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INVESTIGATING BEHAVIOR AND ENERGY ABSORPTION IN FRONTAL IMPACT OF A RECTANGULAR METAL WORKPIECE WITH AN ORIGAMI CORE

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Abstract: The structural elements known as bumper systems, which include beams and face bars, are vital parts of a vehicle's body framework, serving a critical function in dissipating impact energy by undergoing deformation. This research follows to examine and refine the design of frontal member beams within the durable framework of automobiles, specifically focusing on their ability to absorb internal energy generated from frontal collisions while upholding principles of sustainability. By merging conventional techniques in vehicle manufacturing with the innovative approach of "Origami Engineering," commonly employed by entities like NASA and professionals across diverse sectors such as aeronautics, nanotechnology, and medical technology, this study aims to advance our understanding and application of crashworthiness principles. Through the utilization of finite element methods in simulation analyses, diverse configurations including various types of thin–walled metal tubes and structures inspired by Origami were assessed. This interdisciplinary investigation holds promise for enhancing the safety and efficiency of automotive designs, aligning with evolving sustainability objectives. The findings of this research hold significant implications for improving the safety and performance of vehicles in frontal impact situations.
Keywords: bumper systems, frontal impact, sustainability, Origami engineering, finite element analysis

1. INTRODUCTION

The automotive industry continually strives to enhance vehicle safety standards, particularly concerning frontal impacts, which remain a leading cause of injuries and fatalities. Traditional bumper systems, comprising beams and face bars, have served as primary mechanisms for dissipating impact energy, presented in Figure 1 [1–3]. However, there is a recognized need for innovative approaches to further improve energy absorption capabilities and overall crashworthiness. This chapter provides an overview of the challenges associated with frontal impacts and introduces the concept of integrating Origami engineering principles into automotive design to address these challenges.

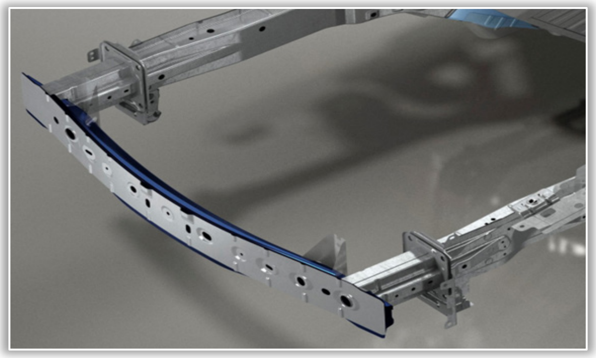

Figure 1. Front bumper automotive model

This study aims to contribute to the ongoing efforts to enhance vehicle safety by investigating the potential of a novel composite material—a rectangular metal workpiece with an Origami core—to improve energy absorption during frontal impacts, the structure and design is presented in Figure 2. By evaluating the structural behavior and crashworthiness of this innovative design, valuable insights can be gained into its effectiveness in improving the effects of collisions [4]. The findings of this research are expected to have significant implications for the automotive industry, impacting the development of future vehicle safety technologies as Ali J. et al. highlighted this aspect in their research.

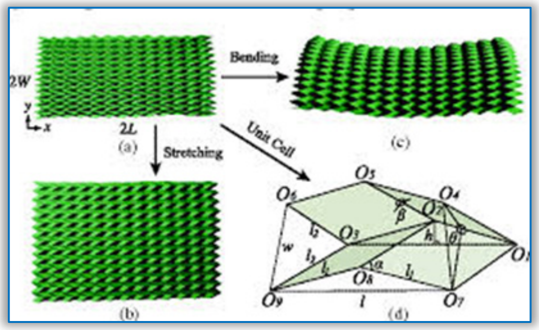

Figure 2. Origami structure and its application

The struts are located in the front part of the vehicles, they come as a continuation of the chassis, having the role of ensuring as much energy absorption as possible in the event of a frontal impact, but also of supporting certain components by mounting it [5–6].

Their shape and model differ from car to car, depending on the importance placed by the manufacturer on this very important part of the vehicle. The spars are found in a number of two pieces, being made in the mirror of each other.

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

The struts can be mounted on the chassis by means of screws or can be welded, at the other end they join the metal bumper, together constituting the most important part of the vehicle's resistance structure in terms of the mechanical field [7].

