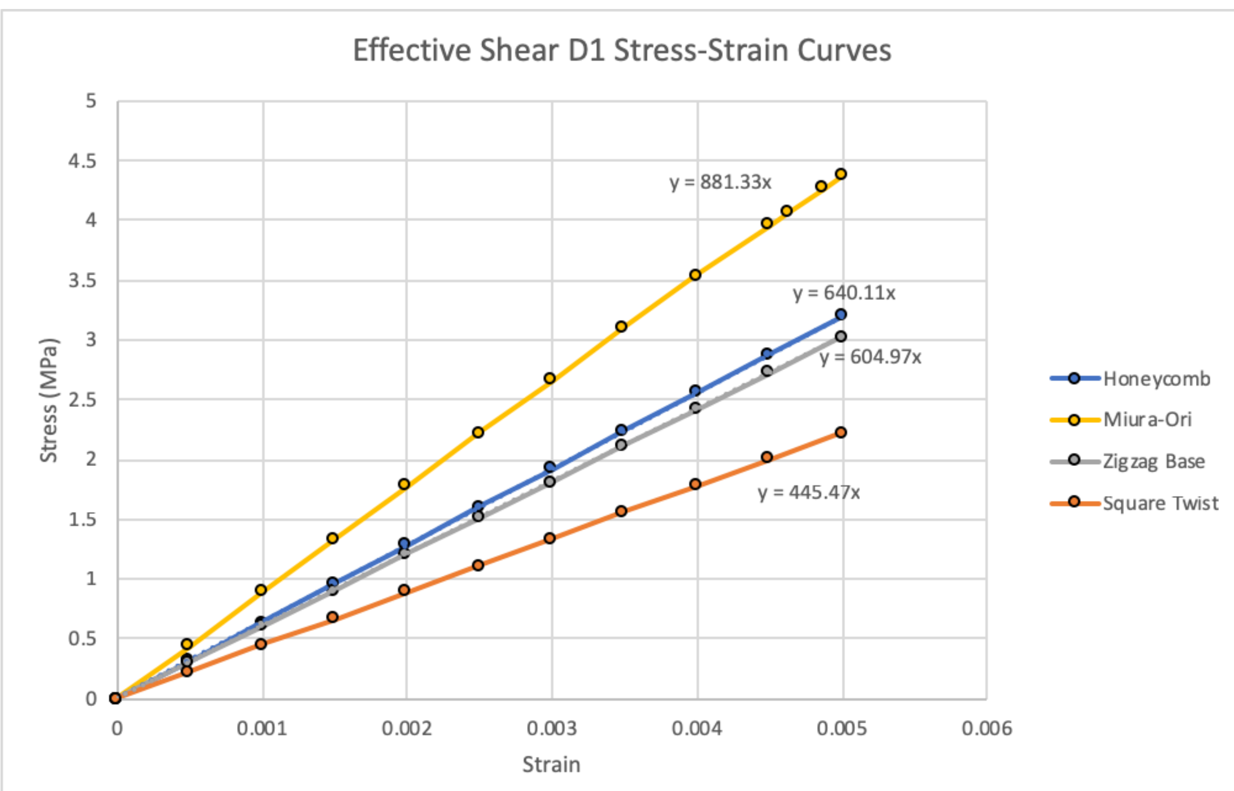
[7] Mesh refers to the network of elements that approximates the structure being analyzed in FEA.

[8] Effective stress (both compressive and shear) was calculated by dividing the reaction force by the total projected area of the core into the plane of the bottom plate. Compressive strain was calculated by dividing the displacement of the top plate by the original height of 10 mm. Shear strain was calculated as the ratio of the lateral displacement of the top plate to the 10 mm height of the plate.

