VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

FACULTY OF ENVIRONMENTAL ENGINEERING

DEPARTMENT OF ROADS

Austėja Brazdeikytė

DESIGN AND ANALYSIS OF ADDITIVE MANUFACTURING-ENABLED LIGHTWEIGHT COMPONENTS FOR PEDESTRIAN BRIDGES

Master‘s degree Thesis

Innovative Road and Bridge Engineering study programme, state code 6281EX002

Civil Engineering study field

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Title	**Design and Analysis of Additive Manufacturing-Enabled Lightweight Components for Pedestrian Bridges**
Author	**Austėja Brazdeikytė**
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Annotation

In the contemporary landscape of pedestrian bridge design, there exists a dual imperative bridges must not only be aesthetically pleasing but also structurally resilient to support intricate architectural concepts. The demand for lightweight structures to realize these complex designs is clear, yet traditional materials and production methods often fall short of meeting the multifaceted challenges. Inner structures, made possible through additive manufacturing techniques, have the potential to act as dynamic modifiers, enabling precise control over the structural response. The aim of the work is to develop a structurally adaptable lightweight lattice core sandwich component using additive manufacturing techniques. The master's thesis consists of 3 main parts: reviews of the development and analysis of additive production compatible components for light pedestrians bridges in literature; geometric core design; obtaining experimental studies and diagrams of geometric core samples; Numerical modeling of geometric core samples and results obtained. Experimental (6 geometric cores were tested) and numerical (using computer programs SOLIDWORKS, ZEISS CORRELATE) methods were used for the research. The obtained results showed that the best behavior corresponded to the honeycomb core. The results of the experimental and simulation part showed that the software parts can estimate the behavior of the beams well.

Master's thesis consists of 69 pages, that include 57 figures, 9 tables and 27 literature sources.

Keywords: 3D printing, additive manufacturing, lightweight, lattice core, sandwich structure

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Antrosios pakopos studijų **Inovatyvios kelių ir tiltų inžinerijos** programos magistro baigiamasis darbas 3 (keliai ir tiltai)	
Pavadinimas	**Su adityviąja gamyba suderinamų lengvųjų pėsčiųjų tiltų komponentų kūrimas ir analizė**
Autorius	**Austėja Brazdeikytė**
Vadovas	**Arvydas Rimkus**

Kalba: anglų

Anotacija

Šiuolaikiniame pėsčiųjų tiltų projektavimo kraštovaizdyje egzistuoja dvigubas reikalavimas, kad tiltai turi būti ne tik estetiški, bet ir struktūriškai atsparūs sudėtingoms architektūrinėms koncepcijoms palaikyti. Lengvų konstrukcijų poreikis šiems sudėtingiems projektams įgyvendinti yra aiškus, tačiau tradicinės medžiagos ir gamybos metodai dažnai neatitinka daugialypių iššūkių. Vidinės struktūros, sukurtos naudojant priedų gamybos metodus, gali veikti kaip dinaminiai modifikatoriai, leidžiantys tiksliai kontroliuoti struktūrinį atsaką. Darbo tikslas – sukurti struktūriškai pritaikomą lengvą gardelės šerdies daugiasluoksnį komponentą, naudojant priedų gamybos būdus. Magistro baigiamasis darbas susideda iš 3 pagrindinių dalių: su adityviąja gamyba suderinamų lengvųjų pėsčiųjų tiltų komponentų kūrimo ir analizės apžvalgos; geometrinių šerdžių projektavimas; geometrinės šerdies bandinių eksperimentinių tyrimų ir diagramų gavimo; geometrinės šerdies bandinių skaitinio modeliavimo ir rezultatų gavimo. Tyrimams atlikti buvo taikomi eksperimentiniai (išbandytos 6 geometrinės šerdies), ir skaitiniai (naudojant kompiuterines programas SOLIDWORKS, ZEISS CORRELATE) metodai. Gauti rezultatai parodė, kad geriausią elgseną atitiko korio šerdis. Eksperimentinės ir modeliavimo dalies rezultatai parodė, kad programinės įrangos dalinai gerai gali įvertinti sijų elgsenas.

Magistro baigiamasis darbas susideda iš 69 puslapių, kuriame yra 57 paveikslai, 9 lentelės ir 27 literatūros šaltiniai.

Prasminiai žodžiai: 3D spausdinimas, priedų gamyba, lengva konstrukcija, gardelės šerdis, daugiasluoksnė struktūra

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Austėja Brazdeikytė

DESIGN AND ANALYSIS OF ADDITIVE MANUFACTURING-ENABLED LIGHTWEIGHT COMPONENTS FOR PEDESTRIAN BRIDGES

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THE OBJECTIVES:

Explanatory note: Apžvelgti konstrukciniam taikymui naudojamus adityvia gamyba paremtus sprendinius, jų taikymą lengvoms tiltų konstrukcijoms bei tinkamų medžiagų parinkimo ir objektų struktūros komponavimo principus. Išnagrinėti adityviai pagamintų objektų skaitinio modeliavimo galimybes bei įvertinti modelių adekvatumą. Atlikti lengviems pėsčiųjų tiltams tinkamų elementų modelių konstrukcinį taikymą charakterizuojančius bandymus bei gautų eksperimentinių duomenų analizę. Sukurti nagrinėjamo objekto skaitinį baigtinių elementų modelį, bei patikrinti jo adekvatumą. Suformuluoti išvadas bei rekomendacijas tolimesniam konstrukciniam adityviai pagamintų objektų taikymui.

Academic Supervisor Associated Professor Arvydas Rimkus

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DECLARATION OF AUTHORSHIP IN FINAL DEGREE THESIS

2024-01-03
(Date)

I confirm, that my final degree thesis, which topic is Design And Analysis Of Additive Manufacturing-Enabled Lightweight Components For Pedestrian Bridges

is written independently. The material presented in this final degree thesis is not plagiarized. Quotations from other sources used directly or indirectly are indicated in the literature references.

During the selection and evaluation of the material and the preparation of the thesis, I was advised by scientists and specialists: -

My supervisor is Assoc. Prof. Dr. Arvydas Rimkus

There is no contribution of other persons to the final degree thesis. I have not paid any statutory sums of money for this work.

Signature

Austėja Brazdeikytė
(Name and Surname)

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INTRODUCTION

Relevance of the topic

The use of additive manufacturing has the potential to revolutionize lightweight bridge construction by increasing structural efficiency, minimizing material waste and encouraging inventive design techniques. Additive manufacturing (3D printing) can design geometries that would have been previously problematic or impossible under traditional approaches for producing models. This technology facilitates production of robust yet light-weight components crucial in reducing the overall weight of bridges. Custom additive manufacturing also creates custom designs tailored to specific loading conditions, improving performance with fewer resources. In addition, layered fabrication enables integration with smart materials and sensors, creating responsive bridges that adapt to various environmental factors. Additive manufacturing can reduce material waste and energy consumption compared to traditional manufacturing methods. The ability to build complex structures with minimal material waste contributes to sustainability and cost-effectiveness in construction projects. In summary, additive manufacturing for producing systems is an approach with a broad spectrum of benefits. Revolutionises the way reinforcement is integrated into composite elements, offering superior structural performance, enhanced corrosion resistance, and customisation, ultimately contributing to more resilient and sustainable infrastructure. This innovation is particularly relevant as it addresses key challenges in modern construction and engineering while opening doors to new possibilities for complex and efficient design.

Problem

In the contemporary landscape of pedestrian bridge design, there exists a dual imperative bridges must not only be aesthetically pleasing but also structurally resilient to support intricate architectural concepts. The demand for lightweight structures to realize these complex designs is clear, yet traditional materials and production methods often fall short of meeting the multifaceted challenges presented.

Of particular concern is the dynamic response and vibration control in lightweight pedestrian bridge structures. As designs become more intricate, designers grapple with the responsibility of avoiding resonance through effective damping or altering natural frequencies. This dynamic aspect necessitates a novel approach—one that involves the production of structural elements with intricate inner geometries. These inner structures, made possible through additive manufacturing techniques, have the potential to act as dynamic modifiers, enabling precise control over the structural response.

Research object

Additively manufactured lattice core sandwich structure defines the reseach object.

Aim

The aim of the work is to develop a structurally adaptable lightweight lattice core sandwich component using additive manufacturing techniques.

Tasks

1. Conduct a comprehensive literature review on additive manufacturing solutions for structural applications.
2. Develop a set of principles for selecting appropriate materials and composing the structure of investigated objects.
3. Design and conduct experimental tests to characterize the structural application of investigated objects.
4. Analyze experimental data to validate the performance of additively manufactured structures.
5. Develop a numerical finite element model for the investigated object. Verify the adequacy of the model by comparing its predictions with the experimental data.
6. Formulate comprehensive conclusions and provide recommendations for the further structural application of additively manufactured objects in lightweight bridge structures.

Research Methods

The developed lightweight lattice core sandwich structure will be investigated by theoretical (numerical and analytical) and experimental methods. The experimental investigation will contain three-point bending tests.

Practical significance of work results

The practical significance of the work results in this work on 3D-printed sandwich beams for lightweight bridge components lies in the potential advancements and applications in the field of civil engineering and infrastructure development. Lightweight materials are crucial for reducing the overall weight of the structure, which could lead to cost savings and improved structural efficiency. Lightweight materials are often easier to transport and handle, potentially reducing construction costs and making the overall construction process more efficient. Lightweight materials often have a smaller environmental footprint compared to traditional construction materials. Investigating the three-point bending experiment and numerical models can provide insights into the structural performance of 3D-printed sandwich beams. If these components demonstrate sufficient strength and durability, it could lead to safer bridge designs. The use of 3D printing in bridge construction is an innovative approach. If the research proves to be successful, it could open up new possibilities for incorporating advanced manufacturing techniques into the construction industry, leading to further innovation and advancements.

1. LITERATURE REVIEW ON LIGHTWEIGHT BRIDGE DESIGN AND ADVANCED STRUCTURAL APPLICATIONS

1.1 Lightweight structures in bridge design

The latter half of the twentieth century and the early twentieth century have seen remarkable strides in reinforcement materials and construction techniques. The development of fibre-reinforced composites, advanced concrete mix designs, and computer-aided design and analysis tools have expanded the possibilities of bridge engineering. Engineers are now able to design structures that are not only durable, but also energy-efficient and environmentally friendly. Although history has had a great influence on the composition and arrangement of structures, there are scientific sources which says that (Wilkie & Dyer, 2022) while many of the bridges are at risk from durability-related issues, there appears to be no correlation between the year they were built and the level of risk, i. e. the oldest structures are not necessarily the ones most at risk. In fact, results of this study suggest that the risk of deterioration of historic concrete structures is dependent on the initial quality of the concrete, the depth of cover to reinforcement, and the environmental exposure conditions, a conclusion which corresponds with the findings of other authors (Bertolini et al., 2011), (Marcos et al., 2016). These research efforts encourage us to find innovative ways to improve bridge construction. A reinforcement system is crucial in bridges to enhance structural integrity, increase load bearing capacity, and extend the overall life of the structure. Reinforcements, typically made of materials such as steel or fibre-reinforced polymers, strengthen bridges against various forces, such as traffic loads, environmental factors, and ageing. This proactive measure helps prevent structural deterioration, mitigates the risk of failure, and ensures the safety and longevity of the bridge.

Considering another option and choosing lightweight construction in bridge construction offers several advantages that make it a preferred option. Lightweight construction typically involves the use of advanced materials, allowing for the creation of strong structures with fewer materials. The use of lightweight materials often results in easier handling, transportation, and installation during construction. Reduced weight may lead to lower labour costs, shorter construction timelines, and less dependence on heavy machinery.

In civil engineering, lightweight structures are defined as constructions that employ materials with a lower density, such as advanced composites and engineered alloys. The importance of lightweight structures lies in their transformative impact on various aspects of civil engineering. By minimising structural material requirements and lowering foundation loads, lightweight structures not only contribute to cost effectiveness but also facilitate easier transport and handling during construction. Their increased sustainability, adaptability in design, and improved seismic performance further underscore their significance. Furthermore, the application of lightweight structures is a promising approach to reduce the energy demand of vehicles and thus to achieve more sustainable mobility (Dér et al., 2018). The versatility of lightweight materials allows for creative architectural designs while promoting energy efficiency in building envelopes. In essence, the adoption of lightweight structures represents a pivotal shift towards more efficient, sustainable, and resilient practices in civil engineering.

Lightweight structures in civil engineering refer to constructions that use materials with low density, often characterised by a high strength-to-weight ratio. These structures aim to minimise overall weight while maintaining or improving structural integrity, functionality, and safety. Lightweight construction materials may include advanced composites, aluminum alloys, and engineered polymers, but are not limited to them.

Lightweight structures typically use materials that are less dense than traditional construction materials. For example, advanced composites, lightweight alloys and engineered materials may be used instead of heavier options like steel or concrete. This reduction in material density directly results in a lower dead load on the structure. Construction materials for lightweight structures are often easier to transport and handle on the construction site. Additionally, the reduced weight of individual components allows for easier assembly and installation. The use of materials with lower density facilitates transportation to construction sites, making the logistics of moving components more efficient. The reduced weight of these materials not only simplifies the loading and unloading processes, but also enhances on-site handling, allowing easier assembly during construction. This characteristic is particularly advantageous in projects where access to remote or challenging locations is a factor. Structures often incorporate environmentally friendly materials, such as recycled composites or materials with a lower carbon footprint. This focus on sustainability aligns with modern construction practices that aim to reduce the environmental impact of building projects.

Lighter structures may experience less inertia during an earthquake, reducing the forces exerted on the building and its foundation. This can contribute to increased safety and resilience. Materials often provide greater flexibility in architectural design. Engineers and architects can explore innovative and aesthetically pleasing designs without compromising the structural integrity of the building. This versatility can lead to more creative and sustainable solutions.

Lightweight construction materials are often conducive to modular construction methods. Modular components can be prefabricated off-site and assembled on-site, reducing construction time and costs. This adaptability is particularly advantageous in projects where speed is essential.

Advantage of lightweight structures is that they can contribute to sustainability by reducing the environmental impact associated with construction. Lower material consumption and energy requirements align with the growing emphasis on eco-friendly engineering practices.

According to statistics, the manufacturing sector is responsible for approximately 33 % of primary energy use and for 38 % of the CO2 emissions globally (He et al., 2016).

The environmental impact of construction projects is a critical consideration and lightweight structures play a significant role in mitigating negative effects. Using materials with lower density and eco-friendly alternatives, these structures contribute to a reduction in overall carbon footprints and resource depletion. Lightweight construction materials' manufacturing processes often involve less energy consumption and emissions compared to traditional, heavier counterparts. The development of lightweight structures often involves the utilisation of advanced manufacturing technologies, such as 3D printing and composite material fabrication. This integration of cutting-edge techniques contributes to the evolution of civil engineering practices.

1.2 Structural applications of additive manufacturing

Additive manufacturing (AM) in construction involves layer-by-layer deposition of materials to create three-dimensional structures. It is a departure from traditional subtractive methods and offers advantages in terms of design flexibility, material efficiency, and potential for automation.

Additive manufacturing's application in the construction industry has ushered in an era of rapid prototyping and iteration. This technology allows for the swift and cost-effective creation of prototypes, enabling architects, engineers, and designers to quickly test and refine their concepts. The layer-by-layer (fig. 1.1) construction process facilitates easy modification of designs, allowing for iterative improvements and adjustments based on real-time feedback. This capability accelerates the design and development phases of construction projects, fostering innovation, and reducing the time traditionally spent on prototyping. The ability to rapidly iterate through various design iterations not only expedites the overall construction timeline, but also enhances the precision and performance of final structures by identifying and addressing potential issues early in the design process.

Fig. 1.1. Layer by layer construction example (BE-AM 2023 Syposium, 2023).

The integration into the construction industry offers unparalleled opportunities for customisation and personalization in building design. This technology allows for the creation of unique and customised components and structures that meet specific architectural preferences, functional requirements, and individual client needs. Architects and builders can leverage additive manufacturing to create intricate details, personalised elements, and diverse textures that may be challenging or impractical with traditional construction methods. From facades to interior components, the ability to customise and personalize construction elements enhances the overall aesthetics and functionality of buildings, creating spaces that reflect the distinct preferences and visions of clients while pushing the boundaries of design possibilities in the construction industry.

Although initial investment in 3D printing technology can be significant, the potential for cost reduction lies in material efficiency, reduced labour requirements, and the ability to produce complex structures in less time. As additive manufacturing continues to evolve, its potential to optimise resource usage and reduce both material and labour costs positions it as a transformative force in achieving cost-effective and sustainable construction practices.

Portable 3D printers enable on-site construction, reducing the need for extensive transportation of prefabricated components. This is particularly advantageous in remote or disaster-stricken areas where quick construction is essential. On-site printing and construction, facilitated by additive manufacturing technologies, revolutionise traditional building methods by bringing the construction site and the manufacturing process closer alignment. This approach involves direct 3D printing of structures on the construction site, reducing the need for extensive transportation of prefabricated components. On-site printing offers significant advantages, such as increased flexibility, reduced logistical challenges, and the potential for rapid construction. The immediacy of building structures on location allows for real-time adjustments, adaptability to site-specific conditions, and customization of designs according to evolving project requirements. This innovative method not only streamlines construction processes, but also minimises the environmental impact associated with transportation, making on-site printing a promising avenue for the future of sustainable and efficient construction practices.

Additive manufacturing in the construction industry facilitates the realisation of complex geometries and organic forms that were once challenging or impossible to achieve using traditional construction methods. Layer-by-layer additive process allows for intricate and customised designs, enabling architects and designers to explore innovative shapes and intricate geometries. This capability is particularly impactful in creating architecturally unique structures, facades, and components that not only serve functional purposes but also contribute to the aesthetic appeal of buildings. The flexibility offered by additive manufacturing technology encourages the exploration of unconventional architectural forms, pushing the boundaries of design, and allowing for the construction of visually striking and structurally efficient buildings that reflect a new era of creative possibilities in construction.

From initial design concepts to the actual construction phase, digital integration involves the seamless exchange of data and information at various stages of a construction project. Building Information Modelling (BIM) systems, computer-aided design (CAD) software, and other digital tools facilitate the efficient translation of architectural visions into 3D printed realities. This integration improves collaboration among architects, engineers, and construction teams, ensuring a more synchronised and data-driven approach to project development. The digital thread weaved throughout the construction lifecycle optimises decision-making, mitigates errors, and fosters greater precision in the execution of complex designs, ultimately contributing to the overall efficiency and success of additive manufacturing applications in the construction landscape.

From robotic construction equipment to automated machinery, the integration of automation technologies significantly accelerates construction timelines while improving precision and efficiency. Automated systems can handle tasks such as building, 3D printing of structures, and even autonomous vehicles for material transport, reducing the need for manual labor and mitigating associated safety risks. The use of drones and sensors also facilitates real-time monitoring and data collection on construction sites, improving project management and decision-making processes. Construction automation not only addresses labour shortages, but also contributes to increased productivity, cost-effectiveness, and the ability to undertake complex projects with greater speed and precision. As technologies continue to advance, construction automation is poised to revolutionise the industry, ushering in a new era of intelligent, efficient, and digitally integrated building processes.

1.2.1 Challenges and limitations

3D printing is an additive manufacturing technique for fabricating a wide range of structures and complex geometries from three-dimensional model data. The process consists of printing successive layers of materials that are formed on top of each other. This technology was developed by Charles Hull in 1986 <…> 3D printing, which involves various methods, materials, and equipment, has evolved over the years, and has the ability to transform manufacturing and logistics processes. Additive manufacturing has been widely applied in different industries, including construction, prototyping, and biomechanical. 3D printing uptake in the construction industry was very slow and limited despite the advantages, eg, less waste, freedom of design, and automation (Ngo et al., 2018).

Engineers can use 3D printing to rapidly prototype and test different designs. This iterative design process can lead to the development of optimised structures that meet the required strength and durability criteria. With improvements in additive manufacturing technology, speed, quality, accuracy, and material properties have all developed to the extent that parts can be made for final use (Gibson et al., 2015). Manufacturing can be used for an accurate and rapid production of steel reinforcement. Fig. 1.2 shows additively manufactured reinforced cages used to construct small-scale specimens (Del Giudice & Vassiliou, 2020).