2. OBJECTIVES AND SCOPE

The primary objective of this study is to investigate the behavior and energy absorption characteristics of the rectangular metal workpiece with an Origami core during frontal impacts. Specific objectives include:

— Analyzing the structural response of the composite material under various impact scenarios.
— Assessing the energy absorption capabilities of the metal workpiece with an Origami core compared to traditional bumper systems.
— Exploring the influence of Origami engineering principles on frontal impact and structural integrity.
— Providing insights into the potential applications and benefits of integrating Origami core structures in automotive safety components.

The scope of this study theoretical testing, numerical simulations, and analysis of the structural performance of the composite material. Computational modeling techniques will be utilized to evaluate the behavior of the metal workpiece with an Origami core under controlled frontal impact conditions. The study will focus on assessing the energy absorption efficiency and crashworthiness of different materials, with a particular emphasis on its potential applications in enhancing vehicle safety.

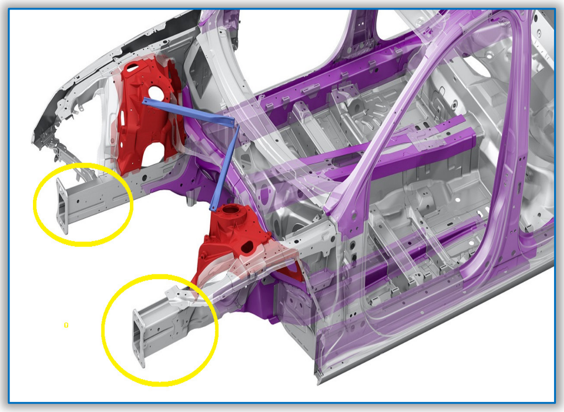

Figure 3. Volvo XC40 side member model

Through this investigation and in the study of Benjamin S.L et al., they studied a deeper understanding of the behavior and energy absorption mechanisms of the rectangular metal workpiece with an Origami core, laying the foundation for further advancements in automotive safety engineering [8].

As a result of the research study, a 3D model was made for teaching purposes, which is a copy of the spar on the VOLVO XC40 car, in Figure 4 above. For its realization, the assisted design program: CREO was used, which is a design software and analysis.

3. METHODOLOGY

Numerical simulation techniques

In this section, the numerical simulation methods employed to analyze the behavior and energy absorption characteristics of the metal workpiece with an Origami core will be discussed. Finite element analysis (FEA) will be the primary simulation technique used to model the structural response of the composite material under frontal impact loading conditions. The software packages and computational tools utilized for FEA will be ABAQUS, along with the material models and boundary conditions applied in the simulations. The validation procedures used to verify the accuracy of the numerical models will also be addressed [9–11]. In the scientific community, many researchers as Kotelko, M. carried a FEA analysis to compare different thin–walled profiles.

Following the research studies carried out, a series of elements were identified that can be modified in order to achieve the main goal of this work, namely: the creation of a structure with very good energy absorption properties, taking into account the principles of implementation. To generate the results, but also to identify the best tube solution for the spar, the following aspects were analyzed with the help of the "ABAQUS" simulation program:

— cross section of the tube
— wall thickness
— material

A displacement of 200 mm was applied to these tubes, which are 300 mm long and 100 mm wide, or in the case of the triangle, 150 mm in order to obtain a graph representing the kinetic energy absorbed by each tube in relation to the displacement at which it is subjected to the tube at the time of application.

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The material from which these shapes are made is aluminum.