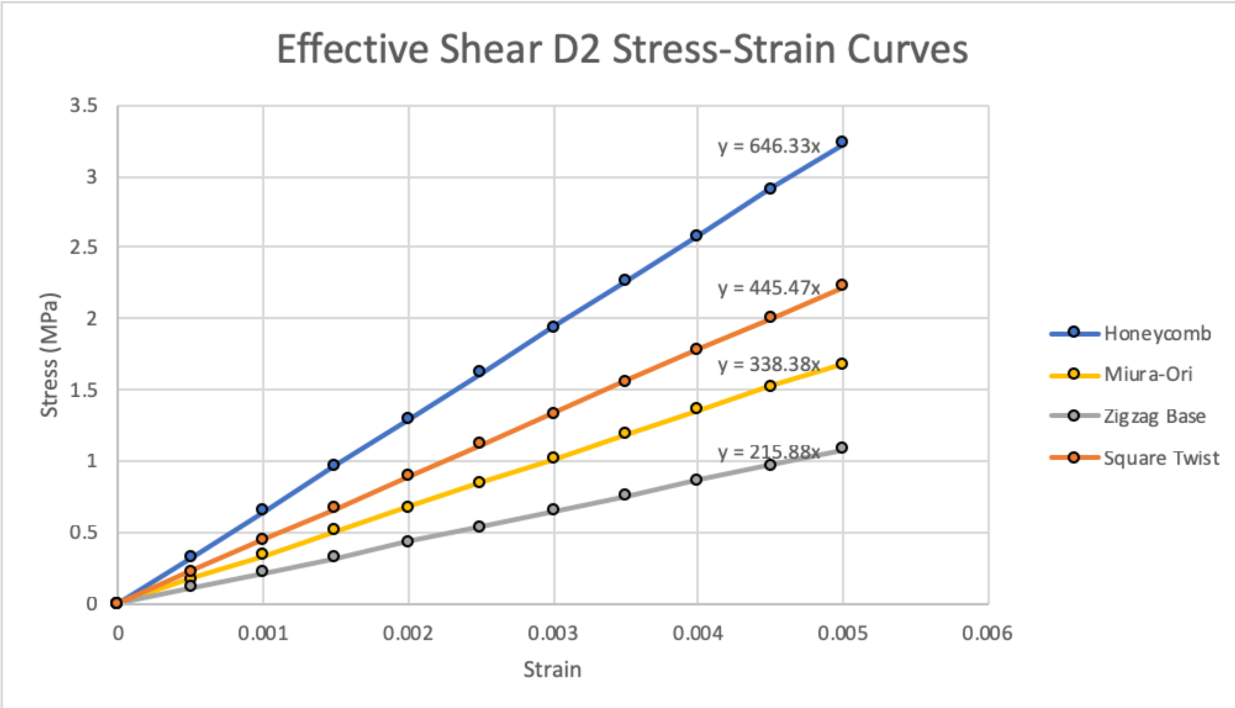
Compression Tests



Shear D1 Tests



Shear D2 Tests



Slope Values, MPa

Test Case:	**Honeycomb Core**	**Miura-Ori Core**	**Zigzag Base Core**	**Square Twist Core**
Compression	3779.3	1760.9	1044.9	1069.2
Shear D1	640.11	881.33	604.97	445.47
Shear D2	646.33	338.38	215.88	445.47

DISCUSSION

The results obtained in this study lend themselves to some meaningful discussion of the mechanical properties of origami-inspired cores in sandwich structures. To glean as much as possible from the data that was collected, the discussion has been parsed into the following sections: compression and shear performances and the properties of the less-commonly explored tessellations in particular.

Compression

As previously established, a stress-strain curve with a greater slope corresponds to a stronger core. In the compression tests, the honeycomb core performed the strongest, with the slope of its stress-strain curve being more than twice that of the next greatest, the Miura-ori core. This is not so surprising as all of the faces of the honeycomb core are oriented orthogonally to the compressive direction. The origami-based cores performed comparably to one another, but the Miura-ori (slope 1760.9 MPa) slightly outperformed the other two cores (slopes 1044.9 and 1069.2 MPa) in the linear portions of their stress-strain curves.