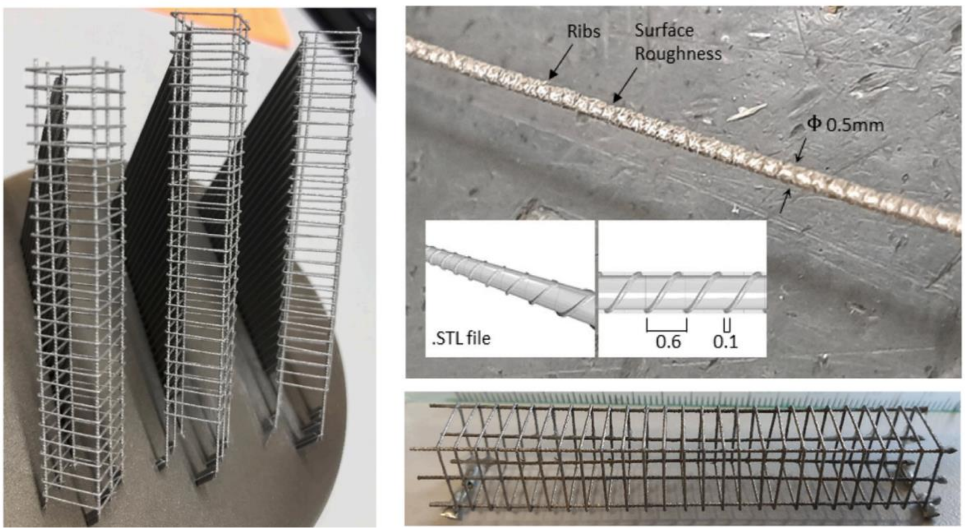


Fig. 1.2. Additively manufactured reinforced cages (Del Giudice & Vassiliou, 2020).

3D printing with PLA (polylactic acid) material has become widely popular due to its versatility and ease of use. PLA is a biodegradable plant-based thermoplastic derived from renewable resources such as corn starch or sugarcane, making it an environmentally friendly choice. One of the key advantages of 3D printing with PLA is its low printing temperature, which reduces energy consumption and makes it compatible with a broad range of 3D printers. PLA is known for its relatively low cost, minimal warping during printing, and wide range of available colors. Its ability to produce detailed and accurate prints, along with its biocompatibility, has made it a preferred choice for prototyping, hobbyist projects, and even certain medical applications. However, it is important to note that PLA may not be suitable for high-temperature applications because of its relatively low glass transition temperature. In general, 3D printing with PLA offers a user-friendly and environmentally conscious option to create a diverse range of objects with additive manufacturing technology.

Polylactic acid (PLA) is a biodegradable and bioactive thermoplastic derived from renewable resources (Fig. 1.3), commonly corn starch or sugarcane.

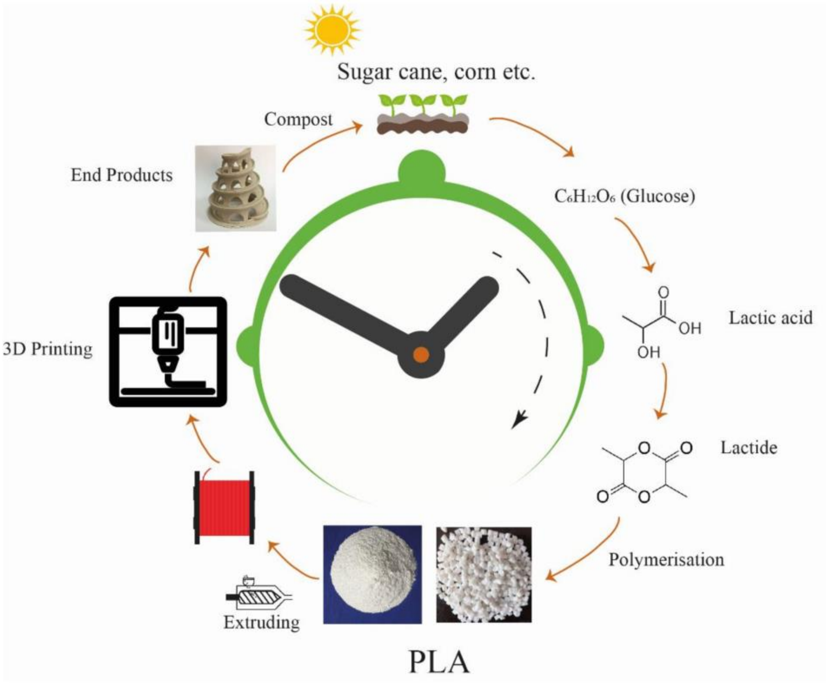


Fig. 1.3. Renewable resources process (Tumer, 2021).

Its popularity in 3D printing and various other applications arises from its eco-friendly nature and versatile characteristics. PLA is known for its low melting point, typically ranging from 180 to 220 degrees Celsius, making it compatible with a wide range of 3D printers. It exhibits excellent printability, producing detailed and precise models with minimal warping during the printing process. PLA is available in a diverse array of colours, offering aesthetic flexibility for various applications. Although PLA is biocompatible and is often used in medical applications, it is not suitable for high-temperature environments because of its relatively low glass transition temperature. Overall, PLA's renewable origin, ease of use, and environmental friendliness contribute to its widespread adoption in 3D printing, packaging, and other industries as a sustainable alternative to traditional petroleum-based plastics.

Polylactic acid (PLA) boasts commendable mechanical characteristics that make it a popular choice in various applications. Its tensile strength, ranging from 45 to 65 MPa, and Young's modulus, typically around 3 GPa, contribute to its ability to withstand considerable loads without undergoing significant deformation. PLA is a rigid material with relatively high impact strength that provides durability in practical applications. Its thermal properties, including a glass transition temperature between 55 and 60 degrees Celsius, make it suitable for a range of environments, but limit its use in high-temperature applications. The mechanical properties, combined with its biodegradability and renewable sources, make it an attractive material for industries such as 3D printing, packaging, and biomedical applications, where a balance of mechanical performance and environmental considerations is crucial.

Lactic acid (2-hydroxypropanoic acid)-based polymers are called poly (lactic acid) or polylactide and they are both abbreviated as PLA. In the last two decades, pure PLA polymer filaments that are used in the FDM approach have become the most important thermoplastic source in the three-dimensional (3D) printing field (Tümer & Erbil, 2021).

Additive manufacturing enables the creation of lightweight and optimised designs. Reinforcements can be designed with intricate internal structures, reducing weight while maintaining or improving strength. This is particularly beneficial for the load-bearing components of the bridge. The latest advancements in this field, the derived trends and projected developments provide a lucid and especially promising future for the generation of lightweight structures (János Plocher & Ajit Panesar, 2019).

Portable or construction-scale 3D printers can potentially be brought to the construction site. This allows for on-site manufacturing of reinforcements, reducing the need for transportation, and minimising logistical challenges associated with prefabricated components. A robotic arm requires less space than a gantry system and can even be mounted on a transportable platform to provide on-site mobility (Delgado Camacho et al., 2018).

3D printing facilitates integration with digital twin technologies. Digital twins can be created to monitor the behaviour, performance, and health of the reinforcement which is going to be created in real-time. These data can be used for predictive maintenance and informed decision making.

Forecasting the information is a way to tailor the process parameters and gain full control of the fabrication process, successfully monitor the surrounding environment conditions, and to reach the desired results. Figure 1.4 shows the process workflow of a digital twin in additive technologies. (Kantaros et al., 2022)

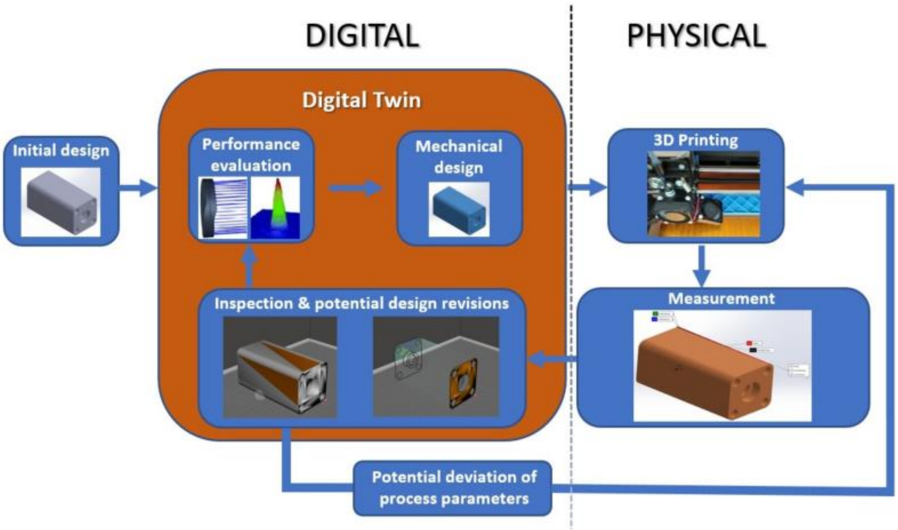


Fig. 1.4. Workflow of a digital twin (Kantaros et al., 2021).

Additive manufacturing is an additive process, which means that the material is deposited layer by layer. This results in minimal waste compared to traditional subtractive manufacturing methods, contributing to more sustainable construction practices.

Additive manufacturing results in the reduction of the waste of expensive metals such as titanium compared to traditional methods. It also eliminates the reinforcement assembly phase, reduces the risks of localised stresses in the assembly process, and substantially increases the freedom of design. (Ngo et al., 2018)

It is important to note that while 3D printing offers exciting possibilities for bridge structural components, the technology is still evolving, and certain challenges and considerations need to be addressed, such as material standards, structural testing, and long-term durability.

1.2.2 Case studies

Castilla-La Mancha 3D Bridge

The world's first 3D-printed pedestrian bridge was built in the urban park of Castilla-La Mancha in Alcobendas, Madrid (fig. 1.5). The Institute for Advanced Architecture of Catalonia (IAAC) spearheaded the architectural design of the bridge, showcasing a total length of 12 metres and a width of 1.75 meters. Crafted from micro-reinforced concrete, this project positions the IAAC as a global leader in large-scale 3D printing innovations. The Alcobendas footbridge marks a significance in international construction, as 3D printing technology has not been widely applied in civil engineering until now. The intricate design, inspired by natural forms, used parametric design principles to optimise material distribution, minimize waste through raw material recycling, and enhance structural performance.

Executed under the leadership of ACCIONA, the executive project involved a collaborative effort among architects, mechanical engineers, structural engineers, and municipal representatives. Unveiled on 14 December 2016, the bridge stands as a testament to the innovative potential of 3D printing in construction.

Using 3D printing allows builders to construct concrete bridges with a certain level of freedom, as they are not beholden to moulds or frameworks. This new technology is also more ecologically friendly, as it reduces waste and uses less energy than conventional construction. (IAAC Institute for Advanced Architecture of Catalonia, 2021)

This bridge is made up of eight parts, each with maximum horizontal dimensions of 2 × 2 m. The bridge was built using fused concrete powder and polypropylene reinforcement, and took two months to complete. Raw materials not used during the construction process were recycled and the design process used generative algorithms to optimise the distribution of materials, which is a key benefit associated with additive manufacturing. (Buchanan & Gardner, 2019)

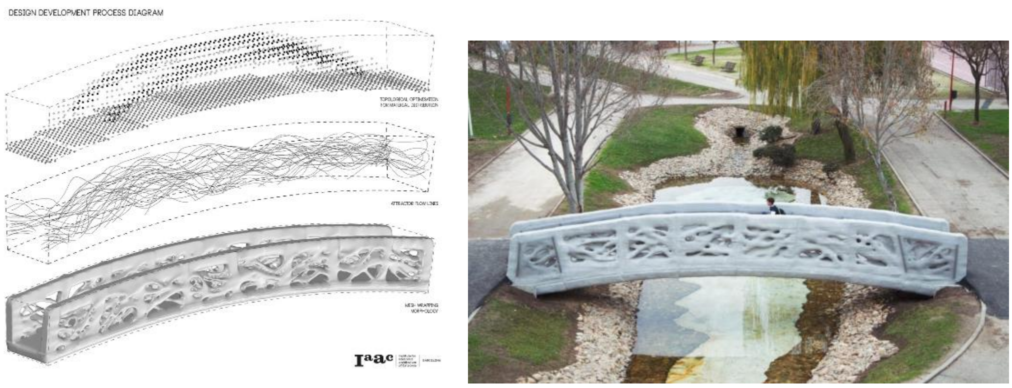


Fig. 1.5. Castilla-La Mancha 3D bridge (Buchanan & Gardner., 2021).

<u>Gemert bicycle bridge</u>

BAM Infrastructure and TU Eindhoven collaborated on an 8 m long, 3.5 m wide concrete bicycle bridge in Gemert (fig 1.6), The Netherlands, which is described as a 3D printed prestressed concrete bridge. In the concrete printing process, 1 cm thick concrete layers were laid down through an additively manufactured nozzle, and the concrete able to maintain its form after deposition without additional formwork. The bridge was built in parts and then joined onsite. Scale models of the structure were built and tested, and the finished bridge was opened in late 2017. In a country where there are more bikes than people, it is expected that hundreds of cyclists will ride over the bridge each day. (Meg, 2017) As the first of its kind in the structural integrity of the country, the structure had to be certified by placing a 4-tonne weight on the bridge deck for a period of several days. Having successfully passed that test, it now forms part of a new traffic bypass for Gemert and is expected to have a lifespan of 30 years. (Smisek, 2017)

It took two weeks to print the 800 individual layers that make up the bridge components.

Fig. 1.6 Gemert bridge (Smisek, 2017).

MX3D Bridge

A 12-metre 3D-printed pedestrian bridge (fig 1.7) designed by the Joris Laarman and built by Dutch robotics company MX3D has opened in Amsterdam six years after the project was launched. The bridge, which was fabricated from stainless steel rods by six-axis robotic arms equipped with welding gear, spans the Oudezijds Achterburgwal in Amsterdam's Red Light District. The structure used 4,500 kilogrammes of stainless steel, which was 3D-printed by robots in a factory over a period of six months before being craned into position over the canal.

Fig. 1.7 MX3D bridge. Side view (Parkes, 2021).

Its curving S-shaped (fig 1.8) form and lattice-style perforated balustrades were designed using parametric modelling software. The team behind the bridge claimed that the technique showed how 3D printing technology can lead to more efficient structures that use less material.

Fig. 1.8. MX3D bridge (Parke, 2021)

The structure was strengthened to be more in line with council regulations and to protect the structure against potential boat collisions. (Parkes, 2021)

1.3 Potencial of sandwich structures

A sandwich structure is a composite material consisting of two outer layers (or facesheets) and a core material sandwiched between them (fig. 1.9 (Zhao et al., 2021)). Beams are known as one class of engineering structures, which are designed to support lateral loads. Other than commonplace beams, design of sandwich beams can be more of an interest to engineers and turns out to be more effective because its mechanical behavior under applied loads could be modulated (Kamarian et al., 2023). The facesheets are typically rigid and bear most of the applied loads, while the core provides separation and maintains overall structural integrity. The combination of facesheets and the core creates a structure with high bending stiffness and strength relative to its weight.

Sandwich structures (Fig. 1.9) in civil engineering represent a versatile and efficient design approach characterised by a core material sandwiched between two outer layers, typically known as facesheets. This design conFiguration imparts unique mechanical properties, such as high stiffness and strength-to-weight ratios, making sandwich structures ideal for various applications in civil engineering. The core material, often lightweight and low density, provides insulation and structural support, while the face sheets distribute loads and offer protective layers. Sandwich structures find applications in bridges, building panels, and composite materials for infrastructure because of their ability to optimise material usage, enhance durability, and improve energy efficiency. The versatility of sandwich structures allows engineers to tailor designs to meet specific performance requirements, making them a noteworthy and innovative solution in modern civil engineering practices.

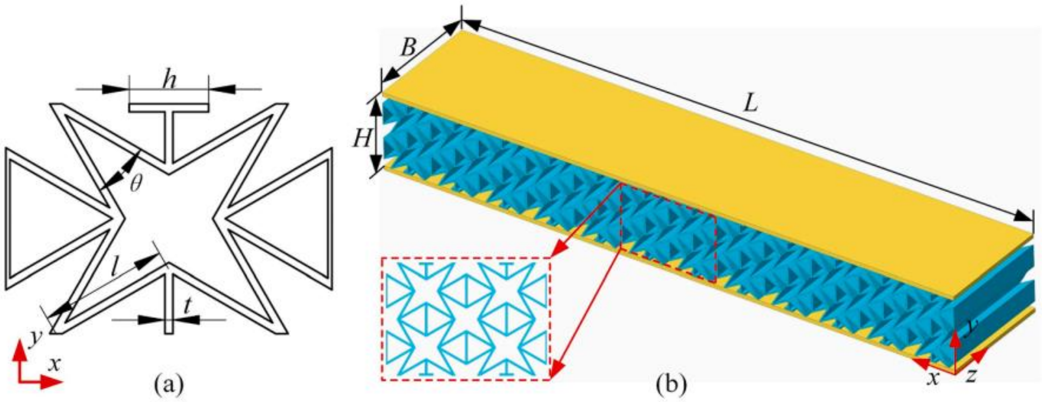


Fig. 1.9. Sandwich structure (Zhao et al., 2021).

Sandwich structures consist of three primary components: facesheets and a core material. Face sheets, typically made of materials such as metal, fiberglass, or carbon fibre composites, serve as the outer layers of the structure and provide protection against environmental factors, loads, and impacts. Sandwiched between these facesheets is the core material, which can be lightweight and low-density substances such as foam, honeycomb, or balsa wood. The core material plays a crucial role in providing structural support, improving stiffness, and increasing the overall strength-to-weight ratio of the sandwich structure. This tripartite composition allows sandwich structures to achieve superior mechanical properties, including high strength, rigidity, and resistance to bending and shear forces. The combination of robust facesheets and an efficient core material makes sandwich structures a versatile choice for applications in various industries, including aerospace, construction, and automotive engineering.

The outer layers of a sandwich structure are known as face sheets. These can be made from materials such as metals (aluminium, steel), composites (fiberglass, carbon fibre-reinforced polymers), or other rigid materials. The choice of facesheet material depends on factors such as strength requirements, weight constraints, and environmental considerations.

In the context of sandwich structures in civil engineering, face sheets constitute the outer layers of the composite material, encapsulating the core material between them. These face sheets play a crucial role in providing structural integrity, protection, and load distribution to the sandwich structure. Typically made from materials such as fiberglass, carbon fibre, or metals, facesheets contribute to the overall strength and stiffness of the structure while resisting environmental factors such as corrosion and weathering. The selection of facesheet materials is critical and depends on the specific application and engineering requirements, as different materials offer varying degrees of strength, durability, and weight. Face sheets are an important component in determining the overall performance and durability of sandwich structures, making them a focal point in the design and engineering considerations of these innovative construction elements.

The core material, located between the facesheets, provides separation and support. It can be rigid, semi-rigid, or flexible and is selected based on the desired mechanical properties of the sandwich structure. Common core materials include foams, honeycombs, balsa wood, and various composite materials.

The core material in sandwich structures within civil engineering serves as the central component between the facesheets, contributing significantly to the overall mechanical performance of the composite. Typically constructed from lightweight and low-density materials such as foam, honeycomb or balsa wood, the core material provides structural support, insulation, and impact resistance. Its primary function is to enhance the stiffness and strength-to-weight ratio of the sandwich structure, making it an efficient choice for various civil engineering applications. The selection of the core material is crucial and depends on factors such as specific engineering requirements, desired performance characteristics, and environmental conditions. The core material plays a pivotal role in determining the overall strength, weight efficiency, and thermal insulation properties of sandwich structures, which makes it a critical consideration in their design and application.

