DESIGN AND ANALYSIS OF A FRICTIONAL MECHANICAL METAMATERIAL FOR ENERGY DISSIPATION

Axel Ugochukwu Fayet

Primary Supervisor: Dr. Maziar Ramezani

A thesis submitted to Auckland University of Technology in fulfillment of the requirements for the degree of Master of Engineering

2025
School of Engineering, Computer and Mathematical Sciences
Faculty of Design and Creative Technologies

Acknowledgments

I would like to deeply express my gratitude to all the people who helped me get this thesis done. First off, huge thanks to my supervisor Maziar for his guidance, patience and consideration throughout my thesis. It really helped keep me grounded and in check in the most compassionate way. To Joshua, thank you for all your help and encouragement, especially during my FEA simulations and printing. I could not have done it without you, and I wish you all the best for your PhD!

To my French crew – Adrien, Alix, Marin, and Daniel – for making AUT a much better place to be. Ludovic, a special shout-out for your CAD skills, which seriously was a massive help. Thanks for all the help and laughs.

Big thanks to all my friends abroad, especially Julien in Canada for the long-distance support and believing in me. And closer to uni, the team at Silky Otter cinemas and my salsa class – you both were my awesome escape from uni stress, kept me sane and healthy.

Of course, my biggest gratitude goes to my family. You made absolutely everything possible, from start to finish. Could not have asked for more.

And finally, I would like to thank God for his intermission in the success of this thesis.

Abstract

This thesis explores the design, fabrication, and testing of a frictional mechanical metamaterial for efficient energy dissipation. Unlike conventional materials, metamaterials derive their properties from their shape rather than their composition. This allows finer and better control over mechanical behavior. In this study, a novel unit cell design is proposed, leveraging friction as the primary mechanism for energy dissipation. The metamaterial is 3D-printed using TPU and CPEHG100 filament, chosen for its flexibility and durability, as well as its use in previous research in the lab. A modular assembly is also manufactured to test scalability and prepare future developments.

The research integrates both numerical simulations and experimental testing to evaluate the performance of the metamaterial under compressive loading. Finite Element Analysis (FEA) is conducted using ANSYS, attempting to come as close as possible to experimental setup. Simulation results are compared with physical tests conducted using a compression machine, focusing on energy dissipation values based on force-displacement hysteresis loops. The study also investigates failure modes and discrepancies between simulation and experimental setup.

Results indicate that the proposed metamaterial exhibits effective energy dissipation through frictional sliding mechanisms within the unit cells. The modular assembly demonstrates consistent energy dissipation values, highlighting its linear scalability. However, discrepancies between simulation and experimental data are attributed to assumptions in contact modeling, material behavior and manufacturing methods.

The findings contribute to the development of frictional metamaterials for energy dissipation, opening pathways for applications in impact protection and seismic engineering. Furthermore, the modular design approach provides adaptability for future research, such as the potential integration of Triboelectric Nanogenerators (TENGs) for energy harvesting.

This research advances the field of mechanical metamaterials by offering a simple solution for energy dissipation through friction. Future work will focus on optimizing model parameters, exploring alternative materials, and investigating fatigue behavior to expand understanding of these designs.

Table of Contents

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed on 21st of February 2025

Introduction

1.1 Background and Motivation

Conventional materials are increasingly reaching their performance limits, prompting a global search for innovative alternatives capable of meeting increasingly complex engineering demands. Metamaterials are a new family of materials that derive their properties not from their composition but from their shape. This unique ability is due to the advancements in additive manufacturing, most notably plastic 3D printing which allows for fast, precise and cheap manufacturing of intricate geometries. The shapes that give metamaterials their properties are indeed often impossible to manufacture with traditional techniques. TPU for example allows for rapid prototyping and quality manufacturing at a faster pace and lower cost. As such, the field of metamaterials has revolutionized several fields of industry. First in optics and electromagnetics, significant advancements in research on mechanical metamaterials have introduced new insights on the benefits of their properties. From acoustic cloaking to vibration dampening to energy dissipation, the applications and potential for future improvements and applications are numerous and would benefit engineering as a whole.