The Miura-ori and zigzag base cores exhibited buckling behavior. Since the strains that the cores underwent were relatively small (0.005 or less), it can be assumed that the other cores would have buckled at higher stresses/strains. Notwithstanding the absence of buckling points on the graphs of the other cores, the points that are present shed light on some notable properties of the cores. Since a linear elastic material model was employed rather than the more accurate plastic material model to save computational time, the particular value of stress and strain at which the cores buckled is of little use. Since this study is interested in these cores from a primarily *structural* perspective, the buckling points are more informative when compared rather than as stand-alone data. While the Miura-ori core had significantly more favorable prebuckling behavior, it buckled much more quickly than the zigzag base core and is, thus, an important consideration in evaluating which core performed better. This is somewhat surprising as these cores had the most similar geometries between any two cores considered by this study. Buckling behavior also helps to distinguish the square twist pattern from that of the zigzag base. While the two patterns' graphs had essentially the same slope, the fact that the zigzag base core buckled and the square twist core did not highlights the square twist core as the stronger-performing pattern.

Shear

Using the same slope criteria to evaluate the performance of the cores in the shear loading cases yields some interesting results. In the first of the two directions, the Miura-ori core performed the best and the square twist base performed the worst with one half of the slope of the Miura-ori. The honeycomb and zigzag base cores performed similarly with slopes between the two extremes. In the orthogonal shear direction, the slopes of the shear stress-strain curves were more uniformly distributed. In this case, the honeycomb core performed the best, followed by the square twist, Miura-ori, and, finally, the zigzag base cores. In application, a shear stress would have components in both of these directions, thus an optimal core is deemed to be one which performs consistently well in both directions. The Miura-ori and zigzag base cores, while fairly strong in one direction (with slopes of 881.33 and 604.97 MPa, respectively), were significantly weaker (slopes of 338.38 and 215.88 MPa, respectively) in the other. The honeycomb and square twist cores, on the other hand, were much more consistent in both shear directions, although the honeycomb core performed significantly better in both cases. For these reasons, the honeycomb core was determined to be the best-performing core for the shear tests.

Properties of Nonstandard Origami Tessellations

In using the data to rank the cores in terms of performance, there are numerous considerations to be taken into account. Though the shear tests in this study constrained the motion of the top plate in the z-direction (a valid simplification under such small strains to ensure simulation completion), shear loading in application inevitably results in some compressional stress. Because of this, compression test performance was considered the primary factor in ranking the cores, followed by shear performance and consistency. The honeycomb tessellation emerged as the optimal core of the four considered in this experiment. However, the noted issue of moisture accumulation that wears down the core over time [2,3,20] highlights the value of considering other tessellations as viable core designs. Not surprisingly given the amount of current research, the Miura-ori pattern performed fairly well across all tests. It had the second best compressional performance and the best performance in the first shear direction. However, it cannot be said that it wholly outperformed the other origami-based cores. It had the earliest buckling point in the compression tests and had the starkest inconsistency between the two shear directions. For these reasons, the other origami-inspired cores are deemed to have more advantageous mechanical properties in certain instances and speaks even more to the need for more research examining uncommon origami-based structures. The two less-commonly explored origami tessellations considered in this study are examined in greater detail below.

Zigzag Base Core. This core had a comparatively weak performance across all three types of tests. Additionally it buckled during the compression test and was inconsistent between the two perpendicular shear directions. While experimental data advocates the exploration of nonstandard origami tessellations, it suggests that this particular tessellation does not have much potential value to add to the field of engineering in cases requiring strength when compared to the other cores. It should be noted that, while this study operated under the presumption that the desired core was strong in all loading cases, these could be applications that necessitate strength in some directions but weakness in others. The results obtained that speak to the weaknesses of this core cannot be immediately discarded as they may inform applications of this tessellation apart from sandwich structures.

One recommendation that the author makes for future study is exploring this core in a kirigami-based variation that more closely resembles that which was studied by Eidini and Paulino [18]. This would be done by removing the large flat face on the top that seemed to make little contribution to the load-bearing capacity of the core. The low stress values on these faces is shown in Figure 3 and led to this suggestion for future inquiry. By removing this face, the projected area of the core decreases, and the other faces could be made thicker to maintain a constant core density while leading to a potentially stronger core. The same could be applied to the square twist core. Though kirigami-based patterns were beyond the scope of this research, their study could very well yield meaningful results.