Sandwich structures find applications in the construction industry, including building facades, cladding panels, and pedestrian bridge construction. In building panels and facades, sandwich structures provide enhanced insulation, structural strength, and weather resistance. They are widely used in bridges, where the combination of lightweight cores and durable facesheets results in structures with improved load-bearing capacities. Sandwich structures are also applied in flooring systems and modular construction, facilitating quick assembly and adaptability. Their exceptional strength-to-weight ratio makes them suitable for lightweight roof structures, enabling the creation of expansive and architecturally innovative designs. In addition, sandwich structures are employed in the development of composite materials for seismic retrofitting, enhancing the resilience of existing structures. The adaptability, durability, and energy-efficient properties of sandwich structures make them an asset in modern construction practices, contributing to advances in both design possibilities and sustainable building solutions.

The negative Poisson's ratio, or auxetic behaviour, is a distinctive mechanical property observed in materials that exhibit the counterintuitive response of expanding laterally when stretched longitudinally.

Auxetic materials that are metamaterials with negative Poisson ratio (PR) express a shrinkage behaviour in the transverse direction under compression, while general materials or referred to positive PR materials found in nature show a swell behaviour in the perpendicular direction to the compression direction (Sengsri & Kaewunruen, 2020).

Unlike common materials, which contract laterally under tension and expand under compression, materials with a negative Poisson's ratio undergo lateral expansion in response to tensile forces. This unique behaviour is attributed to the specific geometric arrangement of their internal structures. Materials with negative Poisson's ratios have garnered interest for various applications, including impact absorption, vibration damping, and the development of innovative engineering structures. The counterintuitive nature of auxetic materials challenges conventional expectations in materials science and offers new possibilities for the design of advanced materials with customised mechanical properties.

The structural analysis of sandwich beams involves a comprehensive examination of their mechanical behaviour, load carrying capacity, and response to various forces. Typically composed of two outer facesheets and a core material, sandwich beams exhibit unique mechanical properties that require specialised analytical approaches. Engineers employ techniques such as finite element analysis (FEA) and classical beam theory to predict the structural performance of sandwich beams under different loading conditions. The analysis considers factors such as bending, shear, and torsion, which account for the interaction between the facesheets and the core. Understanding the mechanical response of sandwich beams is crucial in optimising their design for specific applications, ensuring stability, strength, and durability in diverse structural contexts, ranging from aerospace components to building materials in civil engineering.

Sandwich structures face advantages in Civil Engineering:

- Stiffness and Rigidity
- Thermal Insulation
- Vibration Damping
- Design Flexibility

- Corrosion Resistance
- Impact Resistance
- Reduced Material Consumption
- Adaptability and Retrofitting
- Cost-Efficiency in Certain Applications

Disatvantages of sandwich structures would be these:

- Complex Manufacturing
- Materials Cost
- Repair Challenges
- Environmental Sensitivity
- Limited Shear Strength
- Joining Difficulties
- Fire Resistance
- Limited Thickness Options

Experimental studies have been carried out, which due to the size of the samples, the test method, the choice of material, are limited in providing general conclusions about the structure, but are very good for the initial selection of sandwich structures. In this work, the analysis will be extended to include both experimental and numerical results. The creation of a verified numerical model will allow a wider study of sandwich structures and their application.

1.4 Numerical modeling

The finite model composed using software in parallel with the construction and physical testing of the bridge and was used to assess the performance of the as-built structure, refine stiffener locations, inform decision-making on the deck installation and connectivity, consider load cases (fig. 1.10 and fig. 1.11) and load levels beyond those examined through physical testing and inform the design of the sensor network (Kyvelou et al., 2022).

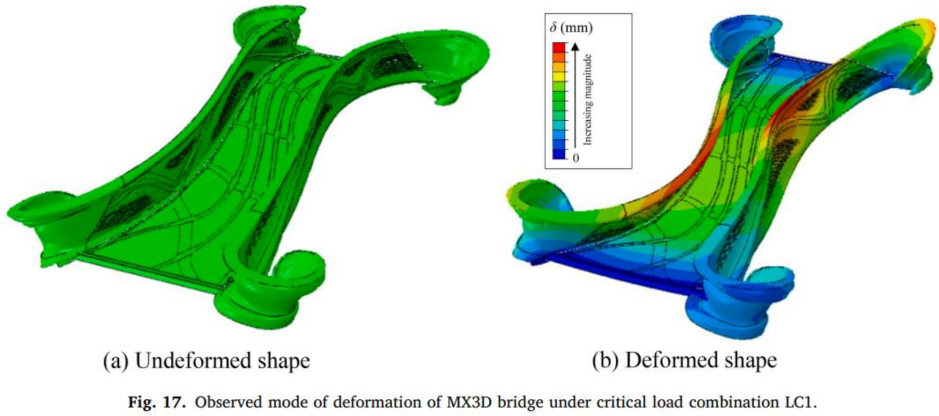


Fig. 1.10. Critical load combination (Kyvelou et al., 2022).

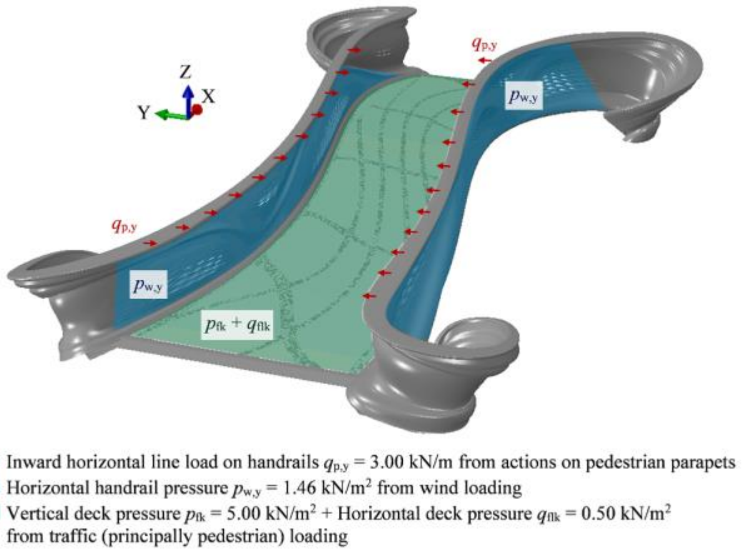


Fig. 1.11. Designed load acting on the bridge (Kyvelou et al., 2022).

After evaluating the analyzed sources, it can be assumed that numerical modeling is a suitable tool for predicting the behavior of such structures.

In this work, Solidworks software is going to be used to design and model structures.

1.5 Regulations and international standards

Standards such as Eurocode 3 and Eurocode 4, specifically EN 1993-1-5 and EN 1994-1-1, provide comprehensive guidelines for the design of steel structures, including sandwich panels and beams. These standards outline considerations for material properties, structural analysis, and design principles to ensure the safety, durability, and performance of sandwich structures. They address factors such as load capacity, stability, and fire resistance, offering a systematic and harmonised approach to structural design in European countries. By adhering to these standards, engineers and architects can implement sandwich beam designs that meet rigorous safety and performance criteria, fostering consistency and reliability in the construction of modern structures throughout the European Union.

A relevant standard is EN 13706-2, which addresses the characterisation of plastic products used in construction. This standard provides guidelines for the determination of properties related to the mechanical performance of plastic materials.

However, it should be mentioned that since the field of additive manufacturing is very new, there are no appropriate regulations that indicate how products for the conatruction of bridge or other structures should be designed and built. A lot of research, tests and expertise have been carried out on this topic as to how it would be possible to apply additive manufacturing to constructions, but there are no final rules, regulations, and documents.

1.6 Conclusions of chapter 1 and formulation of the objectives of the thesis

Based on the literature review, the following conclusions can be drawn:

1. Lightweight structures, incorporating advanced materials and additive manufacturing, are pivotal in civil engineering for their cost-effectiveness, sustainability, and ease of handling.
2. Additive manufacturing's adoption in construction, with a focus on 3D printing technology and sandwich structures, offers transformative potential, accelerating prototyping, enhancing design flexibility, and contributing to cost-effective and sustainable practices.
3. The integration of auxetic materials in pedestrian bridge design introduces a paradigm shift in engineering, providing unique opportunities for impact absorption, vibration damping, and the creation of advanced materials with tailored mechanical properties.
4. Finite Element Analysis (FEA) emerges as an indispensable tool for designing lightweight pedestrian bridges with sandwich structures, ensuring optimal performance, durability, and compliance with safety standards.

Experimental studies have been carried out, which due to the size of the samples, the test method, the choice of material, are limited in providing general conclusions about the structure, but are very good for the initial selection of sandwich structures. In this work, the analysis will be extended to include both experimental and numerical results. The creation of a verified numerical model will allow a wider study of sandwich structures and their application.

The object of research is additively manufactured lattice core sandwich structure. The study is dedicated for the development of a structurally adaptable lightweight lattice core sandwich component using additive manufacturing technique. Inorder to achieve the objective, the following tasks are formulated:

1. Develop a set of principles for selecting appropriate materials and composing the structure of investigated objects.
2. Design and conduct experimental tests to characterize the structural application of investigated objects.
3. Analyze experimental data to validate the performance of additively manufactured structures.
4. Develop a numerical finite element model for the investigated object and verify the adequacy of the model by comparing its predictions with the experimental data.
5. Formulate comprehensive conclusions and provide recommendations for the further structural application of additively manufactured objects in lightweight bridge structures.

2. EXPERIMENTAL INVESTIGATION ON DEFORMATION OF ADDITIVELY MANUFACTURED SANDWICH BEAMS

The workflow of the research is showed in the Figure 2.1. It consists of creation of models in 2D and 3D space, then printing and performing the experiment. Afterwards numerical model and simulation are done. Work is finalised by comparing the results of experiment and simulation.

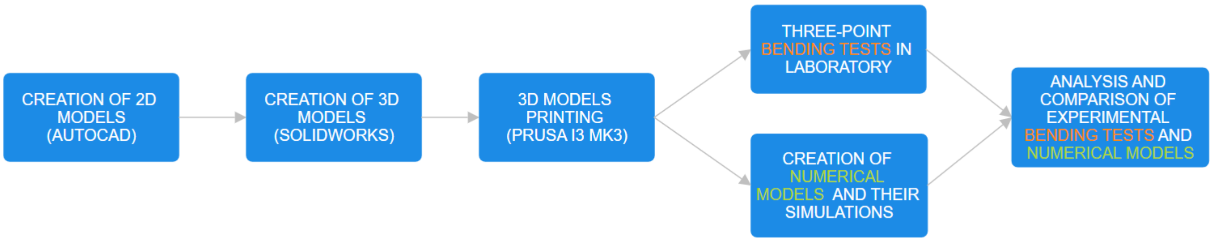


Fig. 2.1. Process of work.

2.1 Experimental programme

In this work, an experiment is carried out during which several variants of sandwich beam models are designed, and they are printed with a 3D printer. Then three point bending tests are performed in the laboratory, and the results are obtained.

Six lattice cores (fig. 2.2) with different geometries were used in this experiment. Four of them were with the same walls thicknesses of 1,00 mm, and two of them were with rescaled geometry and thinner walls of 0,6 mm. All specimens were designed to ensure uniform weight, thereby enabling the test results to indicate the flexural performance of the specimens driven by their inner structure.

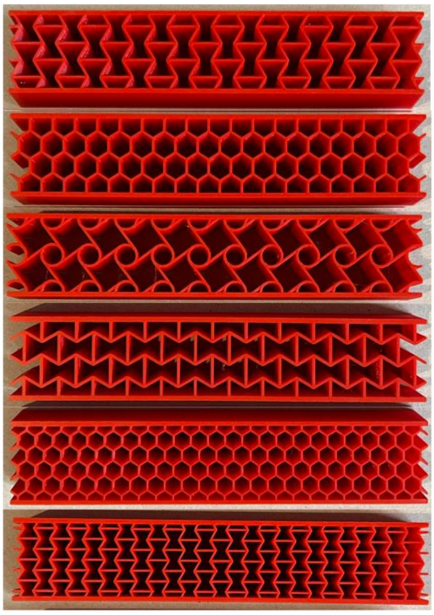


Fig. 2.2. Six laticce cores.

Used material characteristics were selected taking into account the previous studies ((Indres, 2021; Prusa Josef, 2022)) and the manufacturer's specifications.

2.2 Material characterisation

Shkundalova et al. explored the mechanical characteristics and tensile failure behavior of thermoplastic polymeric materials: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), high impact polystyrene (HIPS), and polyethylene terephthalate (PETG). The investigation revealed that specimens composed of ABS, HIPS, and PETG exhibited ultimate strain localization between the printed filaments, leading to local brittle failure in the tensile samples. In contrast, PLA demonstrated a ductile failure mode, displaying the highest nominal tensile strength among the considered polymers. Consequently, PLA was selected for 3D printing in this study (Shkundalova et al., 2018).

The material used for printing is PLA, or polylactic acid. In this experiment red colour PLA spool material (Fig. 2.3) is used. It is 1,75 mm ± 0,015 mm thick. Its nozzle temperature can range from 205 to 225° C and the heatbed temperature is 40 – 60° C. Table 2.1 demonstrates nominal mechanical characteristics of PLA material provided by the producer.

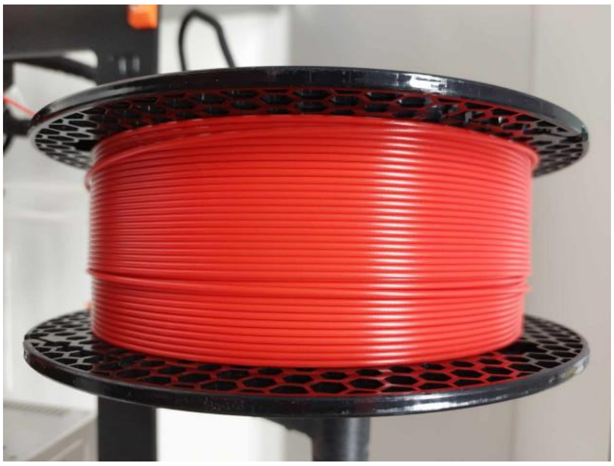


Fig. 2.3. Spool used in the experiment.

The characteristics of the material used are presented in the following table 2.1. Horizontal and vertical printing direction explained in a figure 2.4.

Table 2.1. Nominal mechanical properties of PLA

Property\Print Direction	Horizontal	Vertical xz
Tensile Yield Strength [MPa]	51 ± 3	59 ± 2
Tensile Modulus [GPa]	2.3 ± 0.1	2.4 ± 0.1
Elongation at Yield Point [%]	2.9 ± 0.3	3.2 ± 1.0
Flexural Strength [MPa]	83 ± 6	99 ± 1
Flexural Modulus [GPa]	3.1 ± 0.1	3.2 ± 0.1
Deflection at Flexural Strength [mm]	7.4 ± 0.2	8.3 ± 0.2
Impact Strength Charpy [kJ/m2](4)	13 ± 1	14 ± 1
Impact Strength Charpy Notched [kJ/m2]	not applicable	not applicable

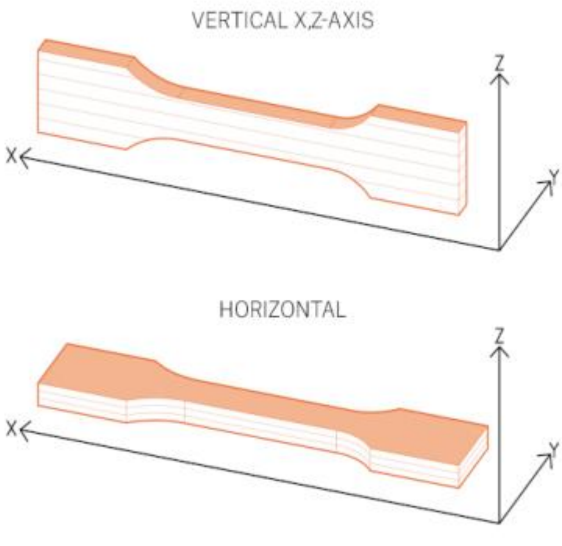


Fig. 2.4. Vertical and horizontal printing directions.

2.3 Additive production

Based on the literature review, four lattice pattern topologies were identified as proper alternatives for sandwich beams integrated in pedestrian bridge deck.

Research have indicated that sandwich structures with conventional honeycomb core are stiff, strong, and light and absorb a considerable amount of energy when crushed, especially in out-of-plane direction. In the other hand, the re-entrant honeycomb core has enhanced shear properties by exhibiting a snap-through instability which significantly enhances the energy absorption capability as compared to conventional materials (Indres, 2021). In this work four beams were designed, they have two 2 mm thickness facesheets and 1 mm walls in the core: Honeycomb, Re-entrant, Re-entrant (90 deg.), Chiral.

The idea of the planned experiment is to examine different sandwich structures by recording their weight. In this way, the structure will be the only variable parameter that will allow us to evaluate and compare their behavior.

A 2D model for the samples were designed. This was done with the Autocad programme. The desired geometry is outlined in it. The geometry was chosen considering the existing tests, improving it, changing wall thicknesses, specimen lengths, compacting or thinning the mesh sizes.

The dimensions of the cells (Fig. 2.5) were designed to create neatly arranged core with multiple cells and two facesheets.

Four beams were designed (fig 2.6), they have two 2 mm thickness facesheets and 1 mm walls in the core: Honeycomb No.2, Re-entrant Scaled, Re-entrant (0 deg), Chiral.

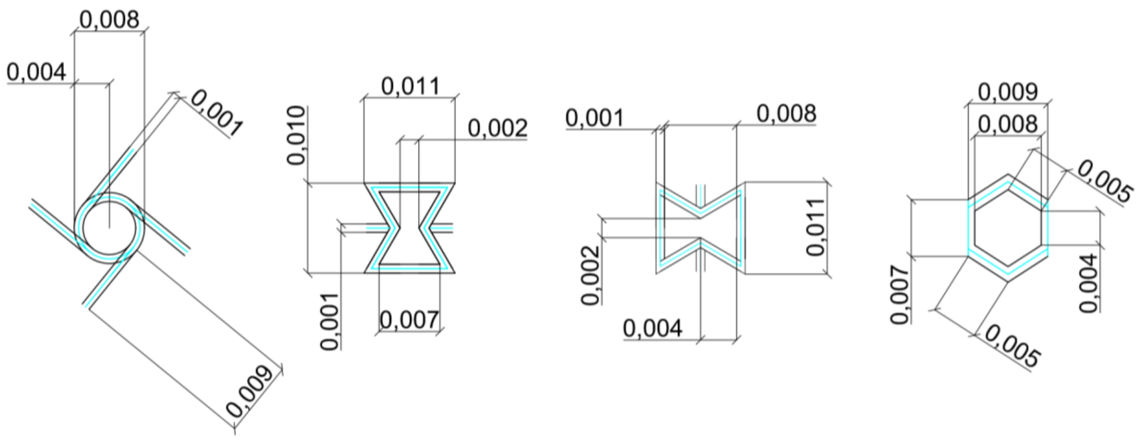


Fig. 2.5. Cells of the beams

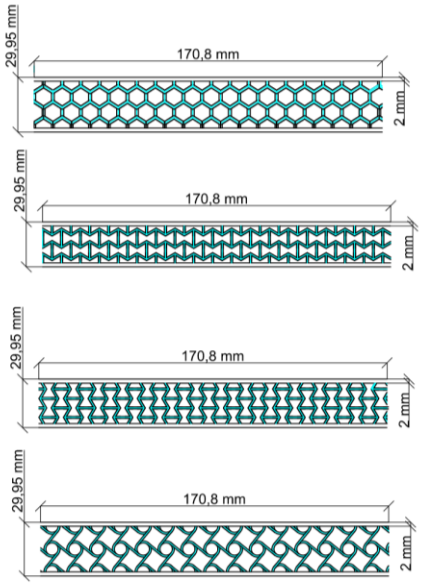


Fig. 2.6. Sandwich beams geometry. Wall thickness – 1 or 0.6 mm

As a comparative beams two other elements were designed, they had two 2 mm facesheets, and 0,6 mm core wall thickness: Honeycomb and Re-entrant (90 deg). It is important to mention that these two beams have smaller and more units of cells.