A prime example of this would be frictional energy dissipation. Friction is present in all areas of industry, inducing wear and tear on machinery, and leading to loss of efficiency and even failure of mechanical systems. Harnessing and controlling its mechanisms could potentially benefit machines, industrial and even biomedical processes. In order to fine tune friction phenomena, the associated energy dissipation and best use it to an advantage, current designs rely on breakable structures or inefficient and heavy mechanisms. This is where frictional metamaterials are at an advantage. Through additive manufacturing, metamaterials can be produced at lower costs, faster and lighter, making them more efficient. Frictional metamaterials allow for the design of materials that are specifically tailor made for energy dissipation. This allows means that by adjusting their shape and geometry, the material can be tuned to better suit different energy dissipation applications.

They can also be designed to not be affected by external factors such as temperature or humidity, depending on the material used during the additive manufacturing. Potential applications are numerous. These include more efficient shock absorbers, lighter crash boxes improving safety and reliability of vehicles, but also seismic engineering for structural protection of buildings against earthquakes and natural disasters.

1.2 Research Objectives and Questions

The field of metamaterials being relatively new, there was a call for new research on alternate metamaterial designs. New shapes, geometries and characteristics need to be tested and enable research to find the best compromise between different designs. This will allow cheaper and more efficient models to be manufactured. Based on research already done in the lab [18], a call for a simple, modular design for energy dissipation was made. Also, other research on frictional metamaterials relies on complex lattice structures or breakable structures, leading to poor reusability. This new design had to have energy dissipation qualities, but also be scalable, manufacturable in situ and later adaptable for future improvements, on top of being reusable and easy to manufacture. These include skin-like improvements such as metasurfaces for added energy dissipation, or even energy harvesting and generation through the use of Triboelectric Nanogenerators (TENG). This is the focus of this thesis.

This thesis aims to design, fabricate, test and analyze a frictional mechanical metamaterial for energy dissipation. Once the design was set, the unit cell was modeled, printed and tested both experimentally and usign Finite Element Analysis (FEA). This research aims to answer the following questions:

- Can a simple, modular and scalable metamaterial for energy dissipation through friction be designed?
- How much energy can be dissipated by the design? This will quantify exactly the performance of the design.

- How accurately can FEA predict and model experimental results? Having an accurate model will help validate the design and help future research.
- What is the best way to manufacture such a material? Analyzing the quality of the 3D printing is crucial.
- What are the potential applications?
- What are the future developments of such research?

In other words, this research's objectives are:

- **Design:** Develop a novel frictional metamaterial unit cell with optimized geometry and material selection for energy dissipation through friction. The simple geometry of two plates sliding against each other made of high coefficient of friction plastic helps this development.
- **Simulation:** Simulate the metamaterial's behavior under compression using ANSYS FEA software to analyze its deformation and energy dissipation characteristics.
- **Testing:** Fabricate the metamaterial unit cell using 3D printing and conduct experimental tests to evaluate its energy dissipation performance under compression tests.
- **Validation:** Compare the simulation and experimental results to validate the design and identify any discrepancies or limitations, such as adequation between the simulation and the experiments.

1.3 Scope and Limitations

This research only focuses on one design, modeled through CAD and FEA software, and printed using TPU 3D Printing and CPEHG100 filament. The study's limitations hence include the use of only one type of material and one type of 3D printing. This is due to the time frame and availability of materials, as well as to base the research on current developments in the lab. Future research could fine tune the geometry and propose different versions, including using other materials or other 3D printing techniques. This would allow comparison between the results and this thesis. The tested parameters are the energy dissipation as well as the reaction of the metamaterial to compression tests. The design is then set up in a modular 6-unit assembly and subjected to the same tests. The unit cell and the modular assembly are not subjected to long term cyclical endurance and fatigue tests. This means the design may not be ready for long term extreme durability applications yet. The study does not aim to change the fundamental design to absolutely maximize energy dissipation but rather keep the set design's characteristics (simplicity, modularity, scalability) and see how much energy can be dissipated using friction. This facilitates future developments, keeping the focus on the design as a building block for later improvements. Tests are also enabled by the ease of manufacturing of the design.