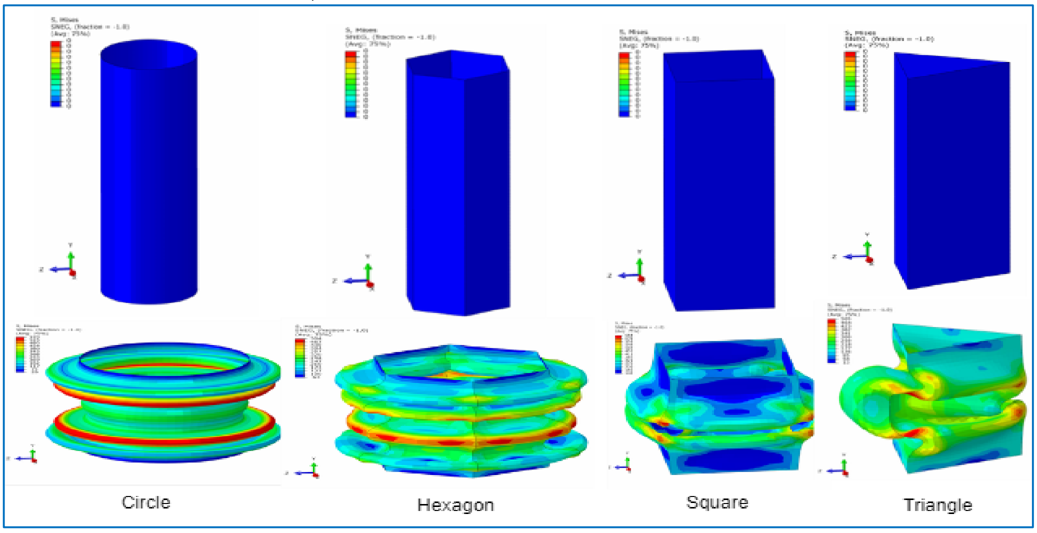

Figure 4. Structural models analyzed and deformation behavior

The square tube obtained an energy absorption of 39000 mJ, as can be seen in Figure 4, the minimum stresses to which the structure is subjected are 140 MPa, and the highest stresses are 684 MPa, they appear especially at the corners of the tube. This structure obtained the best results compared to the other three structures.

The square shape exhibited the highest energy absorption capacity, with a value of 39,000 mJ, followed by the hexagon shape with 34,000 mJ. The circle and triangle shapes displayed lower energy absorption capacities of [value] mJ and 17,000 mJ, respectively.

Maximum Tension: The square shape recorded the highest maximum tension value of 684 MPa, concentrated at its corners. The hexagon shape followed with a maximum tension of 504 MPa. The triangle shape had a maximum tension value of 461 MPa.

Minimum Tension: The hexagon shape displayed the lowest minimum tension value of 6 MPa, indicating relatively uniform tension distribution throughout the structure.

The next parameter analyzed is the wall thickness, which are three different values, as can be seen in Figure 5.

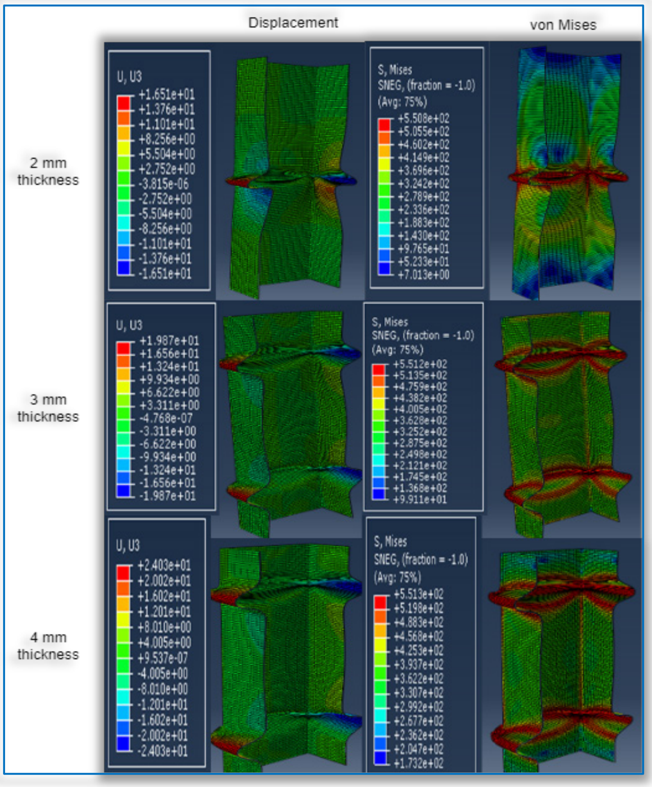

Figure 5. FEA analysis for thickness parameter

The thickness of the square tube significantly influences its energy absorption capacity and mechanical behavior. Thinner tubes offer superior energy absorption and deformation characteristics, while thicker tubes prioritize structural rigidity. Engineers should carefully consider the trade-offs between thickness and performance based on the requirements of the intended application.

Thinner tubes (2 mm) demonstrated superior energy absorption capacity compared to thicker ones (3 mm and 4 mm), indicating a more efficient deformation mechanism. The values obtained for each thickness value is highlighted in the Table 1.

Table 1. Thickness parameter values results

Thickness (mm)	Energy Absorption (kJ)
2	27
3	11
4	7

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

The choice of thickness should be tailored to specific application requirements, balancing considerations such as energy absorption, structural rigidity, and deformation capacity.