Designed elements consist of (fig. 2.7) upper, lower facesheets and core.

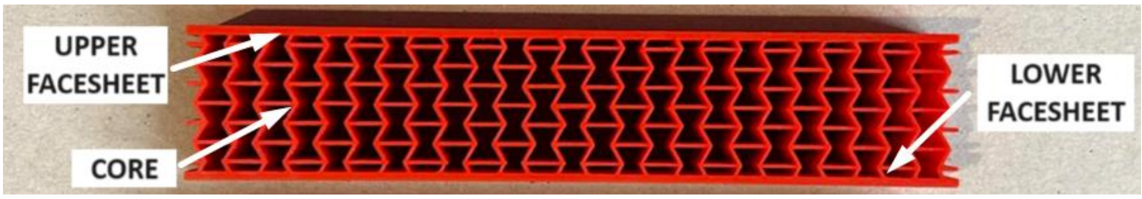


Fig. 2.7. Parts of elements.

6 elements are designed for printing and experimenting tests, all detailed information and figures are listed bellow:

- Name: Honeycomb (fig. 2.7)
- Upper and lower facesheet wall thickness: 2 mm;
- Core wall thickness: 1 mm;
- Units of cells: 57
- Weight: 41 g.

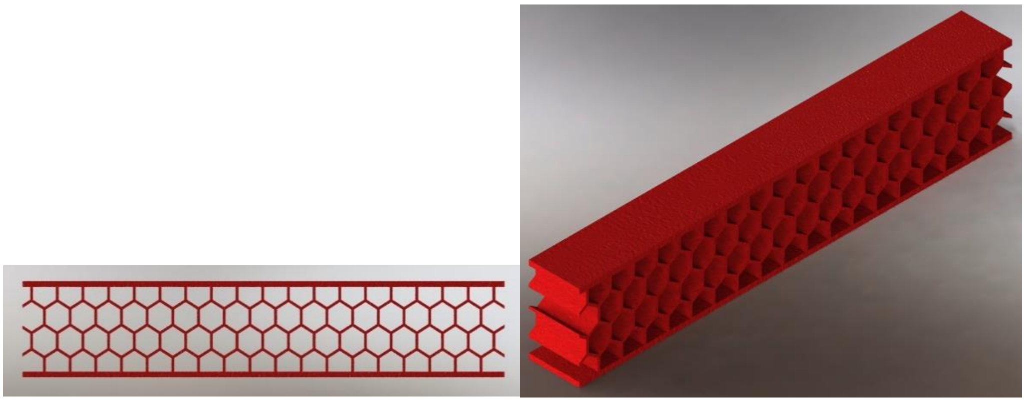


Fig. 2.7. Honeycomb No. 1 2D and 3D view.

- Name: Re-entrant (0 deg) (fig. 2.8)
- Upper and lower facesheet wall thickness: 2 mm;
- Core wall thickness: 1 mm;
- Units of cells: 36
- Weight: 43 g.

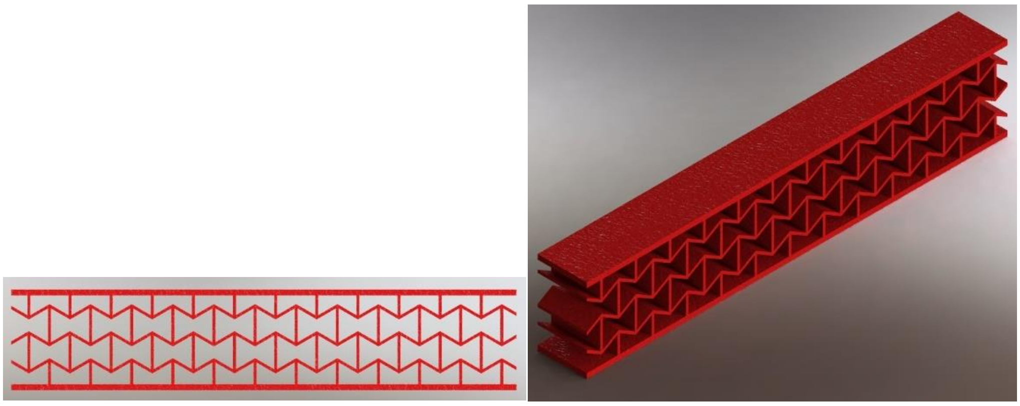


Fig. 2.8. Re-entrant (0 deg) 2D and 3D view.

- Name: Re-entrant (fig. 2.9)
- Upper and lower facesheet wall thickness: 2 mm;
- Core wall thickness: 1 mm;
- Units of cells: 45
- Weight: 45 g.

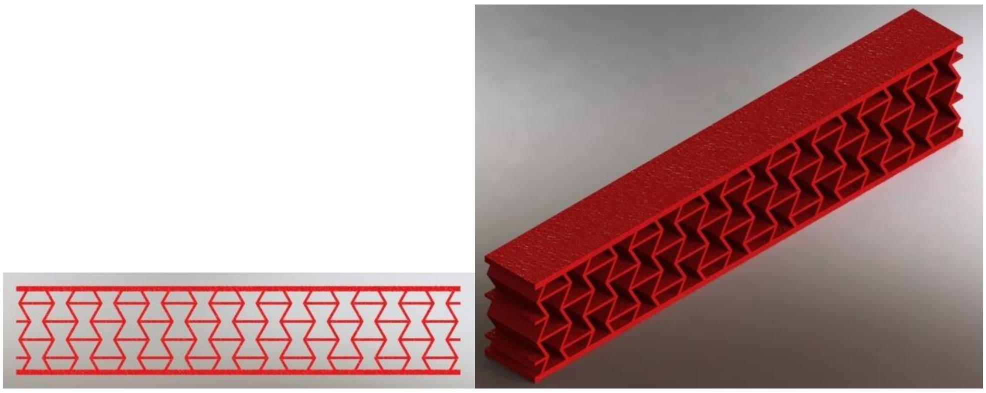


Fig. 2.9. Re-entrant No.1 (90 deg) 2D and 3D view.

- Name: Chiral (fig. 2.10)
- Upper and lower facesheet wall thickness: 2 mm;
- Core wall thickness: 1 mm;
- Units of cells: 24
- Weight: 42 g.

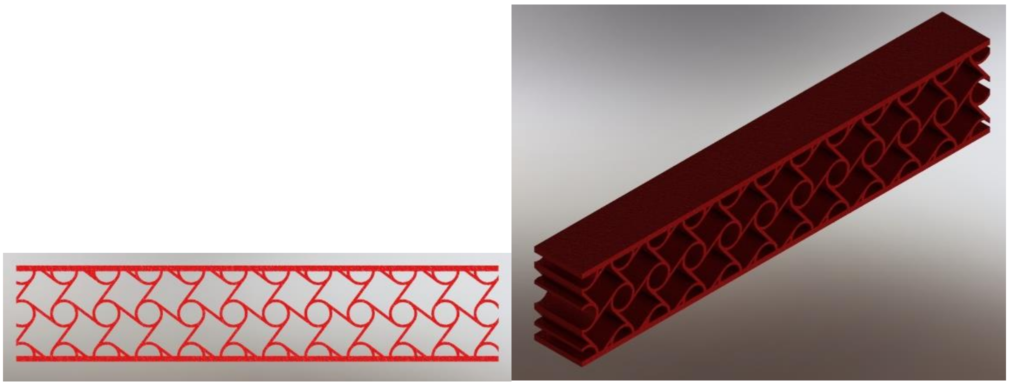


Fig. 2.10. Chiral 2D and 3D view.

- Name: Re-entrant Scaled (fig. 2.11)
- Upper and lower facesheet wall thickness: 2 mm;
- Core wall thickness: 0.6 mm;
- Units of cells: 31
- Weight: 38 g.

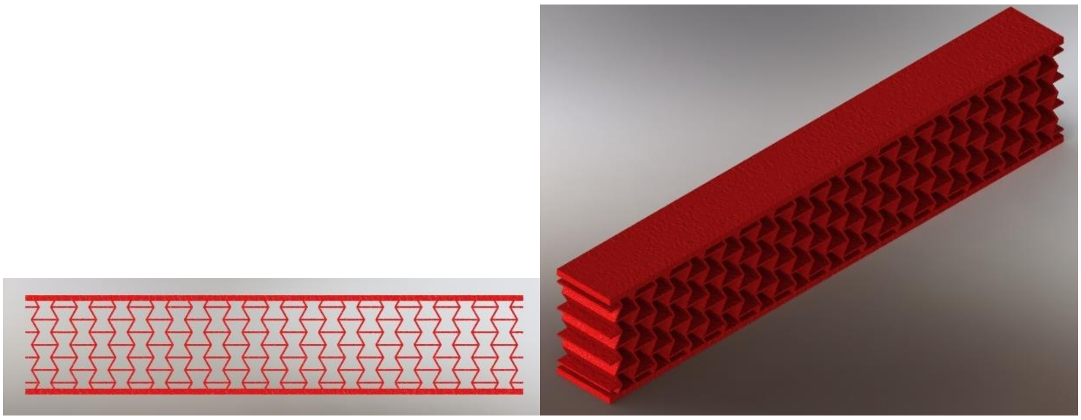


Fig. 2.11. Re-entrant No. 2 2D and 3D view.

- Name: Honeycomb Scaled (fig. 2.12)
- Upper and lower facesheet wall thickness: 2 mm;
- Core wall thickness: 0.6 mm;
- Units of cells: 120
- Weight: 38 g.

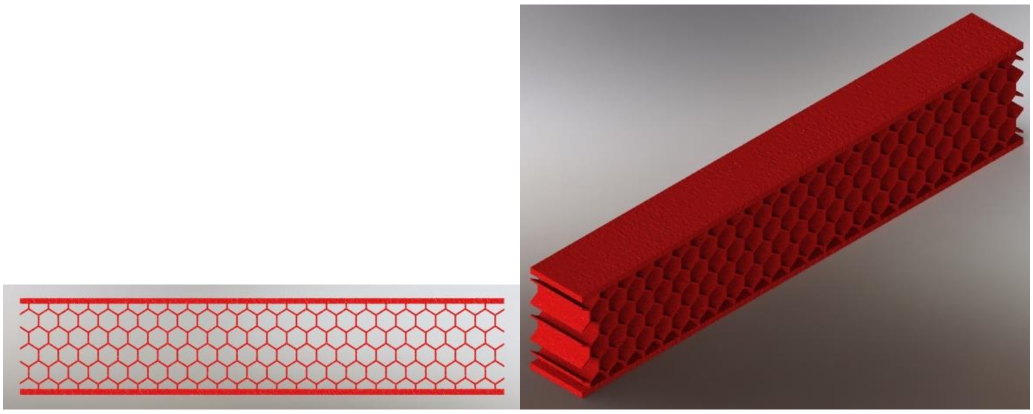


Fig. 2.12. Honeycomb No. 2 2D and 3D view.

Concluded information are presented in the Table 2.2 below:

Table 2.2. Specimens characteristics.

	Core wall thickness, mm	**Upper and lower facesheet wall thickness, mm**	**Units of cells**	**Weight, g**
Honeycomb	1	2	57	41
Re-entrant	1	2	45	45
Re-entrant (0 deg)	1	2	36	43
Chiral	1	2	24	42
Honeycomb Scaled	0.6	2	120	38
Re-entrant Scaled	0.6	2	31	38

The Solidworks programme was used to create the 3D models. These models needed to be designed in this software to get an .STL file, which is compatible with 3D printer.

In this research work, Prusa I3 MK3 3D printer (Fig. 2.14) is used. Slic3r Prusa Edition 1.40.0 was used to create G-code. All specimens were printed using identical printing parameters: extrusion nozzle temperature = 215 ◦C; printing bed temperature = 60 ◦C; print speed = 28 mm/s. The 1.75 mm PLA filament Prusament having 1240 kg/m3 density was used. The beams were printed in the horizontal position; the thickness of each printing layer was 0.2 mm. Such a printing layout is frequent for prototyping purposes.

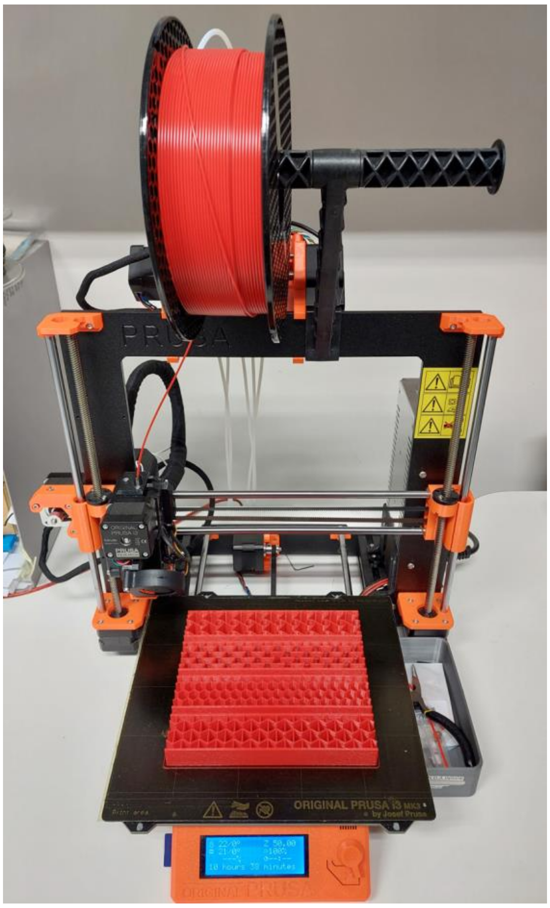


Fig. 2.14. 3D printer Prusa I3 MK3.

Before printing, a 3D model is created in computer-aided design (AutoCAD and SolidWorks). The model is then sliced into layers using slicing software that generates the instructions for the 3D printer. The printer uses a spool of filament (PLA) as the raw material. The filament is loaded into the extruder, which is a part of the printhead. The Prusa i3 MK3 features a Cartesian-style movement system. The printhead moves along the X, Y, and Z axes according to the instructions from the sliced model. Movement is controlled by stepper motors. The printer often has a heated print bed that helps with adhesion and prevents warping. The temperature of the print bed is controlled throughout the printing process. The printer begins by depositing the first layer of filament onto the heated print bed. The extruder, which contains a hotend, heats the filament to its melting point and the melted filament is precisely deposited onto the print bed following the instructions from the slicer. The Prusa i3 MK3 includes an automatic bed levelling system. Before each print, the printer probes the print bed at multiple points to ensure that it is perfectly levelled. The printer continues to add layers one by one, allowing each layer to cool and solidify before the next is deposited. This process is repeated until the entire 3D object is created.

The Prusa i3 MK3 incorporates additional features such as filament sensors, power recovery, and Trinamic drivers, enhancing its overall reliability and performance. The precise movements, temperature control, and layer-by-layer deposition contribute to the printer's ability to create detailed and accurate 3D prints.

Before printing, moisture is removed from a material with the dehydration machine (Fig. 2.15).

Fig. 2.15. Dehydration Machine.

2.4 Testing procedure

For the performance of a three-point bending test in a laboratory, specific equipment was used to accurately measure the mechanical properties of 3D printed specimens.

A testing machine (Fig. 2.16) for applying controlled loads and measuring the resulting forces and displacements during the bending test. The machine includes a load cell to measure force and a crosshead to apply the load.

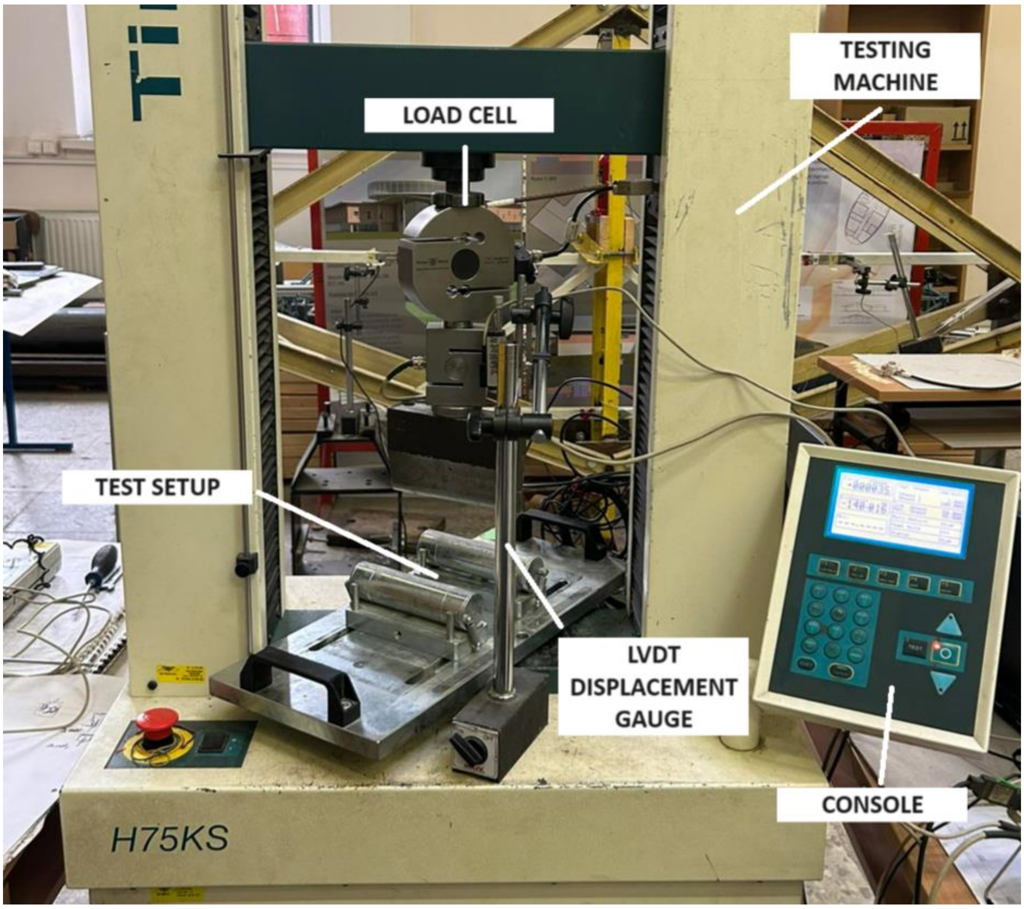


Fig. 2.16. Devices used in the experiment.

A bending fixture (Fig. 2.17), also known as a three-point bending fixture, is used to support the specimen and apply the bending load. It consists of two lower supports and a single upper loading point, defining the points of contact with the specimens.

Fig. 2.17. Bending fixtures.

The materials to be tested, in the form of beams, are prepared and mentioned before.

Software was used for controlling the UTM and collect, analyse and presenting the testing data.

The three-point bending test (Fig. 2.18) is a mechanical testing method used to assess the flexural strength and stiffness of a material. In this test, a specimen is supported at its ends by two fixed supports, forming a span, while a load is applied to the centre of the specimen through a third point. As the load increases, the sample undergoes deformation, and the resulting stress and strain distribution across the material is measured. The maximum stress occurs in the center of the specimen, and the relationship between the applied force and the resulting deflection provides information about the material's bending properties of the material, including its modulus of elasticity, ultimate strength, and toughness. The three-point bending test is widely employed in materials science and engineering to characterise the mechanical behavior of materials, especially those used in structural applications.

In the pictures below schematic (fig 2.18) and real-time (fig 2.19) examples are given.