1.4 Thesis Outline

The remainder of this thesis is organized as follows:

- **Chapter 2, Literature Review:** Provides a comprehensive literature review of metamaterials, friction, energy dissipation, and additive manufacturing.
- **Chapter 3, Methodology:** Details the methodology used in this research, including the design process, simulation setup, experimental procedures, and data analysis techniques.
- **Chapter 4, Results:** Presents the results of the simulations and experiments, including detailed analyses of the metamaterial's deformation behavior, energy dissipation performance, and failure modes.
- **Chapter 5, Discussion:** Discusses the key findings, analyzes the discrepancies, compares them with existing research, and explores potential future research directions and applications.
- **Chapter 6, Conclusion:** Concludes the thesis by summarizing the main contributions, limitations, and recommendations for future work.

Literature Review

This chapter delves into the literature review of this thesis, covering three main areas: metamaterials, friction and energy dissipation, and additive manufacturing. The discussion begins with an exploration of metamaterials, their unique properties, and their applications in various fields. It then examines friction and energy dissipation, focusing on the underlying mechanisms and the importance of these phenomena in engineering design. Finally, the chapter explores additive manufacturing, its capabilities in fabricating complex geometries, and its role in advancing the field of metamaterials.

2.1.1 Metamaterials: An Overview

Metamaterials are a rather novel family of materials that possess the unique characteristic of deriving their properties not primarily from their chemical composition, but rather from their shape and internal architecture [1]. Structure-driven functionality hence defines the core concept of metamaterials. The emergence and development of this field has been made possible thanks to the increasing accessibility and ease of use of additive manufacturing technologies, particularly 3D printing. These technologies provide the necessary precision and design freedom to fabricate the microstructures or unit cells that dictate metamaterial behavior. Although the field of metamaterial research is still relatively young, it is remarkably dynamic and continues to yield novel insights and discoveries at a rapid pace, as evidenced by the consistent stream of publications and evolving understanding documented in state-of-the-art reviews [1] [2].

By now, metamaterials are seen throughout a variety of fields, from optics and acoustics to mechanics and tribology. Initially studied in optics and electromagnetics, where they enabled unprecedented control over light and electromagnetic waves, metamaterials are now making significant strides in acoustics [3], mechanics, and even tribology [1]. Metamaterials, therefore, are not only engineered existing materials; they represent a new artificially created family, designed to exhibit properties and functionalities that do not naturally occur [4,5]. This possibility to separate material properties from structural arrangement allows for unprecedented control and customization, opening possibilities for designing materials with tailored responses for specific applications. For instance, mechanical metamaterials can be designed to exhibit extreme properties such as negative Poisson's ratio, high stiffness-to-weight ratios, or, relevant to this thesis, enhanced energy absorption capabilities [6 ,7]. The programmability of metamaterials, referring to the ability to tailor their properties through design and potentially even dynamically alter them post-fabrication [8], further expands their versatility and applicability across diverse technological challenges.

2.1.2 Mechanical Metamaterials

Mechanical metamaterials specifically achieve property modulation through their intricate internal architecture, often characterized by repeating unit cells with specific geometric features, at a characteristic length for the application [4]. This structural control allows for the design of materials with unprecedented combinations of mechanical characteristics, such as ultra-lightweight yet ultra-stiff structures [9]. Energy absorption in mechanical metamaterials can be achieved through various mechanisms, including plastic deformation, buckling, and as explored in this thesis, friction. [10,11,12]

Beyond static mechanical properties, the concept of programmability is particularly relevant to mechanical metamaterials [8,13]. Programmable mechanical metamaterials are designed to dynamically alter their mechanical response in a controlled manner. This programmability can be achieved through various means, such as incorporating smart materials like shape memory polymers [14,15], or designing architectures that exhibit multistability, allowing for switching between different mechanical states under external stimuli [6,13,16]. This dynamic control over mechanical properties opens up new possibilities for adaptive structures, tunable vibration absorbers, and responsive energy dissipation systems. It is important to note that this thesis heavily relies on the insights and experimental framework established by Jeong et al. [18]. Indeed, this thesis was undertaken in the same lab under the same experimental conditions and draws heavily from that article's methodology and initial findings, extending the investigation into an alternative design for energy dissipation within 3D-printed mechanical metamaterials. Figure 1 shows Jeong et al. design.

