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Modeling and Analysis of Origami Impact Absorbers

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Abstract: The Japanese art of paper folding called origami has underlying principles that can help in the development of complex metamaterial structures. The purpose of the paper is to design, model, and analyze a feasible, more sustainable impact absorbing structure. There has been continuous development in the field of space science and aerodynamics, which has led us to encounter a lot of challenges. One of such challenges is smooth landing of objects. We started by creating tessellations with the help of Miura ori fold to get a repeating structure of the TCO (Triangulated Cylindrical Origami) with an aim to create a general-purpose design for Impact absorbing applications. A comparison between origami TCO's sheets, hexagonal sandwich sheets, and cardboard corrugated sheets was made. The TCO cells are better at absorbing energy absorption due to their physical structure. The *result* shows that the Origami TCO sheets exceed the traditional honeycomb and corrugated sheets. As the model we developed is a general-purpose design, it can be upscaled or downscaled depending on its required application, which can range from nano technology to space technology.

Keywords: Origami, impact, absorption, analysis, metamaterials.

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1. Introduction

Landing an autonomous spacecraft or rocket is difficult and landing one precisely near a target is considerably more difficult. Precision landing has the potential to revolutionize solar system exploration and enable rockets that can be refueled and reused in the same way that airplanes can. Mechanical metamaterials add a new level of complexity to achieving unconventional results and tailored mechanical properties through architecture. The ability to achieve this platform on which we build mechanical metamaterials has a big impact on their mechanical performance. The platform might vary from any regularly planned platform micro lattice structures to self-assembling cells to three-dimensional (3D) manufactured soft/hard developed materials. Recent research has revealed that origami may be used to create mechanical metamaterials that are exceedingly adaptable and programmable. The work by Wegener and Martin (2013) shows how metamaterials can be used in various applications by amalgamating their properties.

The principle of Origami is being sought to inculcate in a wide line of design ideas, which include robotics and architecture, reformable structures, and living cells who perform self-folding. While this research is primarily anchored upon the static or quasi-static properties of Origami, investigating the integration of dynamics in origami-built structures is a logical next step. The relationship between the crease structure of paper and the dynamic folding/unfolding behavior of the art has, however, remained largely unknown. Moreover, only a handful of experimental records, suggesting the same, have been reported. Origami has been used in space applications as well as many other applications. It is mainly used when there is a volumetric space constraint, like foldable solar panels used in satellites that can shrink down to a size that's nearly 10 times smaller.

The art of folding can help fulfill demands that come with applications related to mechanical engineering. While developing a shock absorber, the main focus is mainly on the type of material used, but sometimes the material that is best suitable for absorption is not suitable for the environment it is used in, or it can be extremely expensive. To reduce material dependency, better designs need to be implemented. This can be achieved by using TCO design unit cells. Due to their modularity, they can be adapted to different applications. By applying a compressive force on a linear stack of unit cells made from TCO, it can be found that a tensile wave is generated from the opposite direction, which takes more time to decay. And the subsequent energy absorption takes place. To use these TCO unit cells, we have to first find out how stress distribution takes place. By doing that, we can develop a general-purpose design that can be tweaked to work in many applications. In this paper, we are performing an analysis on several impact absorbers and comparing them with origami TCOs.

TCOs work on a principle of minimum potential energy which can be analysed as elastic potential energy change. The minimal potential energy concept, which may be interpreted as elastic potential energy change, underlies the operation of TCOs. The elastic potential energy (S) is written as a function of s (axial displacement) and φ (rotational angle).

$$S(s, \varphi) = \frac{1}{2} N_p K_a (x - x_0)^2 + \frac{1}{2} N_p K_a (y - y_0)^2 + \frac{1}{2} (2N_p) K (\theta - \theta_0)^2$$

Here, the length of creases are represented by x = x(*s*,) and y = y(*s*,). x_0, y_0 and $_0$ are the initial states. Deformation of TCO cells takes place by coupling axial and rotational motions. Coupling axial and rotational motions leads to deformation in TCO.