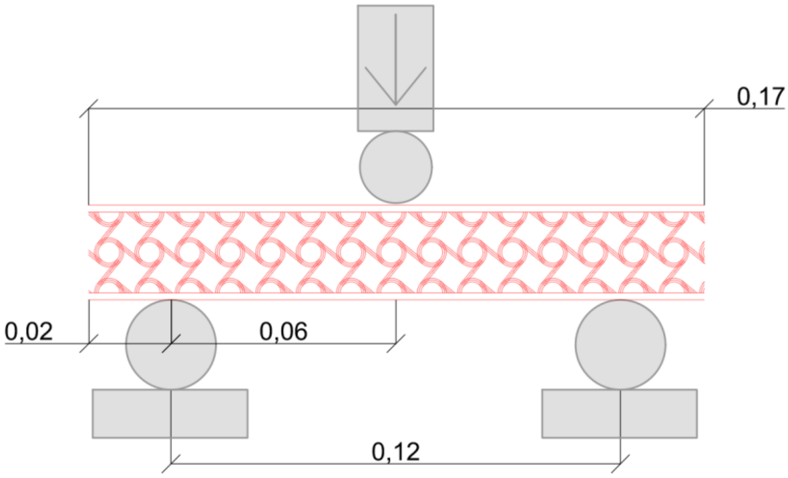


Fig. 2.18. Schematic representation of the test.

Fig. 2.19. Real-time example of element experiment.

Experimental test of the beams involved these following steps described in the table 2.3 (every step was made the same with all six 3D printed specimens):

Table 2.3. Experimental test steps

1. Specimen Preparation	Prepared specimen with specific geometry and dimensions. The specimen is in the form of a rectangular beam.
2. Set Up the testing machine	Calibrated the testing machine and ensured that it is in good working condition. The fixture had two lower supports and a single upper loading point.
3. Mount the Specimen	Place the specimen horizontally on the lower supports of the bending fixture. Ensure that the specimen is centered and level.
4. Adjust the Loading Points	Adjusted the positions of the lower supports to match the specified span length (distance between the supports).
5. Apply the Load	The testing machine crosshead until it contacts the upper surface of the specimen. A controlled downward force at the centre of the specimen using the upper loading point. This force induces a bending moment in the specimen (fig. 28).
6. Record Data	Measured and recorded the applied load (force) and the corresponding displacement and deformation of the specimen. The loading cell of the testing machine and a displacement measurement device, such as an extensometer, are used to collect these data.
7. Continue Loading	Continue applying the load until the specimen fractures.
8. Data Analysis	Analysed the collected data to determine key parameters such as maximum load, displacement at failure.
10. Report Results	Documented the test results in a test report.

2.5 Experimental results

Six elements (Fig. 2.2) were printed using plastic material and a 3D printer. These elements have different geometries, wall thicknesses, and arrangement of cells.

Figure 2.20 illustrates the outcomes of the bending tests, showcasing force-displacement plots obtained from both the testing machine and the specimens following the bending test, specifically after their failure (Fig. 2.23).

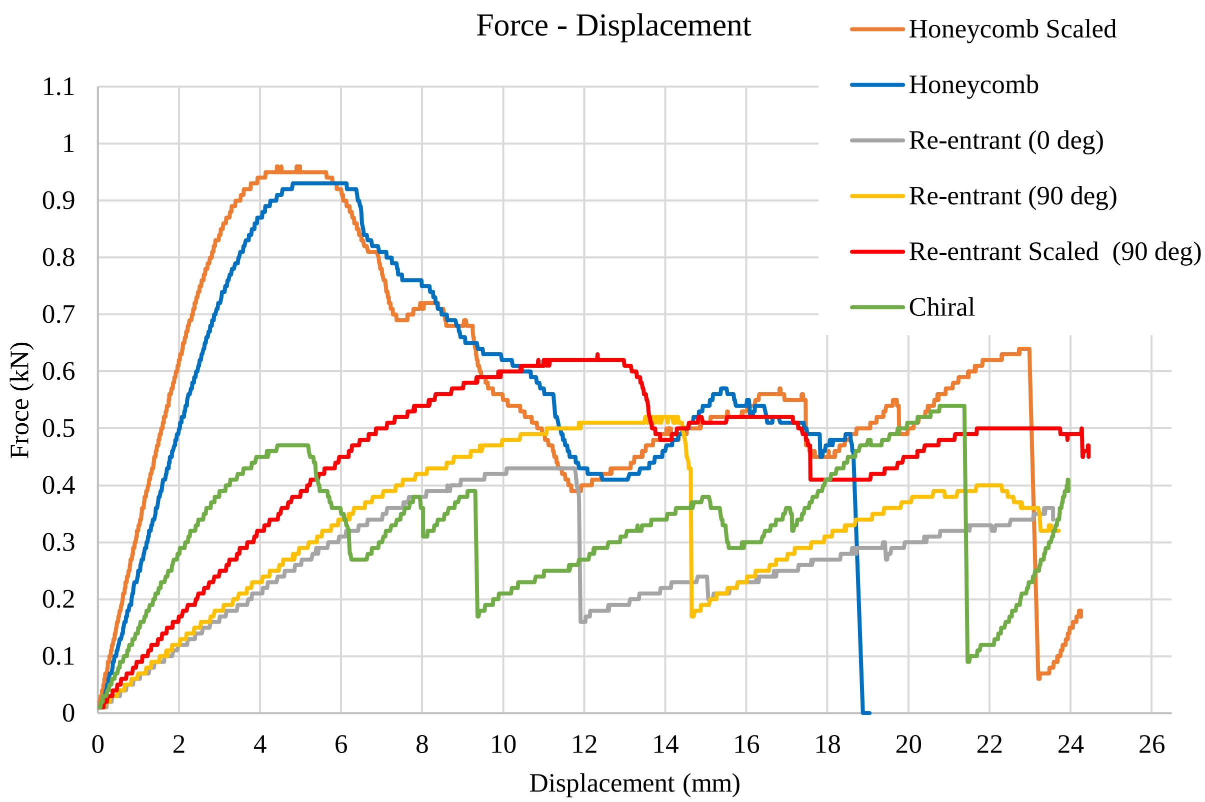


Fig. 2.20. Force-displacement diagram.

Figure 2.21 shows the beams with the same wall thickness (1 mm) during testing in three stages. For each cell topology the first row represents the specimen before the test has started. In the second row corresponds to the moment when the maximum force was attained and in the third row the moment of final failure of the sandwich beams is observed.

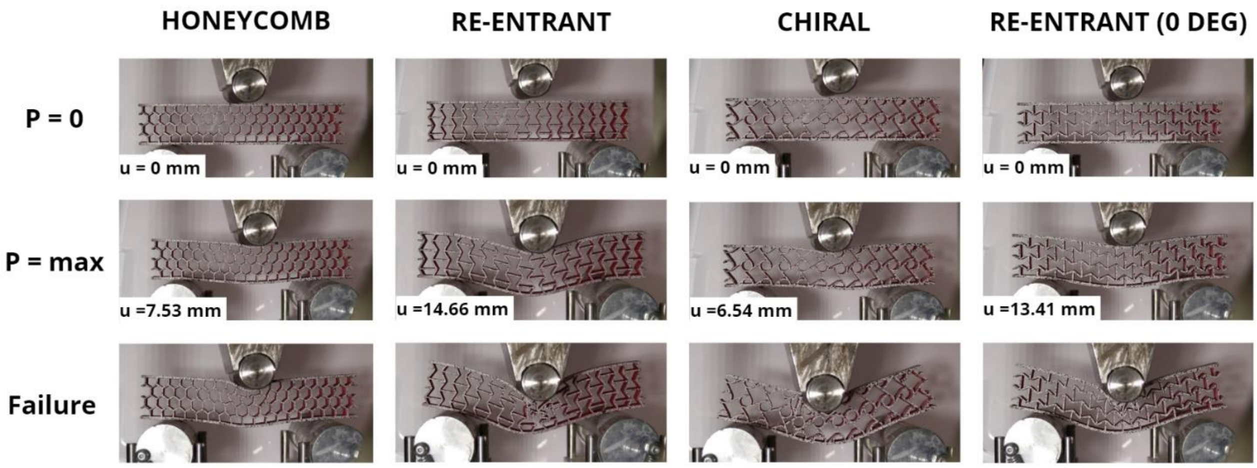


Fig. 2.21. Beams with the same wall thickness.

Digital Image Correlation (DIC) is a precise, non-contact, and non-interferometric optical method used for measuring the displacement/deformation of a structural element/material subjected to external loading.

In Figure 2.22, an instance of deformation evolution is illustrated, as captured by the DIC system.

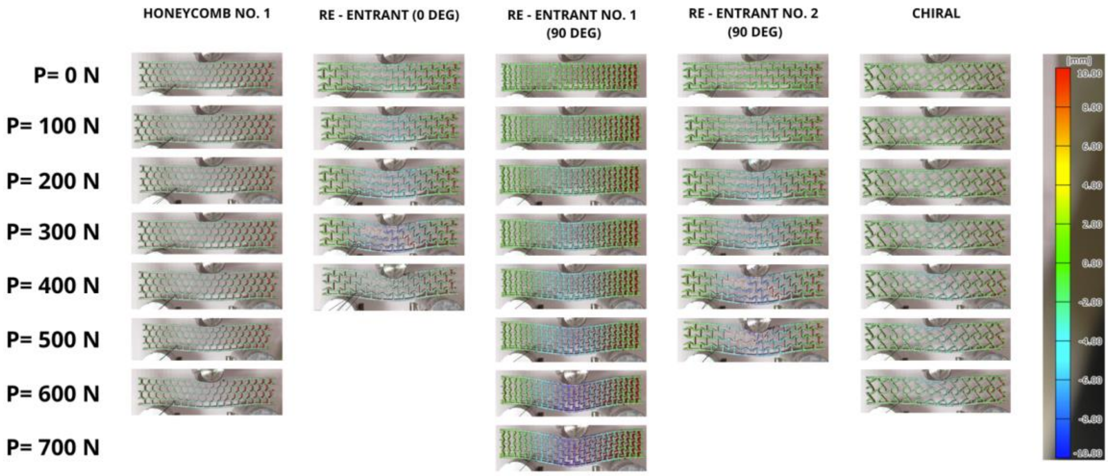


Fig. 2.22. DIC analysis and flexure failure.

After the test, the following elements (fig. 2.23) are inspected and evaluated.

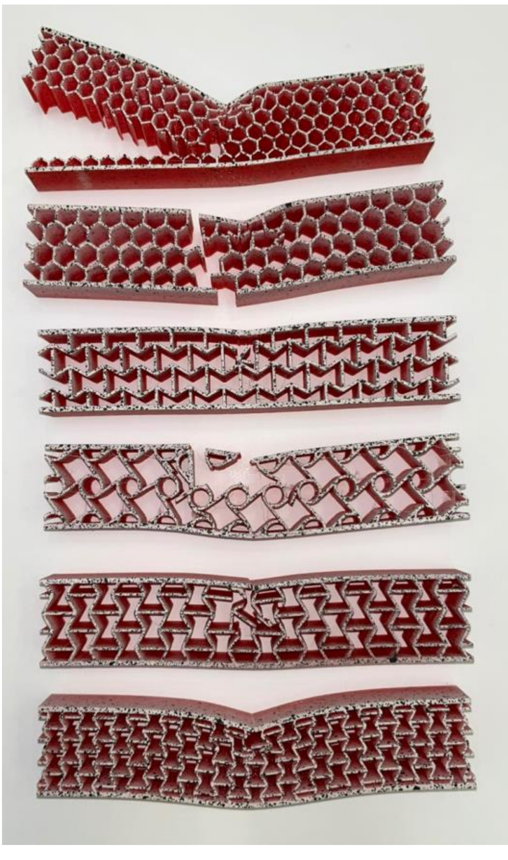


Fig. 2.23. Elements after the failure.

2.6 Conslusions of chapter 2

1. The honeycomb structure demonstrated the highest initial flexural stiffness among all structures investigated, establishing it as the standout performer in this crucial mechanical aspect.
2. The reduction in the wall thickness of the honeycomb structure did not have a significant impact on the initial flexural stiffness; only a modest 5% improvement was observed. In contrast, reducing the wall thickness of the re-entrant (90 degrees) structure led to a substantial 35% increase in the initial flexural stiffness. This sensitivity is attributed to the scale of the structure, given that scaling had no effect on the initial stiffness of the honeycomb but had a pronounced impact on the re-entrant structure.
3. The honeycomb structure displayed robust flexural resistance, with both the original and rescaled versions exhibiting capacities of 950 N and 930 N, respectively. In comparison, the re-entrant (90 deg) structure showed lower resistance, with values of 620 N and 510 N for the original and rescaled versions, respectively. The re-entrant (0 deg) and chiral structures consistently demonstrated resistance levels of 430 N and 470 N, respectively. This underscore the consistent and dependable flexural resistance of the honeycomb structure, establishing it as a reliable choice for applications demanding strength and durability.
4. All re-entrant structures exhibited remarkable ductility, withstanding a substantial vertical displacement from 13 to 16 mm. This exceptional deformability highlights a distinct aspect of the re-entrant structure's mechanical behavior.

3. EXPERIMENTAL AND NUMERICAL ANALYSIS

3.1 Experimental Result Analysis

A three-point bending test was performed during the experiment. During it, the mechanical behavior of the sandwich beam under load was determined. This information is used to confirm hypotheses and achieve research objectives.

Figure 2.20 illustrates the outcomes of the bending tests, showcasing force-displacement plots obtained from both the testing machine and the specimens following the bending test, specifically after their failure (see Fig. 43). The Honeycomb Scaled, a wall thickness of 0.8 mm, reached a maximum force of 0,95 kN. This resulted in a vertical displacement of 7,32 mm. The Honeycomb, a wall thickness of 1 mm, reached a maximum force of 0,93 kN. This resulted in a vertical displacement of 7,53 mm. The Re-entrant, a wall thickness of 0.8 mm, reached a maximum force of 0,62 kN. This resulted in a vertical displacement of 14,48 mm. The Re-entrant Scaled, a wall thickness of 1 mm, reached a maximum force of 0,51 kN. This resulted in a vertical displacement of 16,09 mm. The Re-entrant (0 deg), a wall thickness of 1 mm, reached a maximum force of 0,43 kN. This resulted in a vertical displacement of 16,09 mm. The Chiral, a wall thickness of 1 mm, reached a maximum force of 0,47 kN. This resulted in a vertical displacement of 6,54 mm. The maximum force was reached with Honeycomb Scaled geometry. The beam that could withstand the least amount of force Re-entrant (0 deg). Comparing the Honeycomb Scaled and Chiral beams, they achieved the lowest displacement, but the Chiral beam withstood a very small amount of force of only 0,47 kN.

As can be seen from the obtained results and the curves in the diagram, the curve with the steepest angle is blue curve of Honeycomb Scaled core, and the curve with the smallest angle is Re-entrant (0 deg), it can be said that the bending stiffness of the curve Honeycomb Scaled is the highest, and the bending stiffness of the curve Re-entrant (0 deg) is the lowest. After evaluating the results, it can be said that beam with low bending stiffness is characterized by increased flexibility, leading to higher deflections under applied loads, greater sagging or hogging, and elevated stress concentrations, potentially risking material failure. Such beams may exhibit reduced natural frequencies, making them more susceptible to dynamic concerns.

When evaluating the two Honeycomb cores, which show high bending stiffnesses, it can be seen from the diagram that when load 0.5kN was reached Honeycomb Scaled reaches 1.98 mm displacement, and the Honeycomb core reaches 1.52 mm displacement. The structure that has a rarer honeycomb geometry has almost 23% lower bending stiffness, so it can be said that a denser structure allows to achieve higher stiffness.

Figure 3.2 shows the beams with the same wall thickness (1 mm) during testing in three stages. For each cell topology the first row represents the specimen before the test has started. In the second row corresponds to the moment when the maximum force was attained and in the third row the moment of final failure of the sandwich beams is observed.

For the honeycomb core at a maximum force of 0,93 kN and a displacement of 7.53 mm the upper facesheet was indented and cells were crushed. This type of beam was the only one which broke in a half. This shows that the element of this geometry and material is very stiff and has rigid behavior.

The sandwich beam with re-entrant core (90 deg) presented at maximum force of 0.62 kN and deflection of 14.66 mm, the upper facesheet crushed.

The sandwich beam with re-entrant core (0 deg) presented an elastic behavior and after the test was completed it recovered almost completely to the initial position. At maximum force of 0.43 kN and deflection of 13.41 mm, the upper facesheet was indented and the second layer of cells were crushed, but after unloading the cells almost regain their initial shape, while the facesheet remains slightly deformed as presented.

For the chiral core, especially the ligaments of the cells broke in the central part, at a maximum force of 0.47 kN and a deflection of 6,54 mm. This means that the beam of such a geometria becomes tense in the central part, i.e. this arrangement of cells provides the possibility to concentrate the power in one area, the power is not distributed over the entire width of the beam.

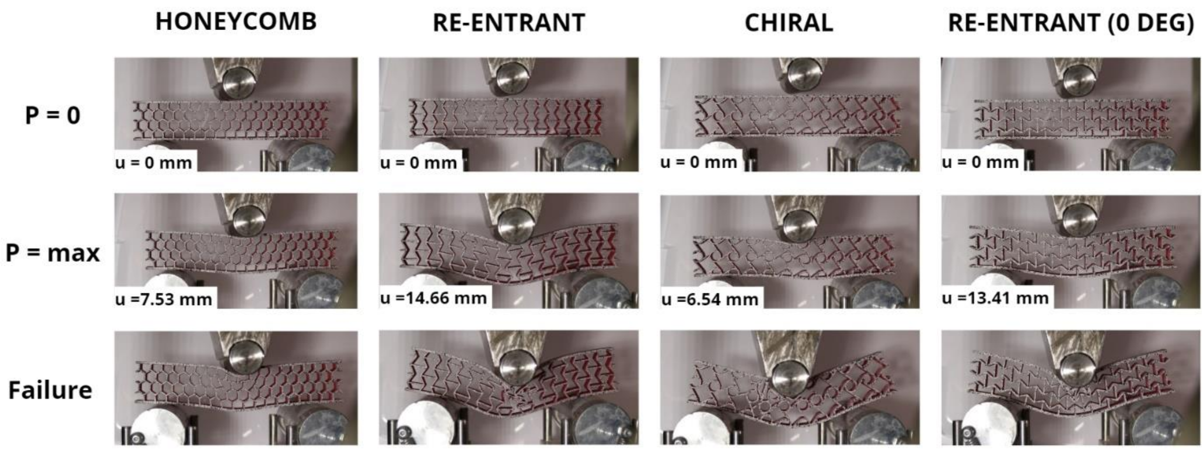


Fig. 3.2. Beams with the same wall thickness

Figure 3.3 shows the experimental results for the average bending stiffness and absorbed energy till the maximum force was reached for each topology and both relative densities. The average bending stiffness was calculated by dividing the maximum force to the corresponding displacement.

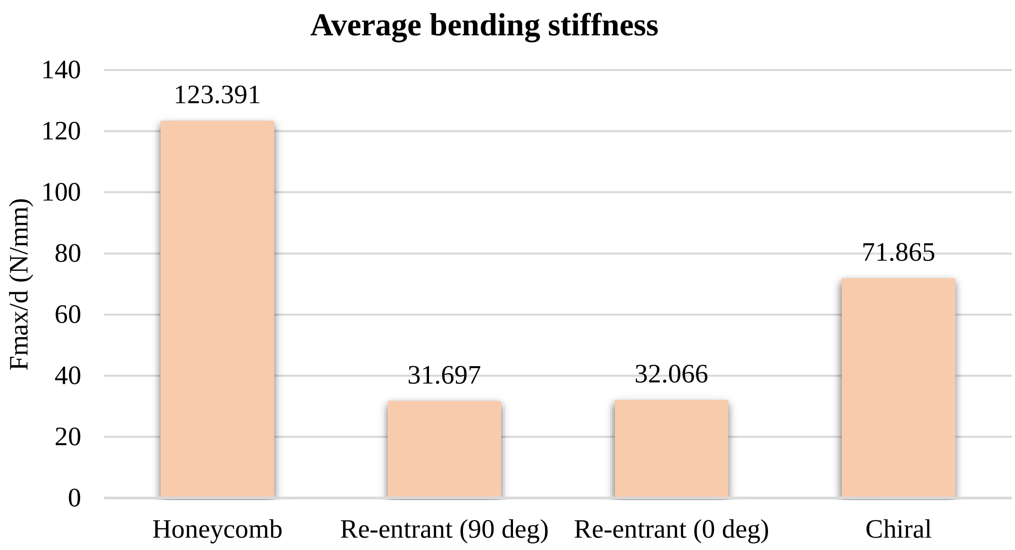


Fig. 3.3. Average bending stiffness

The honeycomb core has the highest stiffness of 129 N/mm (fig. 3.3), followed by the chiral core for which a value of 72 N/mm.