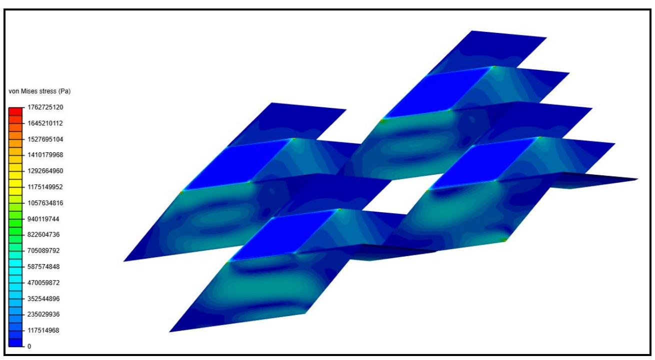


Figure 3 | Zigzag Base Core Stress Diagram. The four top faces endured minimal stresses for compression and shear tests, which prompts inquiry into a kirigami-based variation of the pattern that eliminates these faces. Similar recommendations are made for the square twist core.

Square Twist Core. The square twist core did not prove to be notably stronger than the other cores in any of the tests that were conducted. In fact, it had the weakest overall performance in one of the shear tests. However, simulation data lended results that speak to the potential value of this core design. To begin with, it was the only origami-based core that did not buckle in the range of strain under which these cores were tested. As mentioned earlier, the simplified material model makes direct interpretation of buckling behavior difficult for this experiment. However, the fact that it did not exhibit buckling behavior while the others did, including the well-documented Miura-ori pattern, is a promising sign. Additionally, the slope of its stress-strain curve in both shear directions is identical, a consistency that presumably arises from the core's rotational symmetry. While it had the worst performance in the first of the two directions tested, it had the second best performance in the other direction. These unique properties indicate that this tessellation could potentially be of value in engineering applications. While this study considered cores with a core density of 0.05 times that of the material from which they were constructed, geometric and material variations could lend a core with a much more ideal performance (such is the case for all of these cores). This study begs deeper exploration into this tessellation and its various adaptations to reap the benefits of a ventilatible core with consistent shear performance.

CONCLUSION

There were some limitations to this study that future research could aim to address in order to form a better understanding of the properties of less-commonly explored origami tessellations. Many of these stem from limits in computational time and capacity. With more advanced, specialized software, simulations could include more complex contact algorithms, material models, unit cells, etc., and could extend analysis to postbuckling behavior. Postbuckling data would likely have led to some insightful discoveries about the patterns that would have informed a more complete evaluation of their properties than was yielded by this study. The inclusion of a torsional simulation, in addition to the shear and compression ones, would have likewise improved this study. Alas, both were hindered by technological factors. While this experiment did introduce some simplifications, it was, nevertheless, still able to gain valuable insight into the properties of some nonstandard origami tessellations. Future studies could attempt to use more optimized software to understand these cores more fully without the limits posed by this study.

The results of this study inspire further inquiry into engineering applications of origami tessellations. The square twist pattern was shown to have several favorable properties, including consistency in both shear directions that stem from its rotational symmetry. These findings prompt further investigation into the square twist pattern and other likewise rotationally symmetric patterns. Adjusting geometries could yield a strong, ventilatible core that could be useful in the aforementioned areas of the aerospace and aeronautical industries. Additionally, relevant literature mentions, but rarely explores in detail, many more origami tessellations than the two that were considered by this study. Given the exciting potential of the square twist pattern, it is probable that, among the assortment of other tessellations, there are some with the capacity to even further revolutionize this field. These perhaps includes kirigami patterns, including the two mentioned above that could be derived from the cores considered in this study. Future research should, as this study has, pioneer research into more nonstandard tessellations in search of viable engineering applications.