2. Literature Review

So, through literature review, we found that:

1. Yasuda et al. (2019) found that even though a compressive force is applied, metamaterials based on TCO cells demonstrate the single rarefaction wave, which propagates before the applied compressive strain and shows tensile stresses

2. Tolman et al. (2014) showed in their study that Miura-Ori may be utilized as cushioning inside a shipping box due to its strong elastic energy absorption and force dispersion.

3. Blackmore (2016) explained how high precision landing is a daunting task even on earth as it requires enormous calculations in real-time, and a landing system that has high flexibility can be the solution to this problem.

4. Zhang et al. (2018) found bioinspired landing gear morphologies for small aerial robots can be designed using origami-inspired corrugated shell mechanisms, creating a soft-landing pad**.**

To obtain different desired qualities, the TCO unit cells can be placed in various patterns and orientations. We can determine which layout is more appropriate for the application in terms of impact absorption by analyzing alternative arrangements. We attempted to make a sandwich out of it by placing it in a single plane between two flat sheets. These sheets can also be piled on top of one another to provide an impact absorption block that can be utilized in helmets and armor suits.

3. Methodology

The first step was problem identification, like studying the need for better impact absorbers. Metamaterial impact absorbers can be better suited for aerospace applications than traditional impact absorbers. Metamaterials made of TCO unit cells can be used, so we designed a tessellation where multiple unit cells can be created at once. To predict how the tessellations would fold into unit cells, we used origami simulator, which is online software that allows you to simulate how any origami crease pattern with a fold. Then it was necessary that the impact absorbing sheet we created performed better than traditional sheets like corrugated sheets and hexagon panels. To perform the dynamic stress analysis of honeycomb and TCO tiles, Simscale, which is a cloud-based analysis software, was used.

A Metamaterial is a material selectively engineered to exhibit properties that are unprecedented in nature. These materials are designed using repeating structures called Unit cells that allow them to direct and control the flow of electromagnetic or physical waves through them. Traditionally metamaterials have only been used in the field of optics as optical metamaterials were the predominant field, but now some scientific breakthroughs have drawn attention to mechanical metamaterials. In 2014, Lv et al. studied the intriguing properties present in origami structures in the form of mechanical materials. So, some of these scientific breakthroughs have drawn attention to mechanical metamaterials.

The art of Origami has been used for decades now in engineering and research applications, from space telescopes to deep-sea robotics, artificial muscles, and even drug delivery systems. TCOs, as the engineers call them, are modular structures critically designed to obtain properties unparalleled in nature. Unlike other metamaterials, which tend to harden on compression, this structure tends to exhibit strain-softening behavior; that is, the material turns a compression wave (heavy impact) into a tensile wave (a pull). This structure can literally reverse a physical force. As the compression force propagates through the structure, it creates a tensile wave ahead of it, and this happens so quickly that the tensile wave cancels out the impact significantly. We concluded that if a generic unit cell is created, it can be used in multiple applications with only a few small modifications. This would bring down the cost, and the time required to develop a new absorber for a new application would be less.

We tried to compare this arrangement to its commercially available competitors. In the packaging sector, for example, paper sheets were replaced by better-corrugated cardboard sheets, which were later replaced by better honeycomb structures, which provide superior structural damping. As a result, we compared these two designs to our setup to see if having a better physical design is preferable to employing a superior material. The widespread usage of impact absorbers that are currently in use, such as bubble wraps, packing peanuts, airbags, and other packaging materials for delivery boxes, is widespread. The amount of waste plastic produced accounts for a significant portion of the overall plastic waste problem.