Thinner tubes may be preferred for applications where energy absorption and deformation capacity are critical, while thicker tubes may be suitable for scenarios where structural strength is paramount.

The results indicate that the thickness of the square tube significantly impacts its energy absorption capacity. Thinner tubes (2 mm) demonstrated superior performance in absorbing energy compared to thicker ones (3 mm and 4 mm). This suggests that for applications where energy absorption is crucial, selecting thinner tubes may be more advantageous. Further investigation into the relationship between thickness and mechanical properties could provide valuable insights for optimizing tube designs for specific engineering requirements.

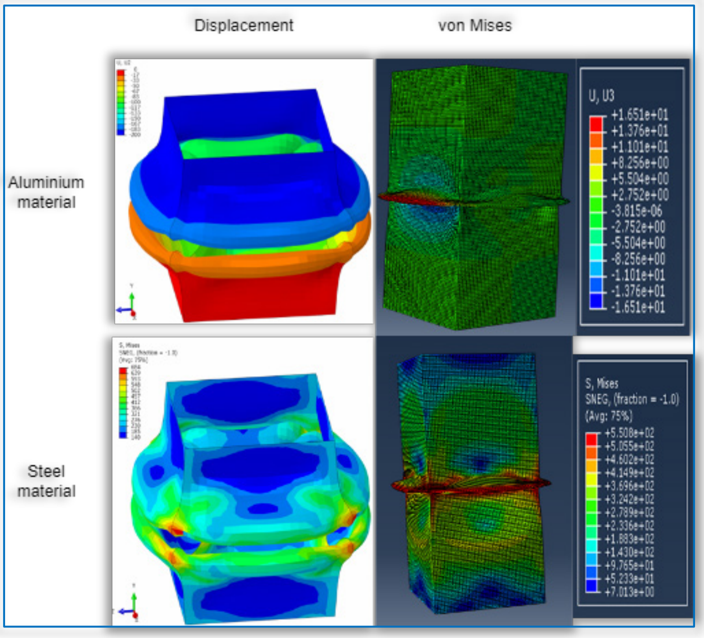

Figure 6. Analysis results for different materials

Aluminium tubes excel in energy absorption and offer lightweight construction, making them suitable for weight–sensitive applications where adequate strength is still required.

Steel tubes provide superior tensile strength and mechanical performance, making them ideal for demanding applications where durability, structural integrity, and resistance to deformation are essential, the results for each material are presented in Figure 6.

The choice between aluminium and steel tubes depends on specific application requirements and priorities. Aluminium is favored for lightweight applications where energy absorption and weight reduction are critical, while steel is preferred for applications where strength, durability, and resistance to deformation are paramount. In this study, aluminium material obtained a best behavior rather than steel [12]. The mechanical properties and its values are presented in Table 2.

Table 2. Mechanical properties for the materials used during analysis

Material	Mechanical properties					
	Density (g/cc)	Hardness	Modulus of elasticity (GPa)	Poissons Ratio	Shear modulus (GPa)	Specific heat (J/g–°C)
Aluminium	2.6989	15	68	0.36	25	0.900
Steel	7.8–8	126	200	0.25	80	0.470

Origami structure and configuration

This subsection focuses on the Origami patterns and configurations investigated in the study. Various Origami folding techniques and designs will be explored to assess their influence on the energy absorption capabilities and crashworthiness of the composite material. The selection criteria for Origami patterns, including factors such as fold density, orientation, and symmetry, will be discussed. Additionally, the fabrication processes and techniques used to create the Origami core structures will be described.

Since the structures are quite varied, the object of study was reduced to two of the most important aspects related to them, but also because they are also built from thin sheet metal, many of the characteristics being analyzed at the spar tube. These aspects are:

- cell shape
- number of rows with cells

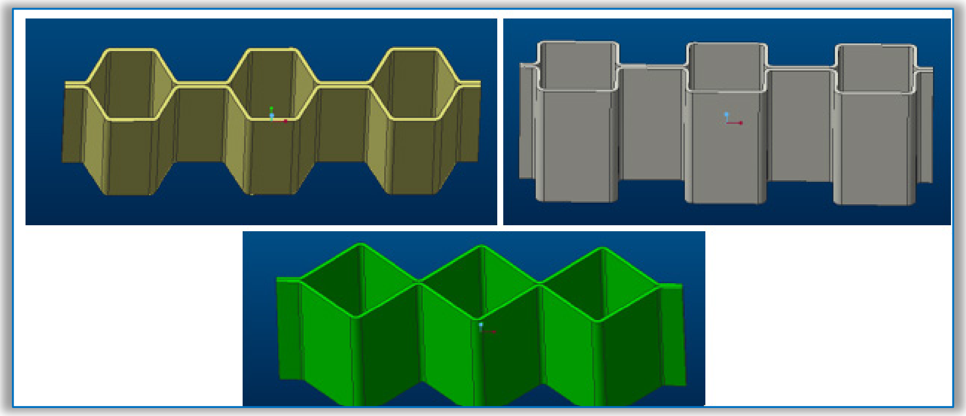

Figure 7. 3D models for cell shape designs

Triangle–shaped origami structures demonstrated the highest energy absorption capacity, followed closely by hexagons, with squares lacking specific data for comparison, in Figure 7.

Hexagonal structures offer a balance between stability and flexibility, while square structures provide simplicity and ease of fabrication.

The choice of origami structure shape should be tailored to specific application requirements, considering factors such as energy absorption, tension distribution, stability, and ease of fabrication.

4. NUMERICAL SIMULATION RESULTS

Stress analysis and deformation patterns

This section presents the results of the numerical simulations conducted to analyze the stress distribution and deformation patterns of the rectangular metal workpiece with an Origami core during frontal impacts. The finite element models will be utilized to visualize the stress contours and deformation modes experienced by the composite material under different loading conditions. The influence of Origami patterns and configurations on stress concentrations and deformation behavior will be analyzed and compared.

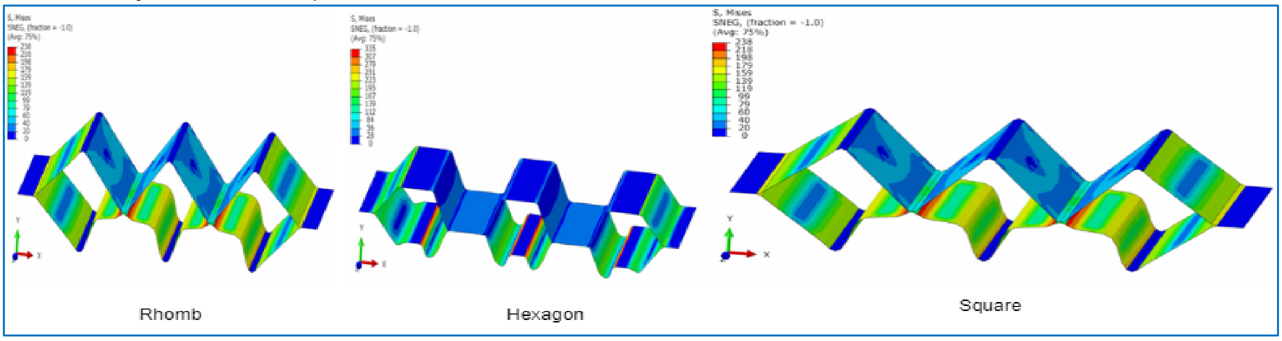

Figure 8. Von Mises stress values

After the analysis with the Abaqus program, an Origami Engineering structure with triangular cells, having two rows of such cells, was subjected to a compression test. This was embedded on one of the sides, and a displacement was applied to the other side in order to deform the structure. Two parameters were analyzed, displacement and von Mises stress, which are presented in Figure 8 and Figure 9. The best behavior was for the triangle shape.

The triangle shape emerged as the most promising origami structure in terms of displacement and stress distribution. Its efficient deformation behavior suggests superior energy absorption capabilities compared to hexagon and square shapes. However, the hexagon and square shapes offer unique advantages, such as higher stress resistance and more uniform stress distribution, respectively.