Ultimately, this study was able to accomplish its primary goal of extending the scope of research on engineering applications of origami tessellations to include more of the vast array of existing patterns. While the honeycomb core, the standard core used in application, had the most favorable mechanical properties of the cores studied, documented problems associated with these cores makes the study of origami-inspired sandwich structures worthwhile. This experiment was able to add to the knowledge about the properties of such nonstard origami-based cores. Despite the generally poor performance of the zigzag base core, the consistency and strength of the square twist core demonstrated in this experiment is exciting news for the field of engineering. Hopefully, as our knowledge of the mechanical properties of origami grows, so too will our ability to improve the human condition through its various applications.

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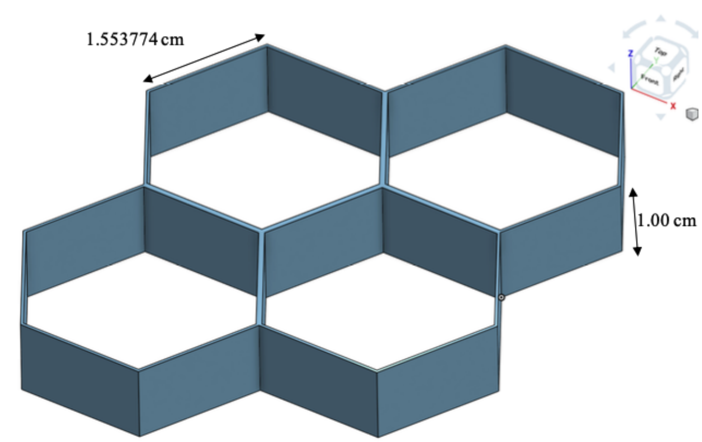
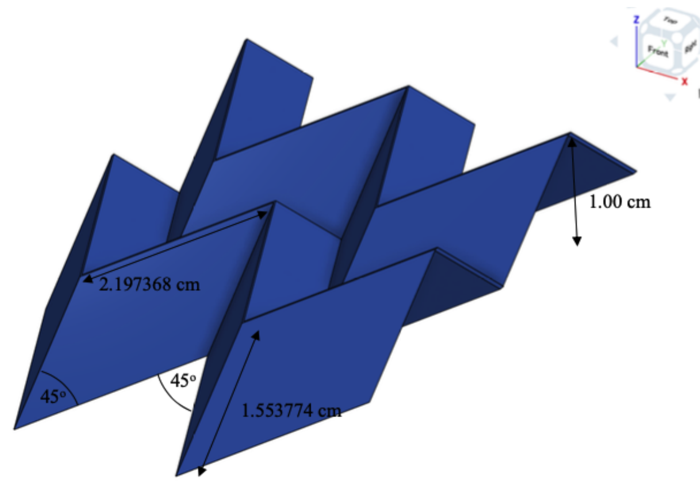
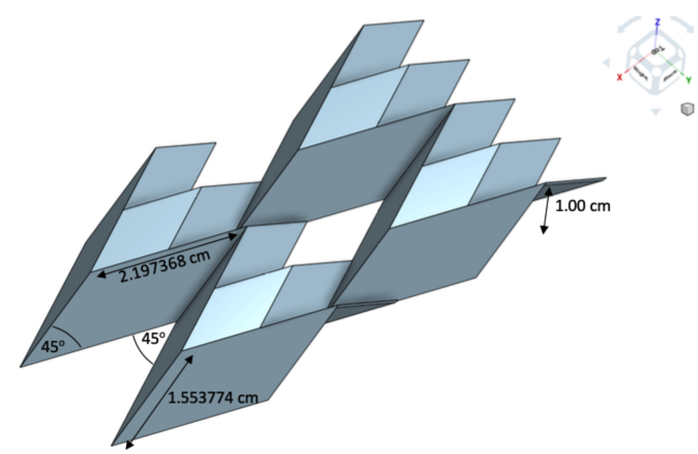
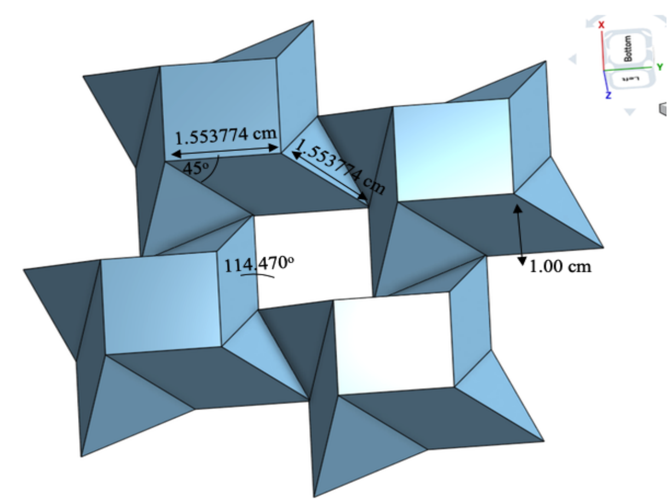
APPENDIX A: CORE GEOMETRIES