General impact absorber materials are either difficult to make or difficult to dispose of. Miura-ori method contributes to art and design focused approaches to parametric origami design. The authors discovered some interesting kinetic properties in irregular, non-rigid foldable patterns. Our approach can help with these issues because the metamaterial unit cell may be made out of anything from paper to metal, and paper is easily recyclable. When compared to paper, the pollution generated by the amount of plastic is extremely large. As a result, employing non-plastic materials has a lower carbon footprint, resulting in less pollution. Because origami impact absorbers are more efficient than regular impact absorbers and can be better in the application as well as for the environment, this approach can be extremely adaptive. And, because they're made of paper or some other material, they're easy to make.

4. Results and Discussions

4.1 Designing Tessellations

4.1.1 Tessellation of the unit cell

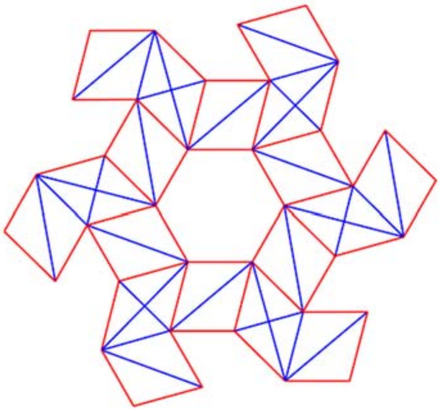

Fig. 1. Svg crease patterns of single unit cell

After going through multiple iterations, we finalized the tessellation shown in fig. 1. The tessellations were designed so that multiple unit cells could be created at once using a single planar sheet of material; here, a paper was used. This allowed for manufacturing multiple unit cells at once, which increased the overall efficiency.

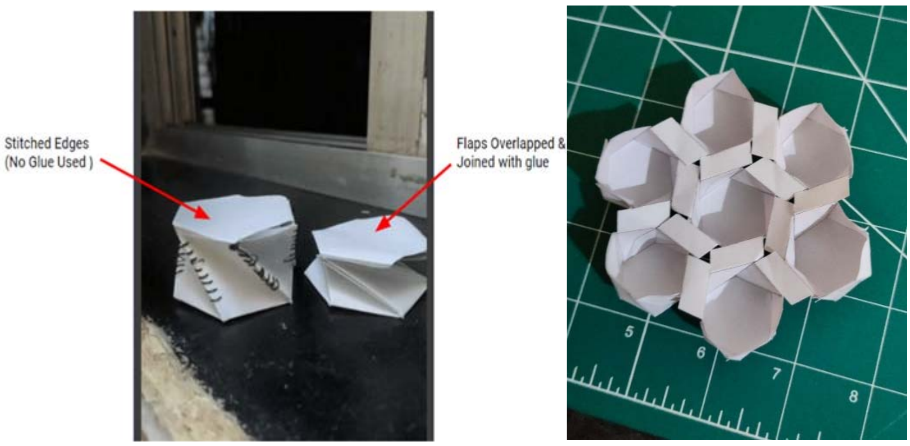

Fig. 2. Deformation comparison of TCO's force bearing capacity

While preparing the TCO for the tessellation shown in fig. 1, we saw that when the flaps are being glued over one another, TCO doesn't retract to its original shape. This can be seen in fig. 2. When only the edges of the TCO are hinged (stitched in this case), then the TCO is retracted in original shape

4.1.2 Arrangement of unit cells

After that, we created a better tessellation which allowed better packing of the unit cells as seen in fig. 3. This will help in providing structural rigidity and increase the overall impact mitigation. The closer the unit cells, the better the overall impact absorption of the tile.

A pack of 7 TCOs was successfully created with a single sheet of paper, as seen in Fig. 4. More such packs can be created and placed beside each other to form a big plane of TCOs.

Here we have assumed a rectangular plane of such planar arrangements as seen in Fig. 5, to perform analysis on it.