The absorbed energy (fig. 3.4) was calculated as the area under the force-displacement curve, till the maximum force was reached.

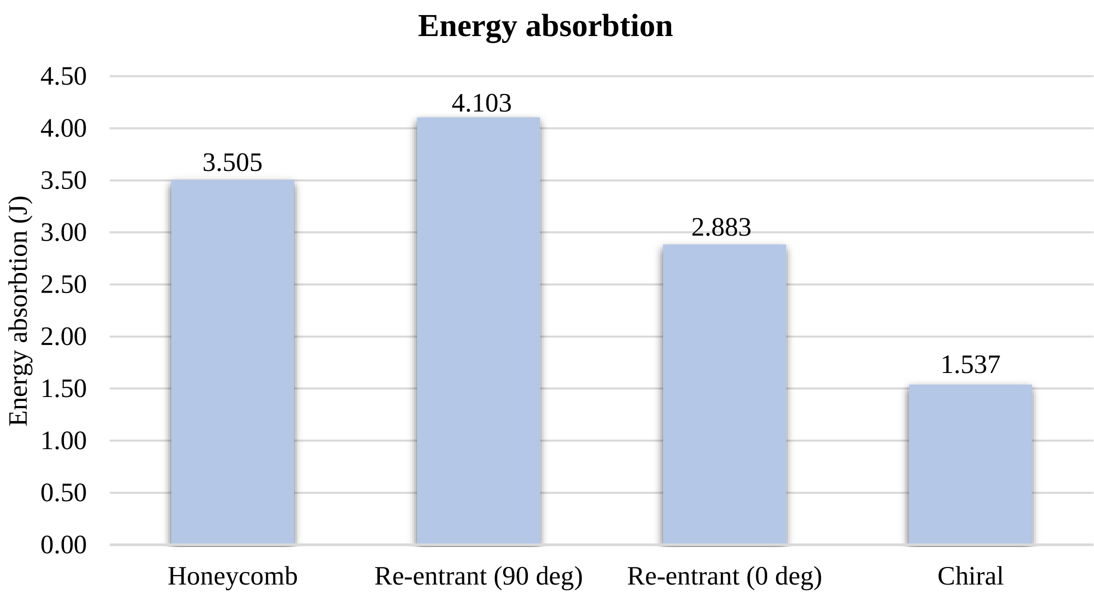


Fig. 3.4. Energy absorption diagram

The honeycomb core is a good candidate, but it is outclassed by the Re-entrant Scaled core. The re-entrant sandwich beam had an elastic response, the maximum force of 0.51 kN being attained at about 16 mm. The the Re-entrant Scaled absorbed energy of 4,103 J is with almost 15% greater than the 3.505 J absorbed by the honeycomb core. In fact, also the re-entrant (0 deg) core proved to be very compliant and absorbed 2.88 J, about 30% less than the (90 deg) oriented cells. In fact, its recovery after complete unloading is remarkable as seen. The chiral core had the worst response as absorbing energy, the ligaments being very susceptible to local buckling and crushing phenomena, as ligaments are not aligned along the loading direction. The local buckling does not result in the catastrophic failure but, on the contrary the periodic re-entrant auxetic core bending is dominated by buckling deformation, leading to the absorption of energy at a larger deformation. Therefore, local failure is produced for the chiral core, and the global failure mode controls the re-entrant sandwich beam. The fractured ligaments observed in conventional honeycomb structures or chiral core configurations within sandwich beams result in irreversible deformation. In contrast, for sandwich beams with a re-entrant core, the predominant global deformation is characterized by the buckling of ligaments rather than fracture. Notably, when the cells are oriented vertically at 90°, the core increased stiffness, resulting in a diminished recovery.

Table 2.4 summarizes the mass, core area, and specific properties of all types of printed sandwich beams. Specific properties are obtained by dividing the initial stiffness, maximum force, and absorbed energy to the mass of each type of sandwich. The specific average stiffness (considering the maximum force divided to the corresponding displacement) and specific maximum strength have the highest values for honeycomb and Re-entrant Scaled cores. Specific absorbed energy is maximum for the re-entrant (90 deg) core, being 15% higher than for the honeycomb core and 2.6 times greater than the one absorbed by the chiral core.

Table 2.4. Summarize of the specimens properties

Specimen type	**Mass (g)**	**Core area (mm2)**	**Mass/core area (g/mm2)**	**Specific average stiffness (N/(mm*g))**	**Specific maximum strength (N/g)**	**Specific absorbed energy (J/g)**
Honeycomb	37.91	70038	0.00054	123.39	24.53	3.50
Re-entrant Scaled	44.49	58243	0.00076	31.70	11.46	4.10
Re-entrant (0 deg)	43.12	56601	0.00076	32.07	9.97	2.88
Chiral	42.33	52274	0.00081	71.87	11.10	1.54

Digital Image Correlation (DIC) is a precise, non-contact, and non-interferometric optical method used for measuring the displacement/deformation of a structural element/material subjected to external loading.

In Figure 3.6, an instance of one deformation evolution is illustrated, as captured by the DIC system. The presented images correspond to the axial displacement of the compression support of the testing machine. The image correlation results the images core-spond to similar loading levels. The differences in the distribution of the deformations of the web are evident. The DIC approach identifies relative displacements of any points recognised on the exposition surface after the physical tests. In this work, local deformations are evaluated with the help of DIC. Local deformations were calculated by dividing the beam upper bar displacement with lower bar displacement.

After calculating all beams, the results (Table 2.5) obtained is that the ratio of all beams is greater than the number 1. This means that there is a large local effect. All tested beams deform locally. Measurements were made at the maximum load of each element.

Table 2.5. Local deformation ratio results

Specimen type	Maximum load, N	Upper bar displacement, mm	Lower bar displacement, mm	Local deformation ratio
Honeycomb Scaled	950	6.45	4.43	1.46
Honeycomb	930	3.03	2.2	1.38
Re-entrant (0 deg)	430	9.03	7.92	1.14
Re-entrant Scaled	620	13.35	11.78	1.13
Re-entrant	510	8.98	7.92	1.13
Chiral	460	2.53	1.72	1.47

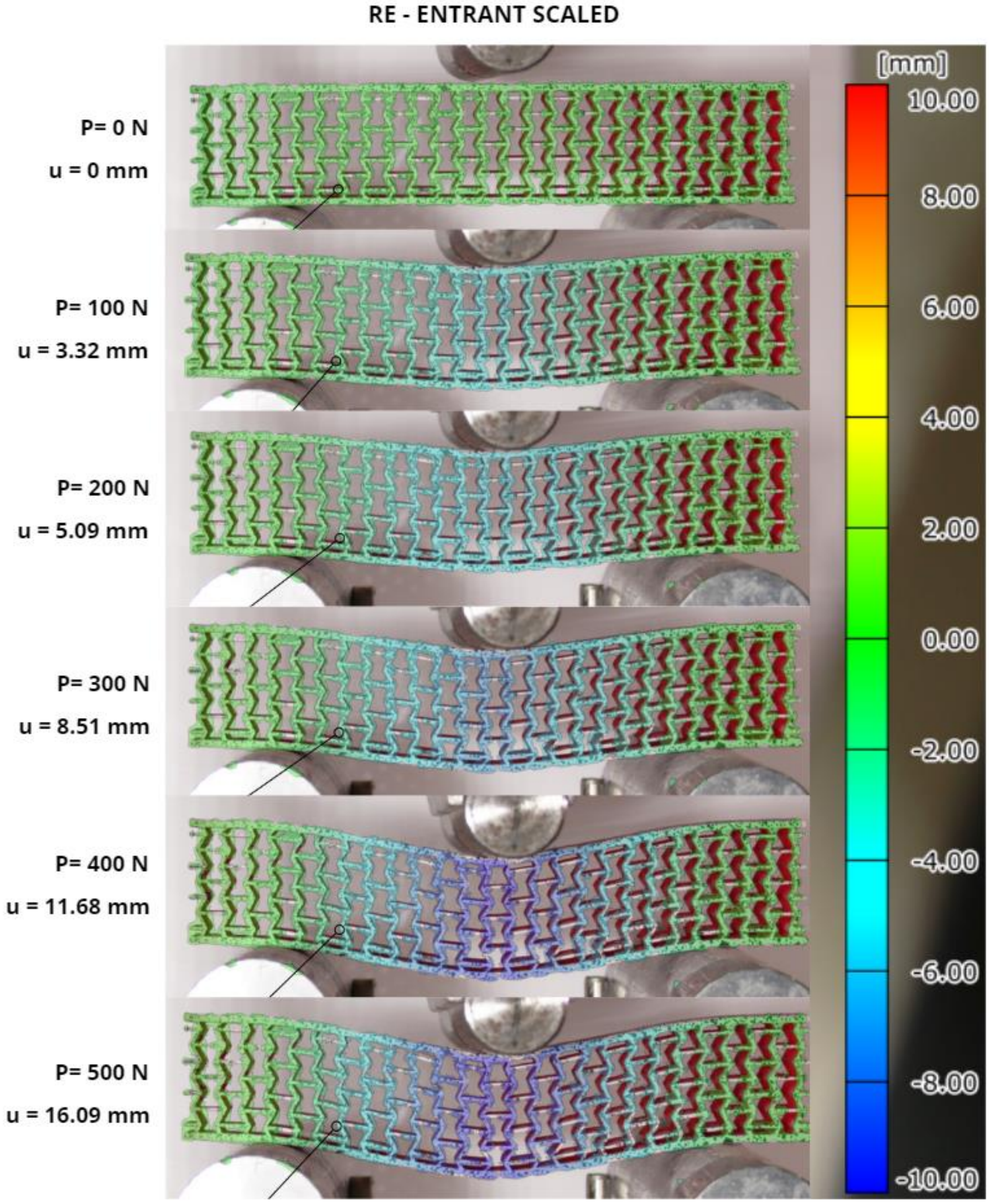


Fig. 3.6. DIC software and displacement measure

To evaluate the capabilities of not only the material, but also the geometry, an additional comparative data calculation was performed. also, during the experiment, two additional specimens were checked, with which the cells were made denser (i.e. smaller cells and more units), and the wall thickness was reduced. Fig. 3.7 shows that Honeycomb Scaled and Re-entrant Scaled were printed as a comparative test elements.

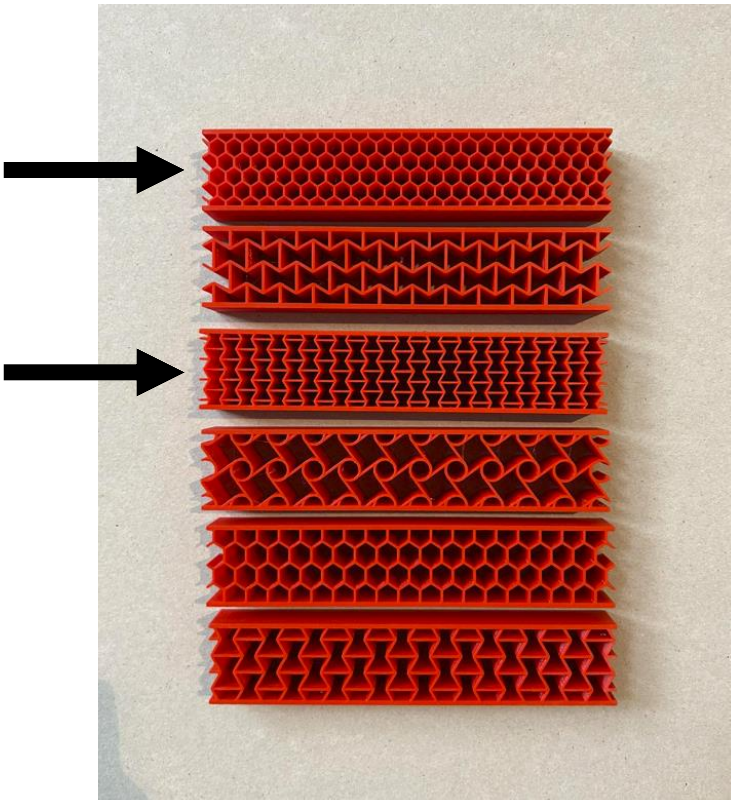


Fig. 3.7. Specimens with wall thickness of 0.6 mm

To evaluate the general information, the best performance were noticed on a Honeycomb Scaled element. It has the stiffnes (fig 3.8) as a 129,7 N/(mm·g) and overtakes even Honeycomb specimen. Re-entrant Scaledspecimen has stiffnes as a 42 N/(mm·g) and also shows better perfomance than Re-entrant No. 1.

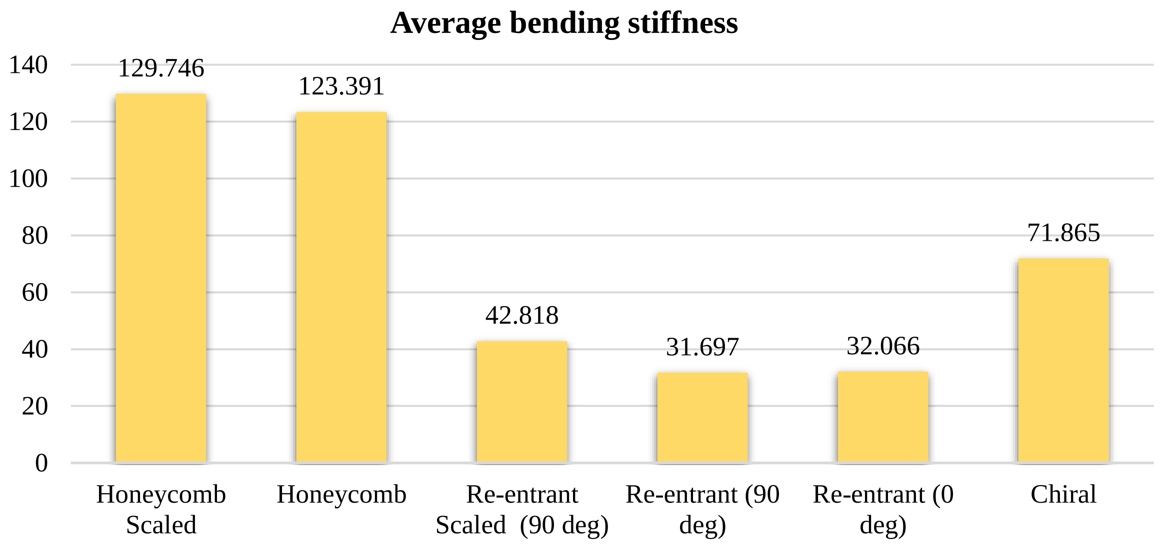


Fig. 3.8. Average bending stiffness of all specimens (1.00 and 0.6 mm wall thickness)

Energy absorption (3.9) as a comparison is the best of Re-entrant No. 2. Honeycomb Scaled absorbs energy 3.47 J and shows worse comparing to Honeycomb.

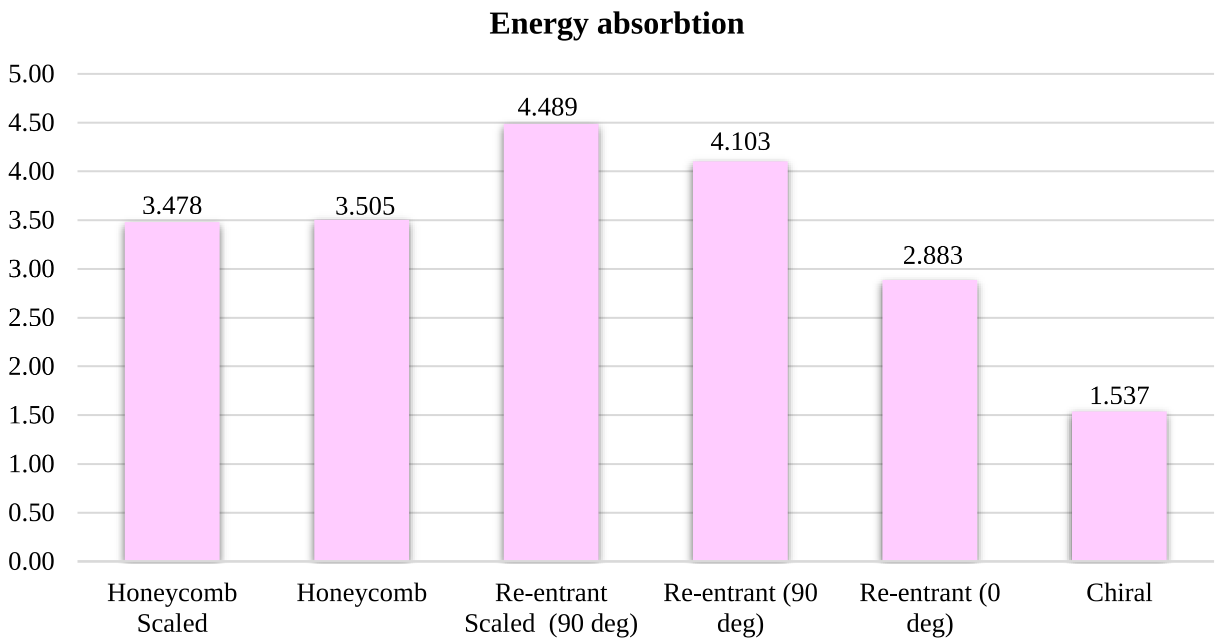


Fig. 3.9. Energy absorption of all specimens (1.00 and 0.6 mm wall thickness)

The initial simulation was performed with Solidworks software. The real behaviour of the beams was simulated, using PLA plastics characteristics, and using the loads which were used in experiment in laboratory.

The sandwich beam with a honeycomb core has the best resistance, with a maximum force close to 0,95 kN, and fails completely at a force of 0,64 kN and a displacement of 24.66 mm. The lowest facesheet bends, the upper facesheet buckles and breaks, and the core fails, especially the lower part of the core, which is broken due to force pressure from the middle to the left end.

The poorest resistance was obtained for the chiral core.

After the experiment and specimens' failure (fig. 3.10) the ruptures and lapses were evaluated visually.

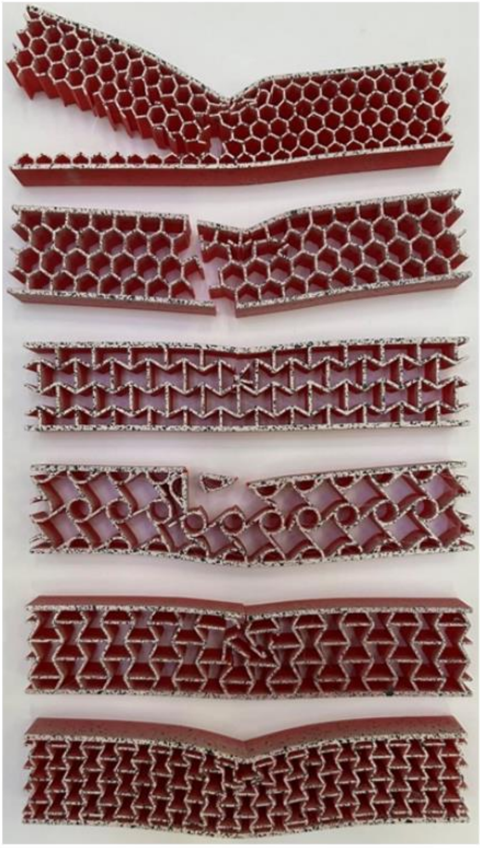


Fig. 3.10. Specimens after the failure.