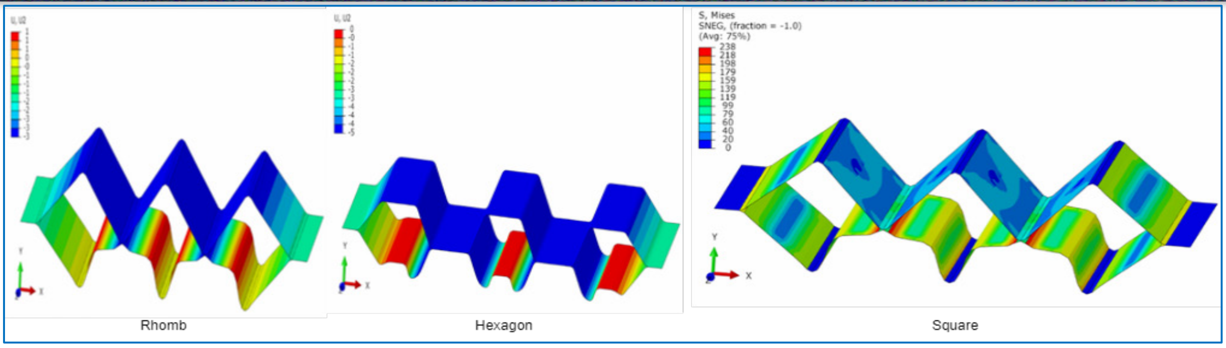

Figure 9. Displacement values for Origami structure

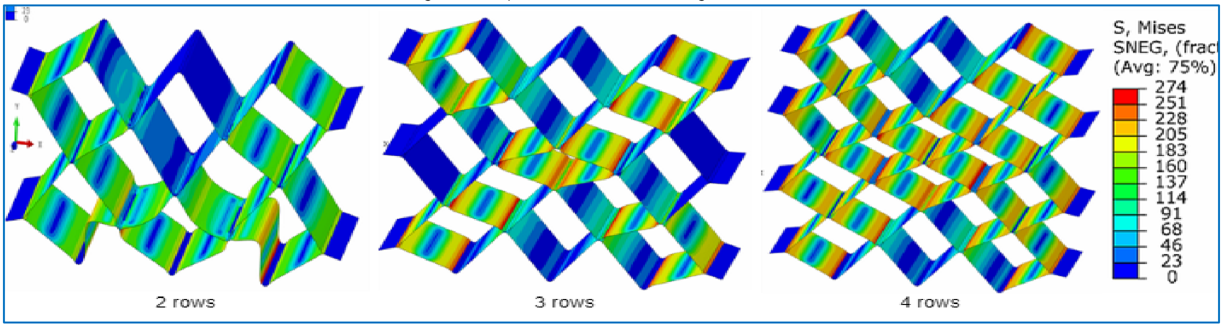

Figure 10. Von Mises values for different rows number

In this study, it was explored the performance of triangle origami structures with varying numbers of rows: 2, 3, and 4. Two critical parameters, von Mises stress and displacement, were analyzed to evaluate the behavior of each configuration. Both displacement and von Mises parameters for two rows structure were analyzed in Figure 10 and Figure 11.

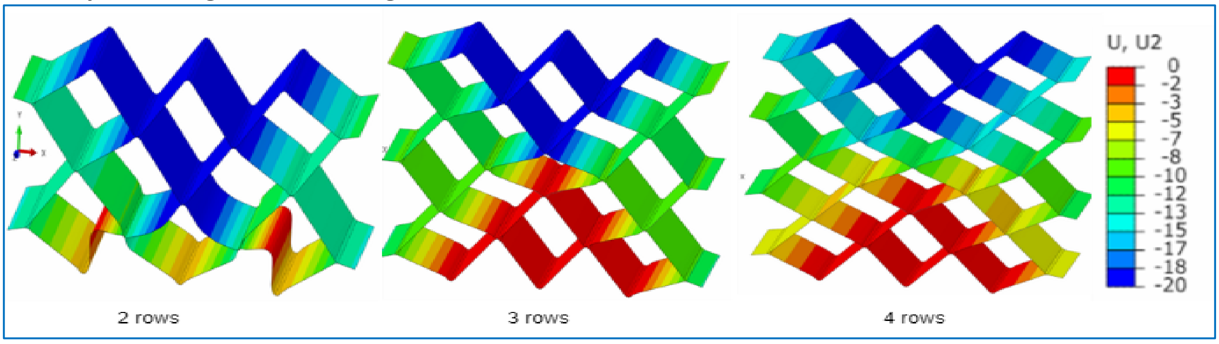

Figure 11. Displacement values for row structures

The performance of triangle origami structures varied depending on the number of rows used. The configuration with 2 rows showed superior displacement and stress resistance compared to configurations with 3 or 4 rows. However, each configuration offers unique advantages and trade–offs, and the choice should be based on specific application requirements and priorities.