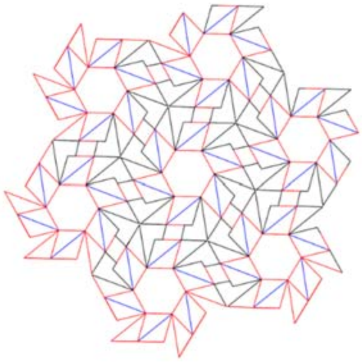

Fig. 3. Svg crease pattern tessellation arrangement of unit cell

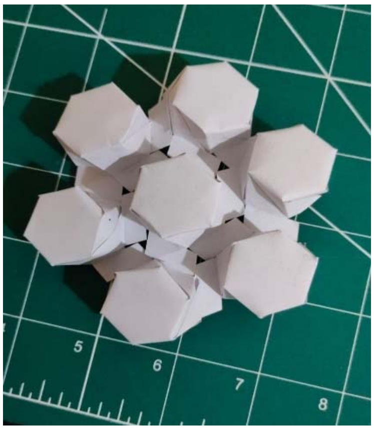

Fig. 4. Unit cells arrangement (top view) made with single sheet of paper (120gsm)

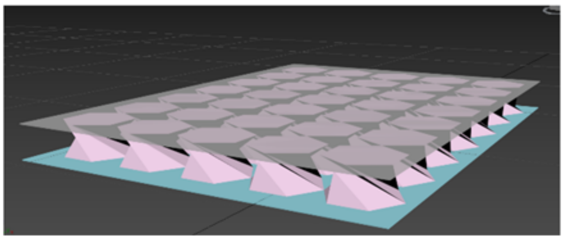

Fig. 5. 3D model of arrangement of TCOs

4.2 Analysis

4.2.1 Stress distribution analysis of singular cells

In order to make a recurring pattern of TCOs, first we determined the stress points on a TCO cell which was made out of our single tessellation (fig. 1). The stress distribution while folding the TCO can be seen in fig. 6.

When a load is applied on the upper surface of a properly closed TCO, we can see in fig. 7 that the maximum stress is getting concentrated on the edges of the TCO cell.

In 2017, Qi et al. showed that there can be designs which can overcome the traditional honeycomb structure in energy absorption characteristics. So, we too compared the TCO cell with the honeycomb cell.

If we performed the same load test on the traditional honeycomb structure (fig. 8), the stress is concentrated on the top vertices on the cell. Which shows that the structure will be crushed after the threshold limit is crossed and cannot be retained again.

4.2.2 Stress distribution analysis of planar sheets

Honeycomb structure from fig. 8 can also be multiplied and assembled in a planar form like we did in the TCOs arrangement from Fig. 5. Stress analysis is performed on both the sheets. Fig. 9 shows the load distribution on the traditional honeycomb structure arrangement. Fig. 10 shows the load distribution on TCO structure arrangement.

● One of the most recurring questions that have been asked is what material can be used. The answer to this lies in principle. Metamaterials are engineered so that their physical structure defines their properties and not the material it is made of. So, the unit cells can be made from virtually anything just by tweaking and modifying the model a little bit.

Terada et al. (2017) found that the application of the origami-foldable structures to the actual mechanical components can be embodied as materials like metals and alloys can be used for shock absorption.

● The main purpose of this paper was the design and analysis; as told before, here, the materials do not matter.

● The difference between absorption and rarefaction is demonstrated where the honeycomb sheets physically deform to absorb the impact while the metamaterial sheets exhibit rarefaction, as it cancels out the compressive wave that is applied to it.