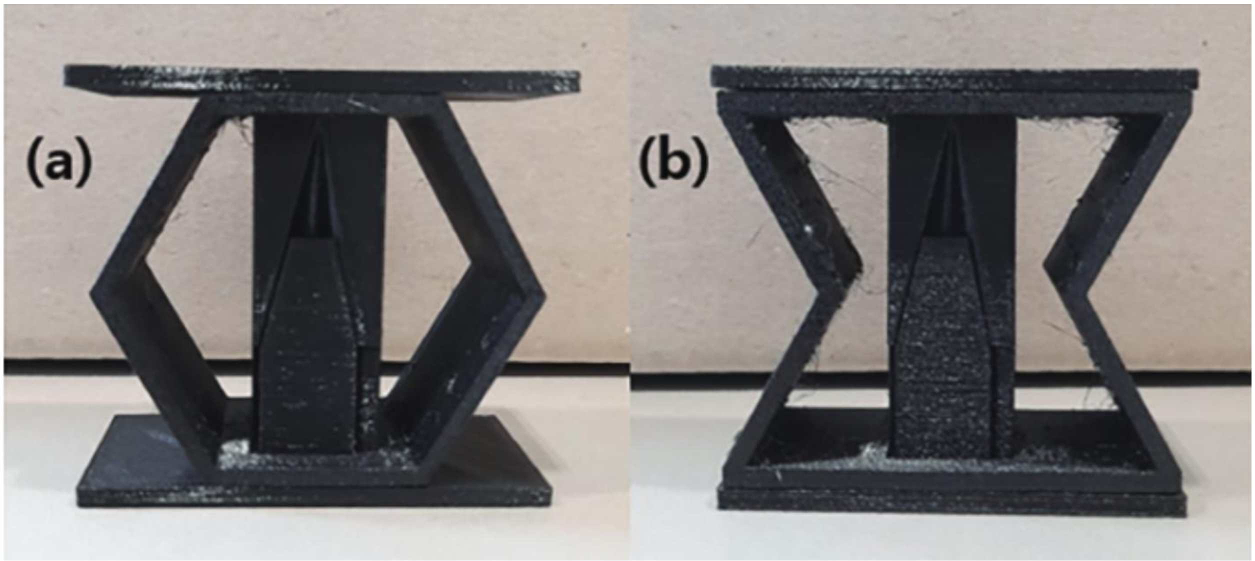


Figure 1: Jeong et al. Designs: conventional hexagonal frame (a) and re-entrant (b)

The alternative design explored in this thesis has a simpler geometry and although less effective, provides opportunities for further developments such as the implementation of Triboelectric Nanogenerators (TENG) [29,30,33] and scalable modular designs. TENG are a promising field of development as these are not well studied and inherently innovative [30,33].

2.1.3 Applications of Metamaterials

The versatility of metamaterials, stemming from their unique ability to manipulate physical phenomena through structural design, has led to a broad range of proposed and realized applications across diverse fields. Initially, metamaterials were used in optics, enabling phenomena such as negative refraction [4]. In acoustics, metamaterials have been designed for sound absorption and acoustic cloaking, with applications ranging from noise reduction in urban environments to advanced sonar systems [13]. Metamaterials are increasingly being explored for structural and mechanical applications. Auxetic metamaterials, exhibiting a negative Poisson's ratio, are designed to expand laterally when stretched, offering potential benefits in areas such as deployable structures and biomedical implants [7][17]. The inherent tunability of metamaterial properties makes them attractive for applications requiring adaptable or responsive materials. Programmable metamaterials, for instance, can be designed to change their shape, stiffness, or other properties in response to external stimuli, enabling functionalities such as adaptive optics or reconfigurable structures [7]. Within mechanical engineering, metamaterials designed for energy absorption are gaining significant attention, driven by the need for improved impact protection, vibration damping, and structural robustness across industries such as automotive, aerospace, and civil engineering [13][4][26][32]. Specifically, the ability to tailor the energy absorption characteristics of mechanical metamaterials makes them highly promising for applications requiring efficient and controlled dissipation of mechanical energy, a key focus of this thesis [6][26][18][32].

2.2 Friction and Energy Dissipation

Friction is a ubiquitous phenomenon in mechanical systems. At a microscopic level, friction originates from the complex interactions between surface asperities, adhesion forces, and interlocking features at the interface of contacting materials. As two surfaces are pressed together, these microscopic irregularities lock together, and adhesion forces contribute to the resistance to sliding. When relative motion is initiated or maintained, energy is required to overcome these adhesion forces. Macroscopically, friction manifests as a force opposing motion, and this frictional force directly leads to energy dissipation.