Honeycomb Scaled experienced a longitudinal shear at the bottom of the core after the experiment. Also, the upper facesheet does not return to its original position, in the middle top part cells crashed. Honeycomb core specimen broke in half. Broken cells are also visible in the viral part. The upper facesheet has bent, and it was no longer able to return to the original position. After the load experienced, the lower facesheet of the Re-entrant (0 deg) core is not damaged. The upper facesheet bent but returned to its original position. The cell core is damaged only in the first and second row, the wall of one cell is broken. Chiral core experienced high local stress and broke the top rows of the cell. The beam itself returned to its original position, but without a single cell on top. Re-entrant core completely returned to its original position, but the upper facesheet was half broken, and the cells next to it were crushed. As for the Re-entrant Scaled core, it reacted similarly to the Re-entrant core, but the top facesheet didn't break in half, it just cracked. A few cells were also broken due to the pull. The beam did not fully return to its original position.

3.2 Numerical modeling of sandwich beams

The initial simulation was performed with Solidworks software. The flexural behavior of the beams, as depicted in Figure 3.11, was simulated based on the characteristics of PLA plastics outlined in Subchapter 2.2. The boundary conditions of the model were established in accordance with the laboratory tests conducted, as specified in Subchapter 2.4. An elastic material model was utilized for the simulations, and the analyses were carried out under force control conditions.

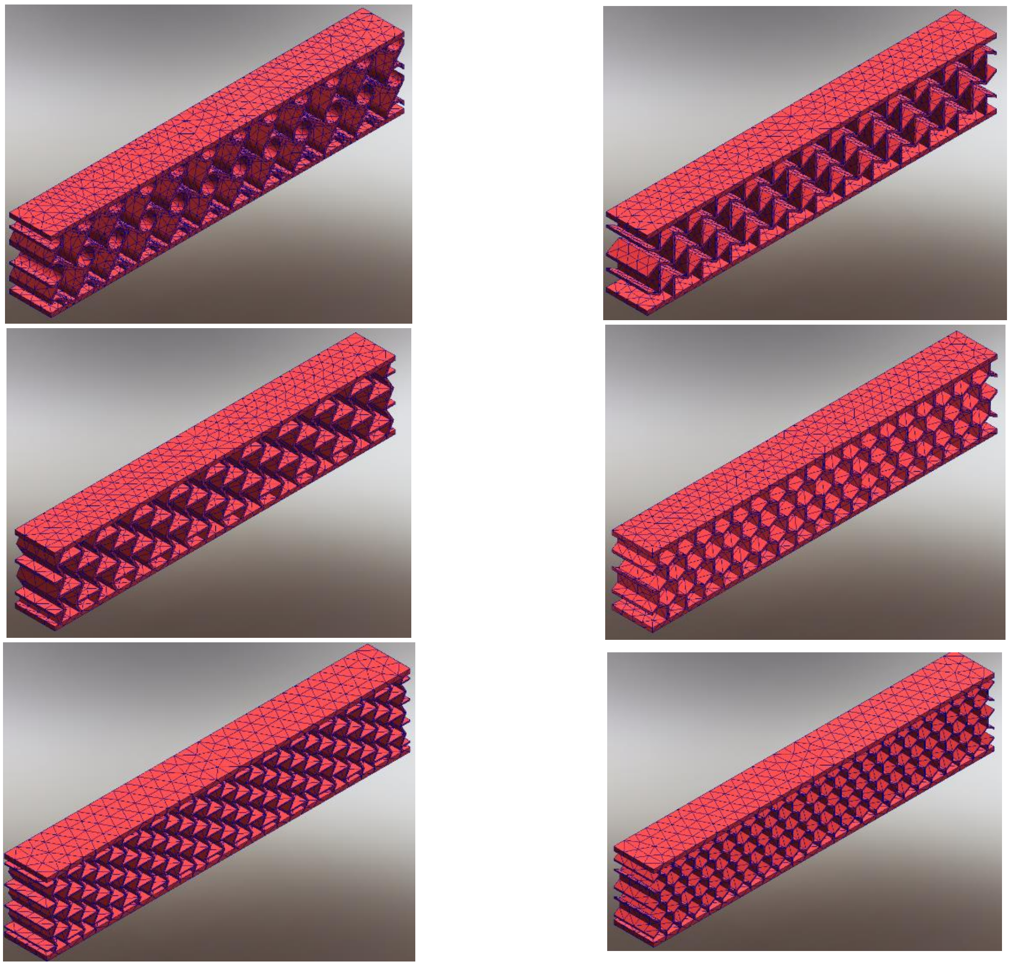


Fig. 3.11. Finite elements mesh.

In the following figure 3.12 the modelated experiment showed.

Applied concentrated load were placed in the middle of the beam, and fixed supports

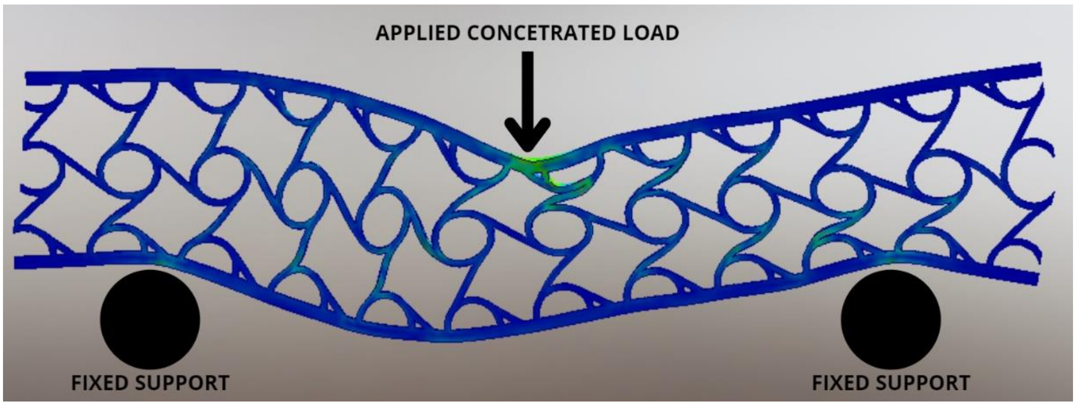


Fig. 3.12. Scheme of experiment in the Solidworks software.

distance where measured from the both sides to place a beam.

The 3D models were designed according to the previously (2.3 chapter) mentioned 2D models. Properties of material applied to them. Places of fixed supports determined. The experiment was repeated during the simulation.

During modeling, the three-point bending method was used on each sample. Results of strain, stress and displacement were received on every beam. Figures 3.13, 3.14, 3.15. shows an example on how one of the beams behave. The results of all beams are displayed in the diagrams.

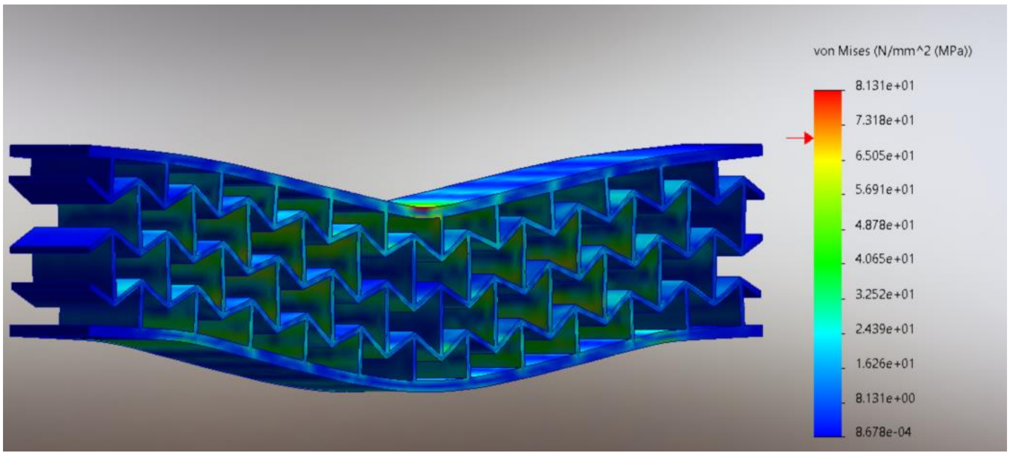


Fig. 3.13. Stress of Re-entrant core.

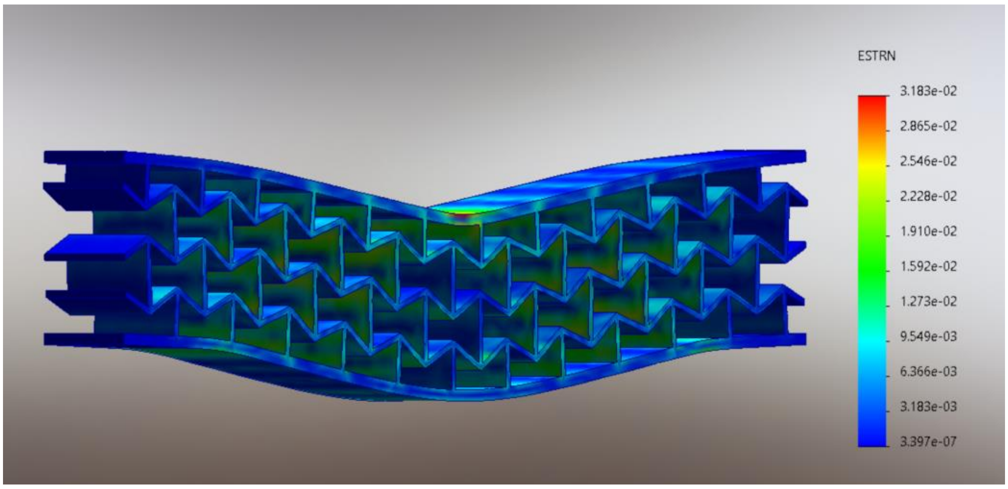
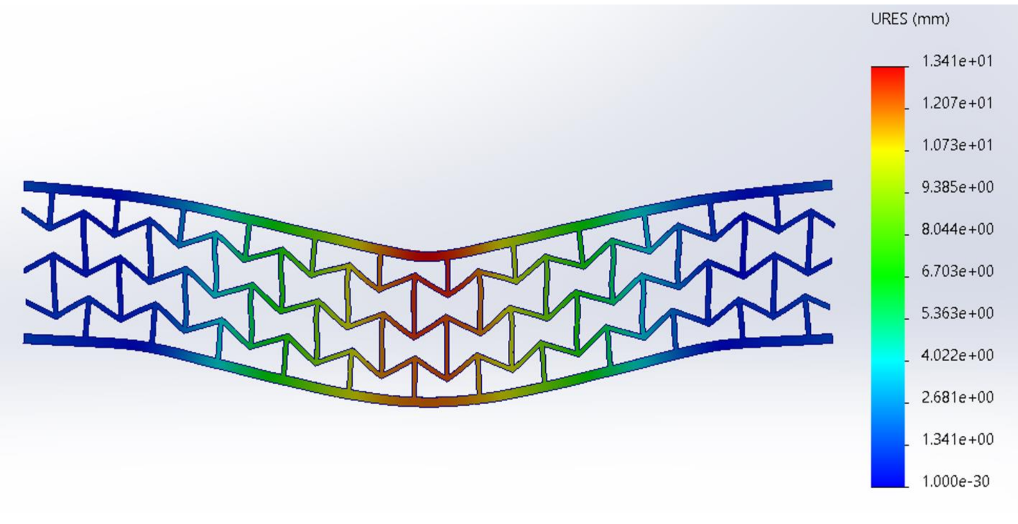


Fig. 3.14. Strain of Re-entrant core.

Fig. 3.15. Displacement of Re-entran core.



To analyse the diagrams (fig. 3.16) the greatest stress experienced by Honeycomb core. It reaches even 82.1 MPa. The least stress experienced by Honeycomb Scaled core, it reached 11.4 MPa.

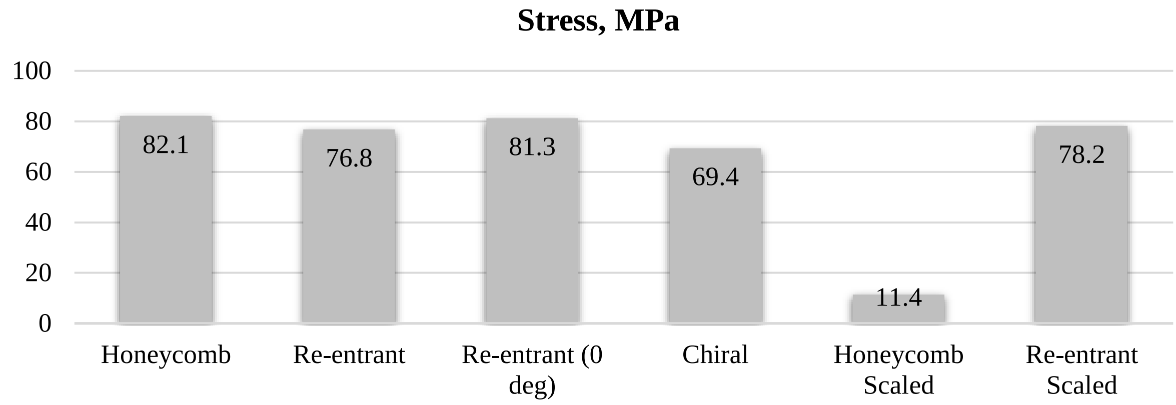


Fig. 3.16. Diagram of core stresses.

The honeycomb core experiences the greatest strain (3.17) of 8.21. All other cores experienced similar stresses from 2 to 3.

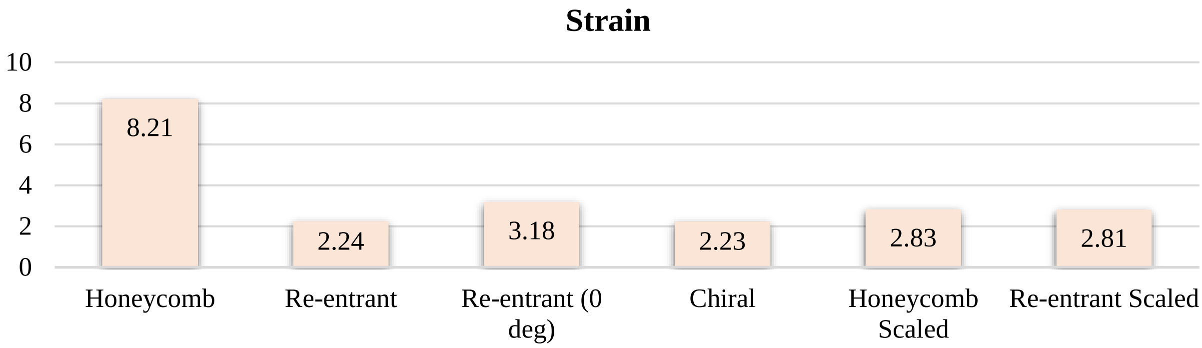


Fig. 3.17. Diagram of core strains.

In the diagram (fig. 3.18) below displacement sizes shown. As results show, despite that Honeycomb core showed the greatest strain and stresses it reached the lowest displacement. The highest displacmenet was reached by Re-entrant Scaled core.

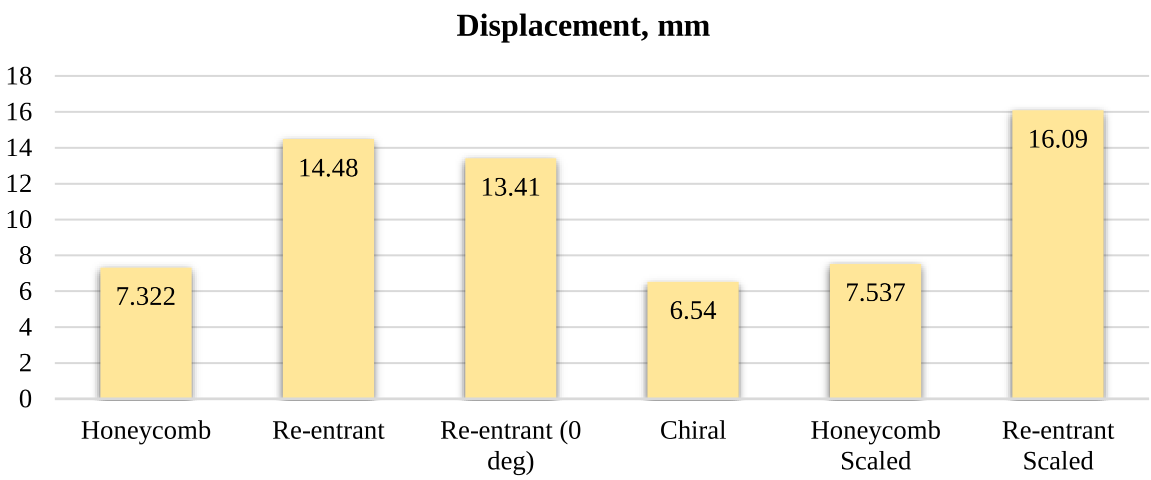
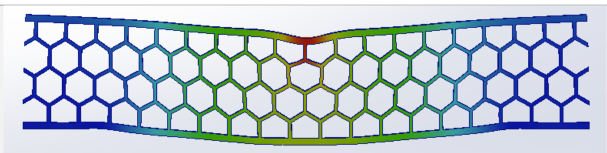
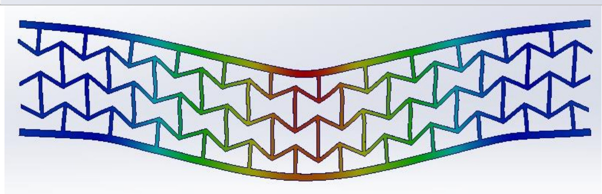
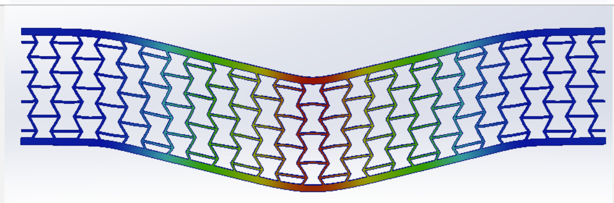
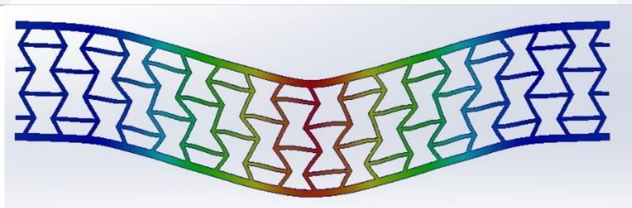
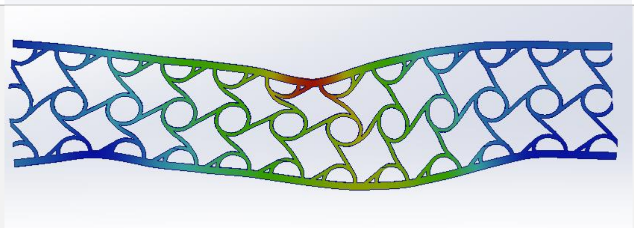
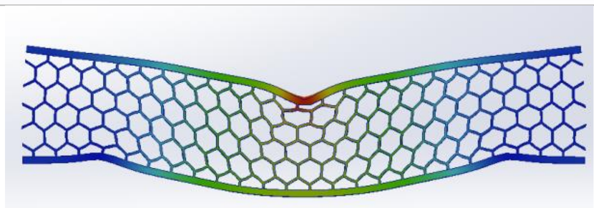


Fig. 3.18. Diagram of core displacements.

Concluded results showed in a tables 2.6 and 2.7 below.

	P_{max}, N	Displacement, mm	Stress, Mpa	Strain
Honeycomb	0.95	7.322	82.1	0.000000821
Re-entrant	0.62	14.48	76.8	0.000000224
Re-entrant (0 deg)	0.43	13.41	81.3	0.000000318
Chiral	0.47	6.54	69.4	0.000000223
Honeycomb Scaled	0.93	7.537	11.4	0.000000283
Re-entrant Scaled	0.51	16.09	78.2	0.000000281

Table 2.7. Results of displacement in numerical simulation with Solidworks

Specimen type	Specimen visualisation	Maximum force, kN	Displace-ment, mm
Honeycomb		950 N	6,8
Re-entrant (0 deg)		430 N	13,41
Re-entrant Scaled		510	16,00
Re-entrant		620	13,90
Chiral element		470	6
Honeycomb Scaled		930	7,8

By systematizing the obtained results, it was found that the displacement obtained during the experiment and the displacement obtained by numerical modeling do not always coincide. In the future, to accurately model the elements with which the results do not match, errors must be evaluated, or an experiment must be performed in the laboratory.