Table 1 (below) shows the geometric designs for each core along with their respective dimensions. The z-axis in each illustration is the direction of the height of the core (1.00 cm). The two rigid 10.0 cm x 10.0 cm plates are centered above and below each core, but are omitted in these illustrations for clarity. For the compression tests, the top plate was displaced along the z-axis. For the shear tests, the plate was displaced along the x or y axes. Though not completely consistent in these illustrations, the boundary conditions in the FEA software were assigned such that all the shear tests were consistent between the cores. For example, in shear D1, the top plate was displaced along the axial direction of the Miura-ori and zigzag base cores, even though this is the -y- and +x-axes respectively in the illustrations below.

<table>
<tr><th colspan="2">Table 1: Core Dimensions and Geometries</th></tr>
<tr><th>Honeycomb Core</th><th>Miura-Ori Core[1]</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><th>Zigzag Base Core</th><th>Square Twist Core</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

[1] The dihedral angles between the faces of the Miura-ori and zigzag base cores were calculated from equations given by Lv et al. [4].

In order to ensure comparable results, the four cores were designed with a constant core density of *0.05* ρ_m. Core density is given by the equation:

$$\rho_c = \frac{t_m S_m}{S_u Hc} \rho_m$$

where t_m, S_m, and ρ_m represent, respectively, thickness, total area, and density of the sheet of material from which the pattern's unit cell was made. S_u and H_c denote the base area of the unit cell and the core height (1.00 cm for each core). This equation was used in designing cores in the CAD software. Table 2 (below) shows the values of each of these parameters for the cores.

Table 2: Core Density Parameters

Core	t_m	S_m	S_u	H_C
Honeycomb	0.0336401937 cm	9.322644 cm^2	6.272311 cm^2	1.000 cm
Miura-Ori	0.0207106787 cm	9.656854 cm^2	4.000000 cm^2	1.000 cm
Zigzag Base	0.0230892702 cm	10.510408 cm^2	4.853553 cm^2	1.000 cm
Square Twist	0.0295917169 cm	12.538693 cm^2	8.071068 cm^2	1.000 cm

APPENDIX B: SIMULATION PARAMETERS

After the designs for each core were completed in the CAD software, they were imported into the FEA software to simulate the compression and shear loading conditions. The table below contains the complete set of parameters for the simulation runs.

Complete Simulation Parameters Static with Nonlinear Analysis Enabled	
Mesh	
Algorithm	Tet-Dominant
Sizing	Automatic
Fineness	Moderate
Order	Second
Allow Quadrangles	Off
Number of Processors	4
Refinements Local Element Size	
Sizing	Manual Mesh Sizing
Minimum Edge Length	0.05 m
Maximum Edge Length	0.1 m
Grading	Automatic Mesh Grading
Fineness	Coarse
Allow Quadrangles	On
Assignment	*The two rigid plates*
Contact 2 Bonded Contacts[2]	
Position Tolerance	Off
Master Assignment	*Interior face of top plate, Interior face of bottom plate*
Slave Assignments	*Top edges of the folded core, Bottom edges of the folded core*
Element Technology	Standard
Model	
Geometric Behavior	Nonlinear
Gravity Magnitude	0 m/s/s

[2] Bonded contact was chosen in order to reduce computational time.