The process of overcoming frictional resistance results in the conversion of mechanical energy into other forms, primarily thermal energy. This energy transformation is the fundamental mechanism of frictional energy dissipation. As surfaces slide against each other, the work done against the frictional force is not recovered as mechanical work, but rather dissipated as heat, This energy dissipation through friction is a crucial consideration in engineering design, impacting efficiency, durability, and safety. Understanding and controlling frictional energy dissipation is particularly relevant in the context of this thesis, where friction is attempted to be intentionally engineered as a primary mechanism for dissipating unwanted mechanical energy. This is explored in dynamic analyses and modeling of metamaterial behavior [7][6][17][31]. Metamaterials hence present a useful solution to tailor energy absorption by harnessing friction.

2.3.1 Additive Manufacturing

Additive Manufacturing (AM), commonly known as 3D printing, represents a paradigm shift in manufacturing processes, building objects layer-by-layer from digital designs, in contrast to traditional subtractive or formative methods [20]. This layer-by-layer construction gives designers freedom and enables the creation of complex geometries that could not be made with conventional manufacturing techniques. A diverse range of AM technologies has emerged, each with its own set of capabilities, materials it can use, and process characteristics [9][11]. For polymers, common techniques include Fused Deposition Modeling (FDM, used in this thesis), Stereolithography (SLA), and Selective Laser Sintering (SLS). FDM, one of the most widely accessible AM methods, extrudes thermoplastic filaments layer by layer, building up the 3D object. SLA utilizes photopolymer resins that are selectively heated by UV lasers or projectors. SLS uses powder beds of polymers which are selectively fused by a laser.

Beyond polymers, AM technologies have also expanded to metals, ceramics, and composites. Metal AM, also known as metal 3D printing, includes techniques like Selective Laser Melting (SLM) and Electron Beam Melting (EBM). The manufactured parts often come with higher equipment and processing costs compared to polymer AM [10][19]. The evolution of AM technologies has been rapid, driven by advancements in materials, equipment, and process control [8][9]. Initially focused on rapid prototyping for design visualization and concept modeling, AM has matured into a viable manufacturing approach for functional parts and end-use products across industries ranging from aerospace to biomedical [19][14]. Key advantage of AM is the ability to produce fast, on-demand and directly in the workshop or lab [24]. Figure 2 shows an example of a Caribou FDM 3D Printer used to manufacture the metamaterial for this thesis.

Figure 2: Caribou FDM 3D Printer used for this research

2.3.2 Additive Manufacturing in Metamaterial Fabrication

Without AM, there would be no metamaterials, as explained in [27]. The unit cell structures that define mechanical metamaterials could not be achieved without the precision and versatility of AM. Traditional manufacturing processes often face significant limitations in fabricating these intricate designs efficiently and cost-effectively. AM overcomes these limitations. [28] This capability is especially crucial for mechanical metamaterials that rely on specific geometric features and arrangements to achieve their desired properties, particularly if these include features such as designed porosity, fine lattice structures, or complex interlocking mechanisms [27][28]

Furthermore, AM facilitates rapid design iteration and optimization in metamaterial research and development [1]. The ability to quickly prototype and test different metamaterial designs, enabled by AM, accelerates the process of trying out new architectures and optimizing metamaterial performance for specific applications. This rapid prototyping cycle is essential in the iterative design process inherent in metamaterial engineering. In the context of frictional metamaterials, AM is particularly crucial as it allows for the precise fabrication of designed frictional interfaces and complex geometries necessary to implement and optimize frictional energy dissipation mechanisms. The synergy between additive manufacturing and metamaterial design has therefore unlocked a new era of material engineering [27][17][14].

In conclusion, this chapter has reviewed the literature on metamaterials, friction and energy dissipation, and additive manufacturing, providing a comprehensive overview of these key areas relevant to this thesis. The chapter has highlighted the unique properties of metamaterials, their potential applications in various fields, and the importance of friction and energy dissipation in engineering design. Additionally, the chapter has discussed the capabilities of additive manufacturing in fabricating complex geometries and its role in advancing the field of metamaterials.
The literature review has revealed the growing interest in friction-based metamaterials for energy dissipation applications. These metamaterials offer several advantages, such as

high energy absorption capacity, reusability, and tunability. The literature has also highlighted the importance of careful design and optimization of these metamaterials to achieve the desired performance characteristics.
With a solid understanding of the relevant literature, the next chapter will detail the methodology employed in this research, including the design process, simulation setup, experimental procedures, and data analysis techniques.