With this simulation, the capabilities and accuracy of Solidworks checked in designing sandwich beams systems.

3.3 Verification of numerical model

The initial simulation was performed with Solidworks software. The real behaviour of the beams was simulated, using PLA plastics characteristics, and using the loads which were used in experiment in laboratory.

Numerical analysis was performed using the Solidowrks program. It replicated the laboratory experiment. during modeling, the three-point bending method was used on each sample. The results were as follows in table 2.8:

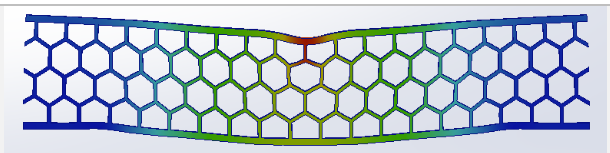
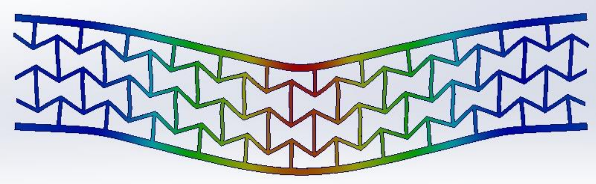
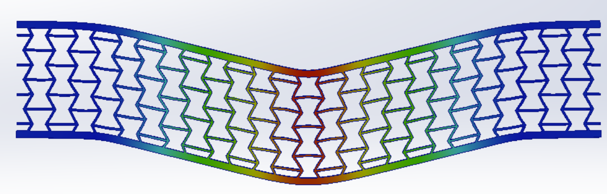
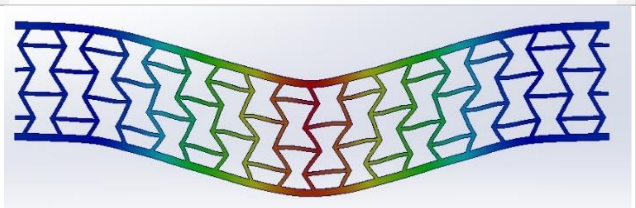
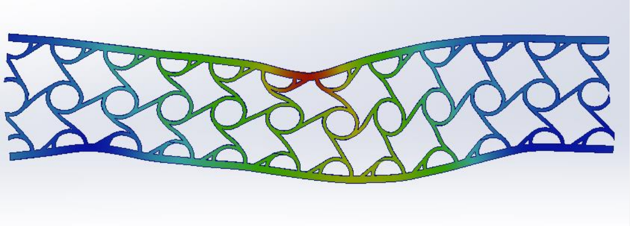
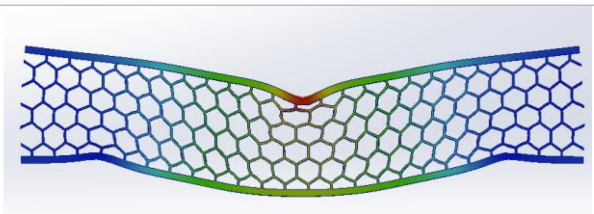
Specimen type	Specimen visualisation	Maximum force, kN	Displace-ment, mm	Actual displace-ment, mm
Honeycomb		950 N	6,8	7,53
Re-entrant (0 deg)		430 N	13,41	13,41
Re-entrant Scaled		510	16,00	16,09
Re-entrant		620	13,90	14,48

Table 2.8. Results of numerical simulation with Solidworks

Chiral element		470	6	6,54
Honeycomb Scaled		930	7,8	7,32

By systematizing the obtained results, it was found that the displacement obtained during the experiment and the displacement (fig. 3.19) obtained by numerical modeling do not always coincide. In the future, to accurately model the elements with which the results do not match, errors must be evaluated, or an experiment must be performed in the laboratory. With this simulation, the capabilities and accuracy of Solidworks checked in designing sandwich beams systems.

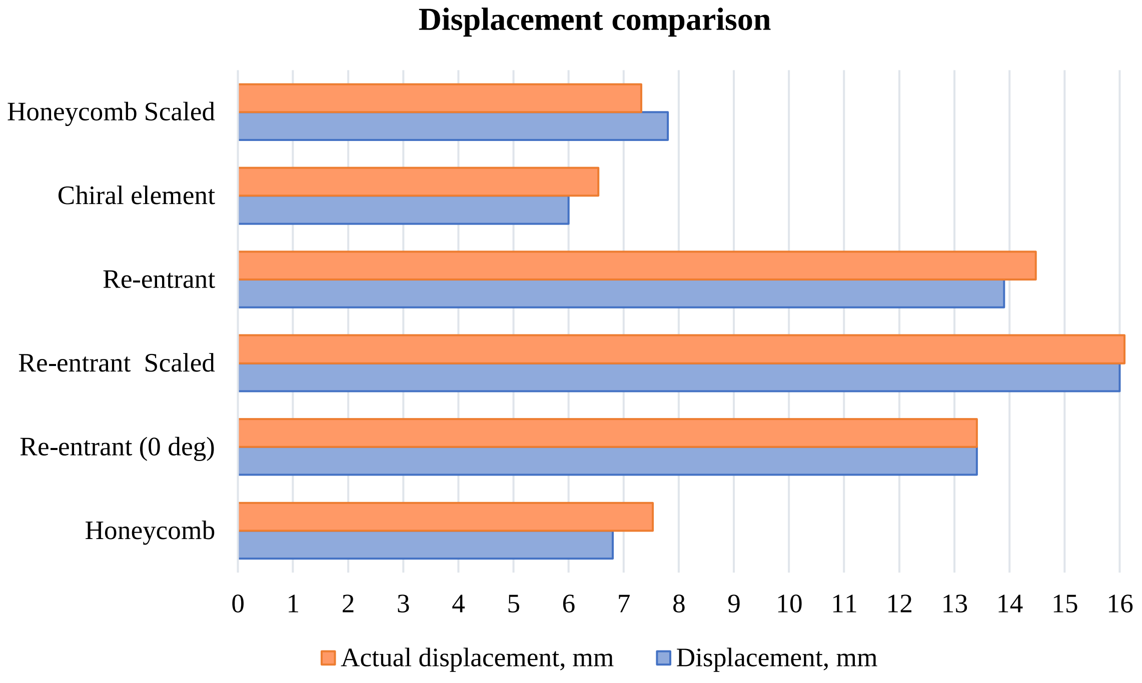


Fig. 3.19. Diagram of displacement comparison.

3.4 Case study

An additional element with a chiral core (fig. 3.20) was created for comparison and for improving the beam element. A 1 mm thick plate was placed on the upper and lower facesheets. Facesheets were reduced to 0,5 mm thickness. Cell wall thickness remained the same as 1 mm and geometry were not scaled or units of cells changed. Table 2.9 summarizes the information of the two comparative samples.

Table 2.9. Chiral and Chiral + plates specimens comparison table.

	Core wall thickness, mm	**Upper and lower facesheet wall thickness, mm**	**Units of cells**	**Weight, g**	**Displacement, mm**	**Note**
Chiral	1	2	24	42	6.54	Specimen is 7 % lighter than the Chiral core + plates element.
Chiral + plates	1	0.5	24	45	3.7	Specimen has two aluminum plates added to the upper and lower facesheets.

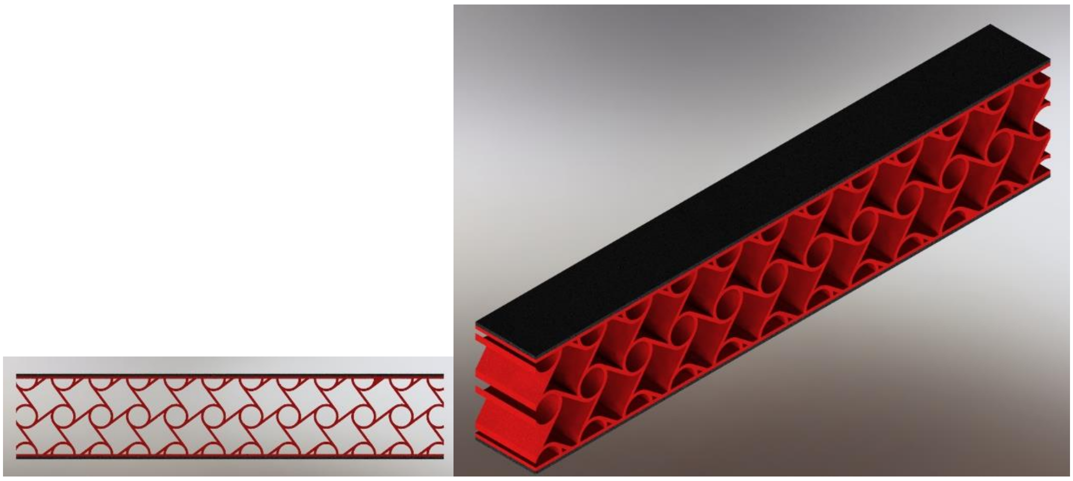


Fig. 3.20. Chiral core specimen with aluminium plates.

During the comparison, the maximum force of 460 N maintained during the experiment was applied in the Solidworks space. After performing the numerical simulation, the behavior was observed - the element bent in the same way as without an aluminum plate, and a displacement (fig 3.21) of 3.7 mm was reached.

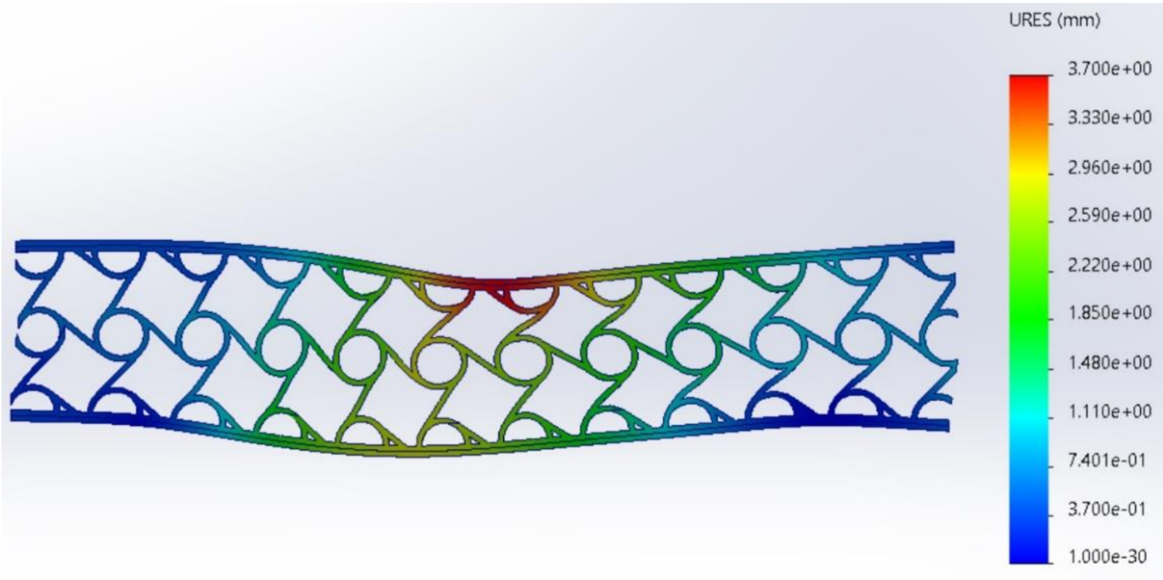


Fig. 3.21. Chiral core specimen with aluminium plates numerical simulation.

To evaluate the general information, the best performance were noticed on a Chiral + plates element. It has the stiffnes (fig 3.22) as a 127.027 N/(mm·g) and overtakes Chiral specimen. Chiral specimen has stiffnes as a 72 N/(mm·g) .

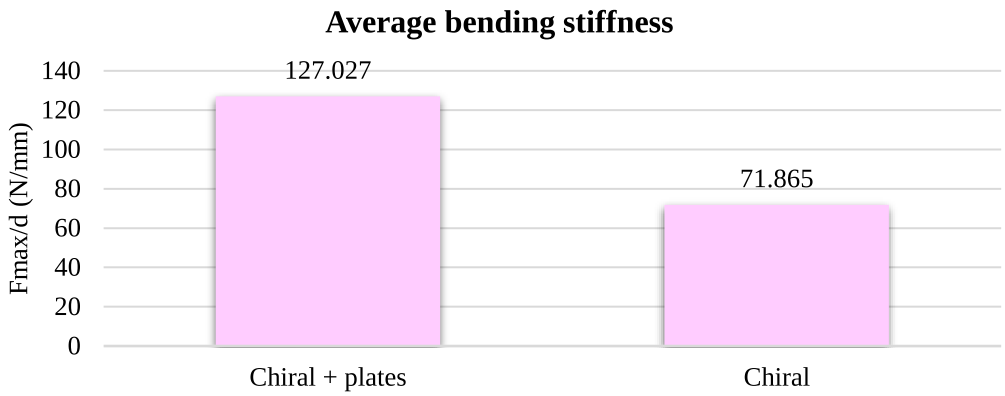


Fig. 3.22. Chiral core specimens average bending stiffness diagram.

Energy absorption (fig. 3.23) as a comparison is the better of Chiral specimen. Chiral + plates absorbs energy 1.20 J and shows worse comparing to Chiral 1.537 J.

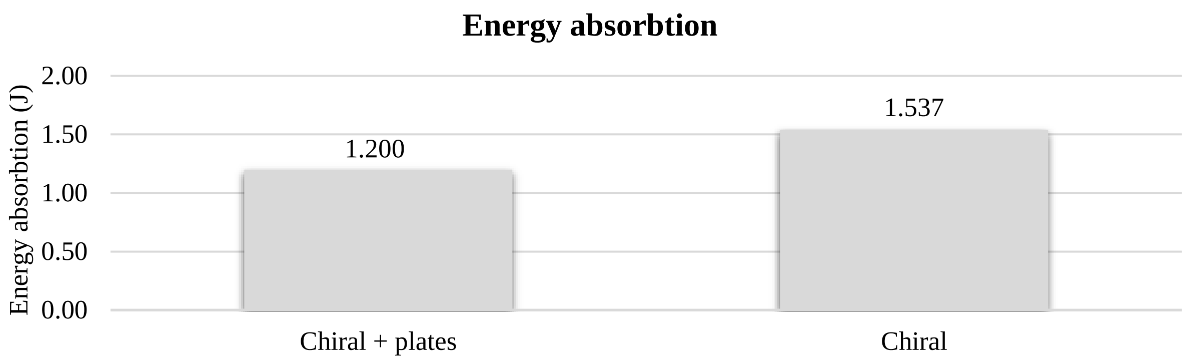


Fig. 3.23. Chiral core specimens average energy absorbtion diagram.

To conclude the comparison, the two analyzed solutions weigh partially the same, the second composite sample, chiral with aluminum plates, is 7 percent heavier. In the second sample, the structure performs its polymer work, and the bending stiffness is generated by aluminum. With the addition of aluminum plates, the simulated beam reduces vertical deformations by as much as 43 percent.

After using this method and integrating aluminum plates, while keeping the weight of a similar element, it is possible to maintain good energy absorption characteristics and at the same time increase stiffness.

In the future, after performing the necessary tests and experiments, and to apply this composite variant, it could be applied to bridge decks or beams. After this comparison, a direction for further research in this area is given.

3.5 Conclusions of chapter 3

This study shows the possibilities of an innovative system, how using experiments and numerical modeling it is possible to study, compare, and determine the capabiflities of the material, design the desired geometry, test it, verify its operation and resistance to forces. The following conclusions are drawn from the obtained results:

1. The numerical simulation results revealed the highest strains in the honeycomb structure. These findings align with experimental observations, indicating that the honeycomb structure undergoes significant local deformations. Honeycomb Scaled performed the best behavior and reached a maximum force of 0,95 kN. This resulted in a vertical displacement of 7,32 mm. The bending stiffness of the curve Honeycomb Scaled is the highest. The structure that has a rarer honeycomb geometry has almost 23% lower bending stiffness, so it can be said that a denser structure allows to achieve higher stiffness.
2. The sandwich beam with Re-entrant core (0 deg) presented an elastic behavior and after the test was completed it recovered almost completely to the initial position.
3. The chiral core had the worst response as absorbing energy, the ligaments being very susceptible to local buckling and crushing phenomena, as ligaments are not aligned along the loading direction.
4. The analysis of surface strain distribution using the Digital Image Correlation technique revealed that the failure of the examined beams is predominantly localized within the core of the sandwich structure for almost all beams. The localized effects, such as strain concentration, were particularly pronounced in chiral and honeycomb structures. Notably, the re-entrant structure demonstrated enhanced resistance to load concentration compared to other analyzed structures.
5. The numerical simulations unveiled distinctions between the experimental and numerical displacement outcomes for the sandwich beams. In order to enhance the precision of modeling, future investigations should prioritize error assessment through experimental validation. Recognizing the potential for numerical simulation inaccuracies, it is recommended to delve into detailed material models that incorporate additive production parameters for a thorough understanding.
6. Honeycomb Scaled core specimens prove to be promising choices for applications requiring high stiffness. Re-entrant core demonstrate increased compliance and exhibit a remarkably recovery, suggesting substantial potential also.
7. The honeycomb beam's stress characteristics ensure efficient load distribution, promoting structural safety and reliability. Its elevated strain capacity signifies elastic

deformation tolerance, maintaining structural integrity. The Re-entrant scaled beam, with pronounced energy absorption characteristics, is advantageous for dissipating energy during dynamic events.

CONCLUSIONS

1. Incorporating additive manufacturing represents a transformative paradigm in civil engineering for crafting lightweight structures. Embracing this technology, especially in lattice core sandwich structures, expedites prototyping, enriches design flexibility, and advances cost-effective, sustainable practices. This fusion of technologies holds significant potential for reshaping construction methodologies, addressing the need for efficient, eco-friendly, and economically viable solutions in the realm of civil engineering.

2. The inclusion of auxetic structures in lightweight bridge design marks a significant shift in engineering. This integration provides unique paths for impact absorption, vibration damping, and the development of advanced materials with tailored mechanical properties.

3. An experimental program was conducted to investigate the flexural behavior and energy absorption of polymeric honeycomb, re-entrant, and chiral core sandwich beams with similar weights. The honeycomb structure demonstrated superior flexural stiffness, whereas the re-entrant auxetic structure exhibited the highest energy absorption, showcasing remarkable ductility and withstanding substantial vertical displacement. This exceptional deformability highlights a distinct aspect of the re-entrant structure's mechanical behavior.

4. The reduction in the wall thickness of the honeycomb structure did not significantly impact the flexural stiffness, as only a modest 5% improvement was observed. In contrast, reducing the wall thickness of the re-entrant (90 degrees) structure resulted in a substantial 35% increase in initial flexural stiffness. This difference is attributed to the scale of the structure, as scaling had no effect on the initial stiffness of the honeycomb but had a pronounced impact on the re-entrant structure.

5. Finite element models of the studied sandwich beams were created and validated with experimental results. The numerical simulation results revealed that a distinctive feature of the honeycomb structure is the concentration of local strain. These outcomes are consistent with experimental observations made using the digital image correlation technique, affirming that the honeycomb structure experiences notable local deformations.

6. The case study revealed that a composite sandwich beam, incorporating a polymeric sandwich and aluminum plates, can maintain the same overall weight while providing a notable 80% improvement in flexural stiffness. This enhancement, however, comes at a minor cost, with a 20% reduction in energy absorption characteristics.

7. The conducted study sheds light on the characteristics and behavior of lightweight sandwich beams. However, given the novelty of this field, further research is

necessary for more precise evaluations. If future regulations align with the elements' characteristics, enabling their utilization in bridge construction, there is potential for reducing construction costs, expediting construction processes, and introducing innovative solutions to bridge construction.

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