Front bumper with Origami structure

In modern automotive design, the integration of advanced materials and innovative structural concepts plays a pivotal role in enhancing both performance and safety. Origami–inspired structures have emerged as a promising solution, offering lightweight and robust configurations that can be tailored to specific engineering applications. In this context, the integration of origami structures into front bumper designs presents a unique opportunity to optimize energy absorption, deformation characteristics, and structural integrity in the event of a collision.

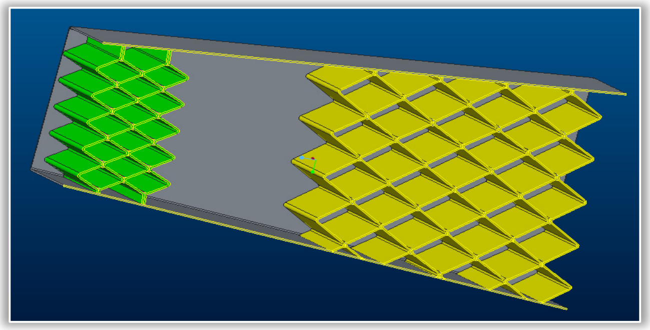

Figure 12. Two structures assembly

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

This time it is proposed to assemble the same tube, with two structures of different configuration present. They are positioned as follows:

- The structure formed by four rows of cells is positioned at the tail of the spar
- The structure made of two rows of cells is positioned at the end of the spar

The integration of the origami structure with 2 rows of cells into the front bumper represents a significant advancement in automotive engineering, providing a robust and lightweight solution for enhancing safety and performance on the road.

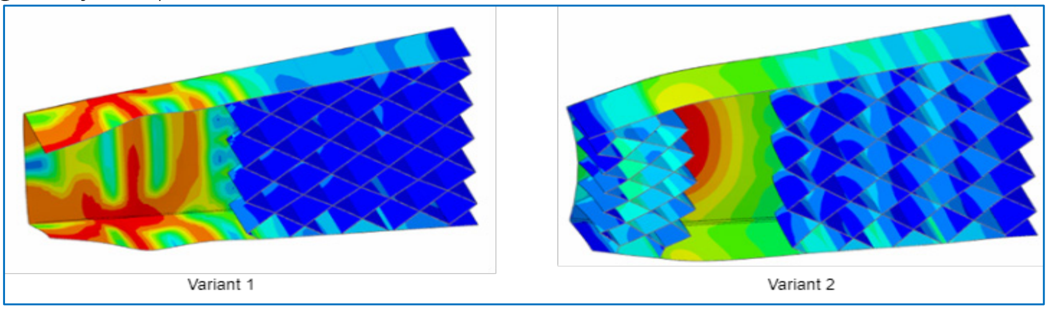

Figure 13. Von Mises tension values for two structure variants

The analysis revealed variations in tension distribution across different configurations of the origami structure, as presented in Figure 13.

Among the configurations studied, the variant with two rows of cells at the end of the spar exhibited the best tension values.

This configuration demonstrated optimal tension distribution, ensuring structural integrity and minimizing the risk of failure under loading conditions.

The finite element analysis of the front bumper with an origami structure featuring four rows of cells positioned at the tail of the spar and two rows of cells at the end of the spar provided valuable insights into its mechanical behavior and performance characteristics. The variant with two rows of cells at the end of the spar demonstrated superior tension values, indicating enhanced structural integrity and improved energy absorption capabilities.

5. CONCLUSIONS

The conclusion chapter serves as a summary and synthesis of the key findings and insights gained from the investigation into the behavior and energy absorption in frontal impact of a rectangular metal workpiece with an Origami core. It provides a comprehensive overview of the study's objectives, methodologies, results, and implications. The primary purpose of this chapter is to draw conclusions based on the research findings and offer recommendations for future studies or practical applications.

This section recaps the main findings of the study, highlighting significant observations and results obtained from numerical simulations. It summarizes the structural response, energy absorption characteristics, and performance of the different metal workpiece with an Origami core during frontal impacts.

The conclusion section offers a concise summary of the study's main findings, implications, and recommendations. It reaffirms the significance of the research in advancing the understanding of energy absorption in frontal impacts and underscores the potential of Origami–based designs in improving vehicle safety. The chapter concludes with a call to action for further research and innovation in the field of automotive safety engineering.

Through the conclusion chapter, the study aims to provide a comprehensive synthesis of the research outcomes, offering valuable insights and recommendations for advancing knowledge and practice in automotive safety engineering.

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ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665