METHODOLOGY

Building upon the solid understanding of the relevant literature, this chapter details the methodology employed in this research, including the design process, simulation setup, experimental procedures, and data analysis techniques. The field of metamaterials is relatively novel, with a limited number of existing examples necessitating the exploration of innovative designs. Consequently, this research aims to develop a novel metamaterial design to investigate its frictional energy dissipation capabilities. The proposed design emphasizes several critical properties: functionality, simplicity, scalability, manufacturability, and the maximization of contact surfaces for friction, which serves as the primary energy dissipation mechanism. Furthermore, the design is intended to withstand repeated loading without failure while consistently maintaining its energy dissipation performance.

3.1 Design Choices for the Unit Cell

Designing frictional metamaterials presents specific challenges due to the need to optimize these essential properties. The metamaterial must effectively dissipate energy through friction while remaining simple to manufacture and scalable for various applications. It must also withstand repeated loading without failure, maintaining its energy dissipation capabilities. The proposed design addresses these challenges by utilizing a hexagonal unit cell with central sliders. This configuration is functional, as demonstrated through experimental testing and simulation. It is also simple, avoiding complex shapes that could hinder manufacturability. The design's scalability is evident in the ability to reduce its overall size by 40% while maintaining functionality. The use of 3D printing makes the design easily manufacturable. Additionally, the metamaterial is inherently reusable, as it lacks crushable or breakable structures found in other designs. It is lightweight, durable, and adaptable to other materials, further enhancing its potential for various applications.

To maximize energy dissipation through friction, it's essential to consider the relationship between friction force, coefficient of friction, and normal force. Friction force is the force that resists motion between two surfaces in contact. It's directly proportional to the normal force, which is the force perpendicular to the contact surface. The proportionality constant is the coefficient of friction, which depends on the nature of the surfaces in contact. The design of the metamaterial aims to maximize friction and energy dissipation by maximizing the contact surface area between the components and utilizing a material with a high coefficient of friction.

The theoretical basis for energy dissipation through friction can be understood through the following equation:

$$Ff = \mu \, . \, Fn$$

where Ff is the friction force, μ is the coefficient of friction, and Fn is the normal force. The energy dissipated through friction is equal to the work done by the friction force, which can be calculated as:

$$W = Ff \, . \, d \quad W = Ff. \, d$$

where W is the work done and d is the sliding distance.

The unit cell of the metamaterial was to be designed with an external frame to hold an internal structure that was to be the main area of frictional energy dissipation. As such, the first design consideration was the external shape of the unit cell's frame. Repeatable patterns were of particular focus, considering squares, plates, and regular polygons. Figure 1 shows the early design thought process for the unit cell.