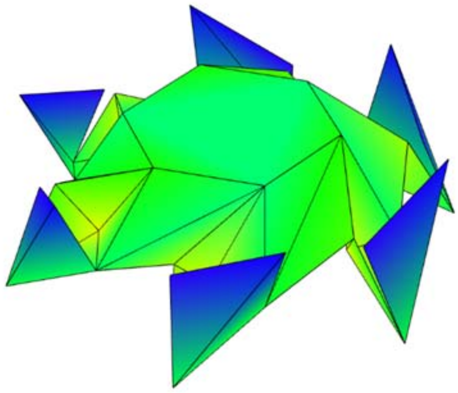

Fig. 6. Stress points on unit cell

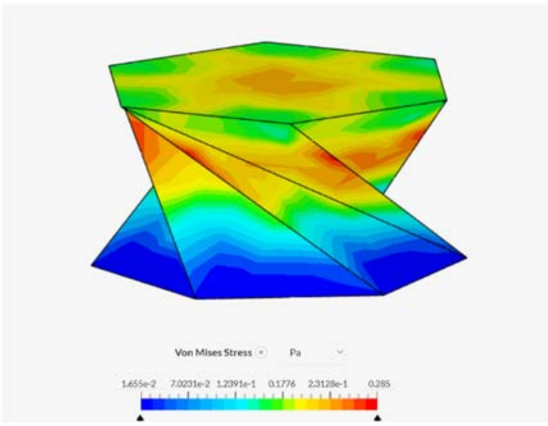

Fig. 7. Stress distribution on TCO

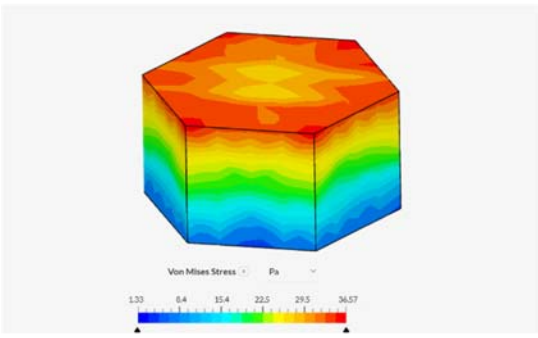

Fig. 8. Stress distribution on honeycomb unit cell

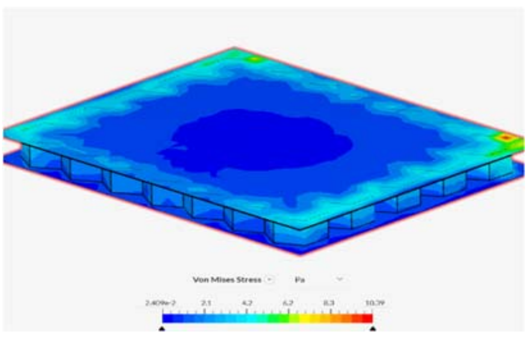

Fig. 9. Load distribution on honeycomb structure sheet

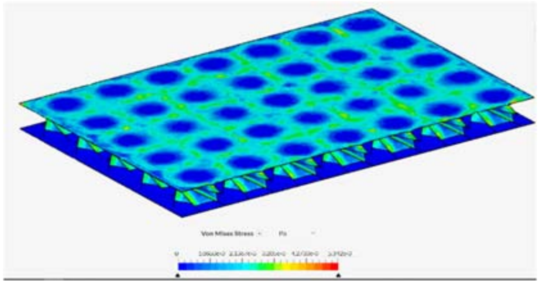

Fig. 10. Load distribution on TCO structure sheet

5. Conclusions

● It is not necessary for the material to be the prime parameter while designing an impact absorber. If the structural properties are altered in the desired way, simple materials can be turned into impact absorbers.

● While comparing two-unit cells, if one unit cell performs better and gives better results, then its planar sheet will also give a better result.

● After analysis, it is found that honeycomb structure unit cells physically collapse and permanently deform. On the contrary, TCO unit cells are made to deform, resulting in Impact absorption.

● The stresses are acting on angular side edges of the TCO due to its unique wave rarefaction property; on the contrary, the stresses are acting on the top plane of the honeycomb structure as its sides cannot deform, so it collapses and crushes.

● This was just to demonstrate and compare the TCO. These TCOs can be arranged in different manners, and desired properties can be achieved according to the required application.

● Rockets or space launching vehicles, hot air balloon landers, delivery packaging, car frames, airbags, helmets, armor suits, etc.

● Elastic energy absorption and force distribution are required in a variety of applications. Some origami-inspired devices based on folded tessellations, such as the Miura-ori pattern, have unique mechanical properties that could be useful in various applications.

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Institutional Review Board Statement

Not applicable.

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