Gravity Direction	*0 in x, y, and z directions*
Materials Aluminum	
Material Behavior	Linear Elastic[3]
Directional Dependency	Isotropic
(E) Young's Modulus	7 x 10^10 Pa
(v) Poisson's Ratio	0.34
Creep Formulation	No Creep
(p) Density	2700 kg/m^3
Assignments	*Entire structure*
Initial Conditions	
Displacement	*0 in x, y, and z directions*
Stress	*0 in all cases*
Boundary Conditions	
Fixed Support	
Assignments	*Bottom plate*
Fixed Value	
Displacement	*5 x 10^-5 * t m in the appropriate direction, 0 in all others*
Assignments	*Top face of top plate*
Numerics	
Solver	MUMPS
Force Symmetric	Off
Precision Singularity Detection	11
Stop if Singular	On
Matrix Type	Automatic Detection
Memory Percentage for Pivoting	20
Linear System Relative Residual	-1
Matrix Filtering Threshold	-1
Single Precision	Off

[3] This material model is a simplification that was chosen due to the software's limited ability to cope with large postbuckling nonlinear deformations.

Preprocessing	On
Prenumbering Method	SCOTCH
Postprocessing	Automatic
Distributed Matrix Storage	On
Memory Management	Automatic
Nonlinear Resolution Type	Newton
Convergence Criteria	Relative
Tolerance	0.0001
Prediction Matrix	Tangent
Jacobian Matrix	Tangent
Maximum Newton Iterations	15
Update Every nth Iteration	1
Update Every nth Increment	1
Change Jacobian Matrix	False
Mechanical Line Search	True
Method	Secant
Residual	0.001
Max Iterations	3
Simulation Control	
Time Step Definition	Automatic
Simulation Interval	1 s
Initial Time Step Length	0.1 s
Maximum Residual	100000
Retiming Event	Error
Time Step Calculation	Manual
Additional Newton Iterations	20
Number of Subdivisions	4
Max Subdivision Depth	3
Newton Iteration Threshold	5
Time Step Augmentation	100
Write Control Definition	All Computed

Number of Processors	8
Number of Parallel Processes	4
Maximum Runtime	5400 s
Result Control	
Solution Fields	Displacement, Cauchy Stress, von Mises Stress, Total Strain
Area Calculation	Sum
Field Selection	Force
Force Type	Reaction
Component Selection	All
Assignment	*Top face of top plate*

AP® RESEARCH
2019 SCORING COMMENTARY

Academic Paper

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Sample: A
Score: 5

This paper earned a 5 because it presents a focused topic of inquiry (page 3: "How do the mechanical properties of less-frequently explored origami tessellations compare to those of the Miura-ori pattern and other recognized standards?"). The method is elegantly defended (e.g., page 4: "Four cores were considered ..."), as is the use of a computer simulation (page 4). The paper reaches a new understanding on page 9, "While the honeycomb core, the standard core used in application, had the most favorable mechanical properties of the cores studied, documented problems associated with these cores makes the study of origami-inspired sandwich structures worthwhile" that is both justified closely tied to student-generated evidence. Its overall communication is elegant, and the paper is clear to the nonexpert.

This paper went beyond a 4 because it justifies the way it reaches its new understanding at every step of the inquiry process. This is especially true in its highly detailed "Discussion" section (pages 7–8). Each step of the inquiry process is detailed and explained. The care at which the paper goes to properly contextualize its conclusions is evidence of a high score. The paper's graphs and visuals emphasize the results of its analysis. The paper is elegantly written and interweaves limitations and implications throughout. In the discussion, the paper again circles back to the community of practice implications. Toward the end, the paper also discusses each of the origami tessellations, explaining the individual limitations for each tessellation (page 8). The organization of the paper enhances the communication, and the student's voice is clear from introduction to conclusion.