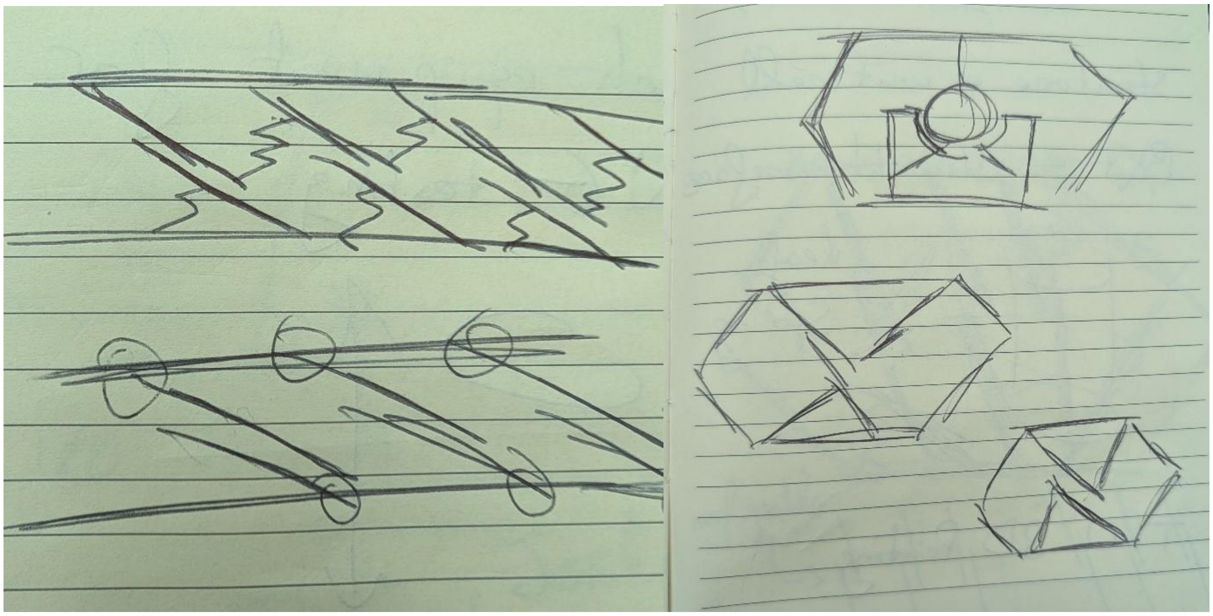


Figure 1: Early design sketches

The hexagonal shape was ultimately chosen for the unit cell's exterior due to its repeatable pattern in a tile or lattice, ease of manufacture, and minimal stress concentration. The initial version, with a width of 100 mm (figure 2), proved to be too large and time-consuming to print.

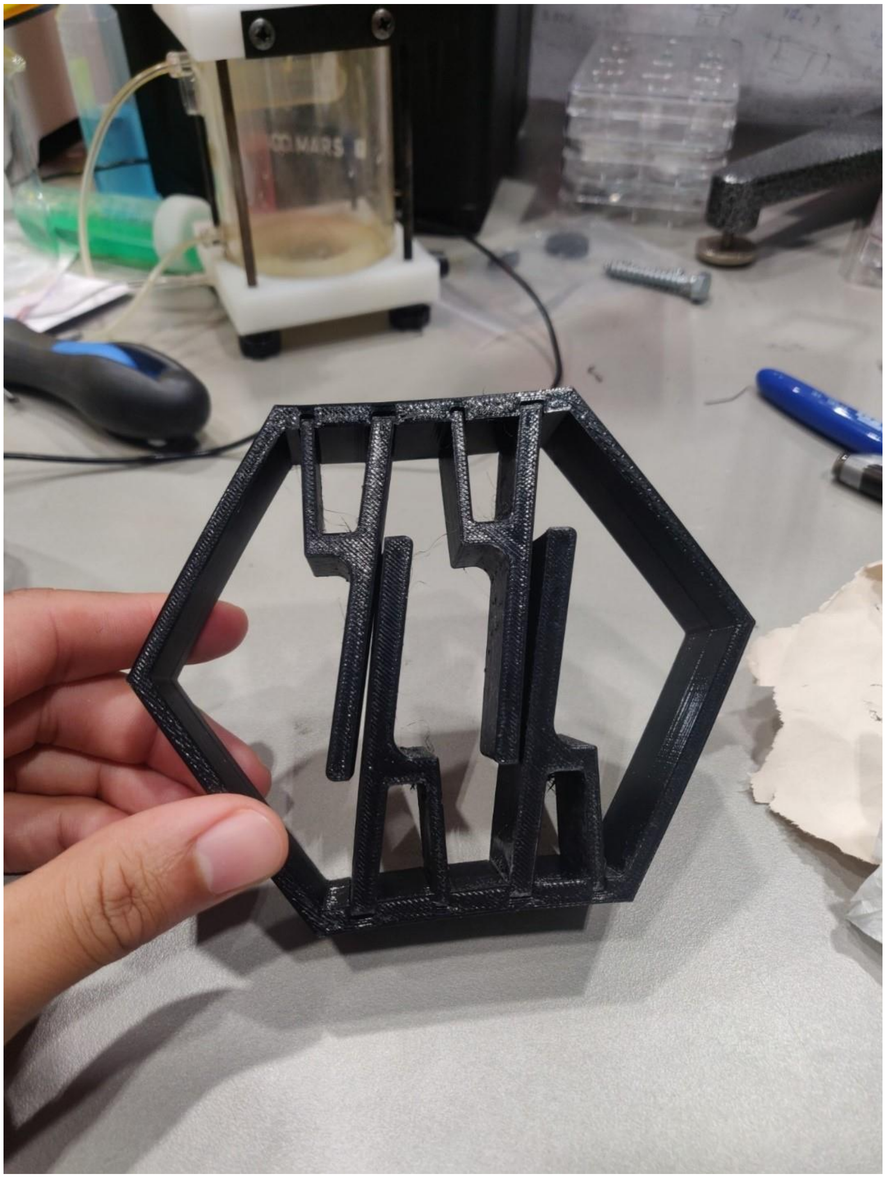


Figure 2: First Iteration 100mm tall

Therefore, the size was reduced by 40% to 60 mm, resulting in a significant reduction in printing time. The first iteration was also too thin, leading to breakage of the hexagonal frame. The final hexagonal unit cell design has dimensions of 60 mm x 30 mm, with a thickness of 4 mm. An additional 1 mm of thickness was added to each groove section to prevent this failure. The grooves are 3 mm deep, leaving 2 mm on each side of the hexagon to withstand the load (figure 3).

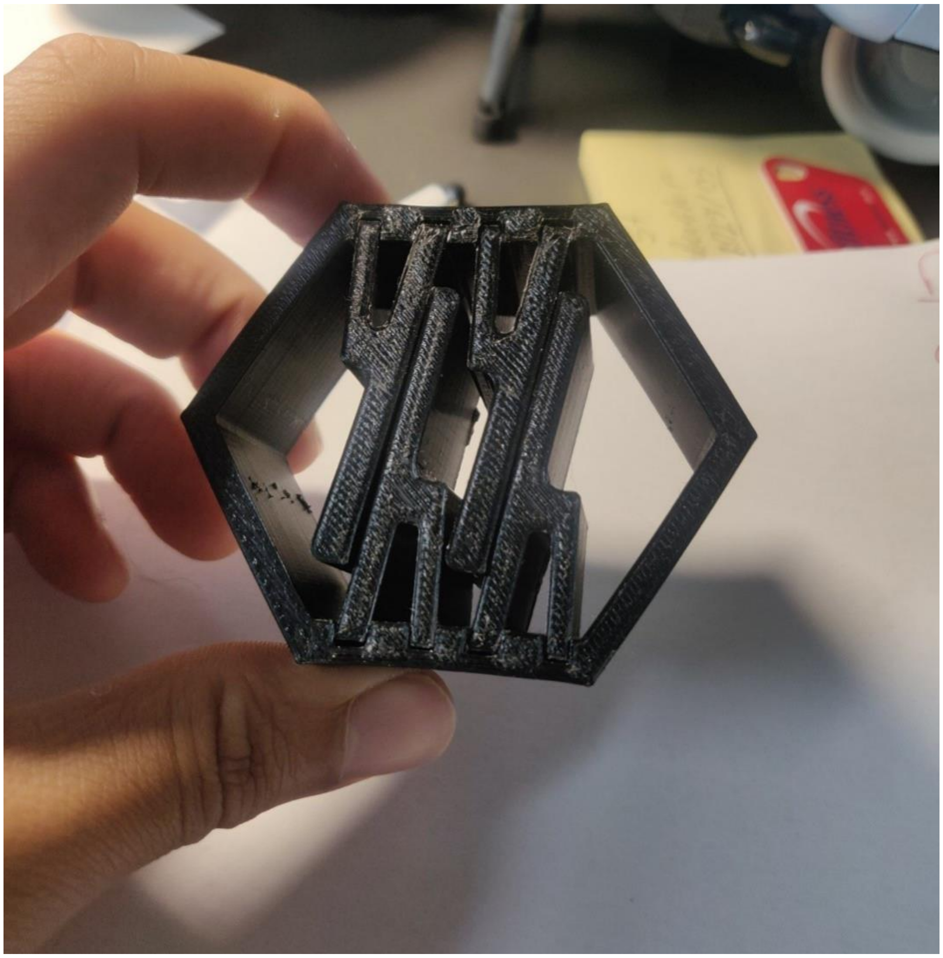
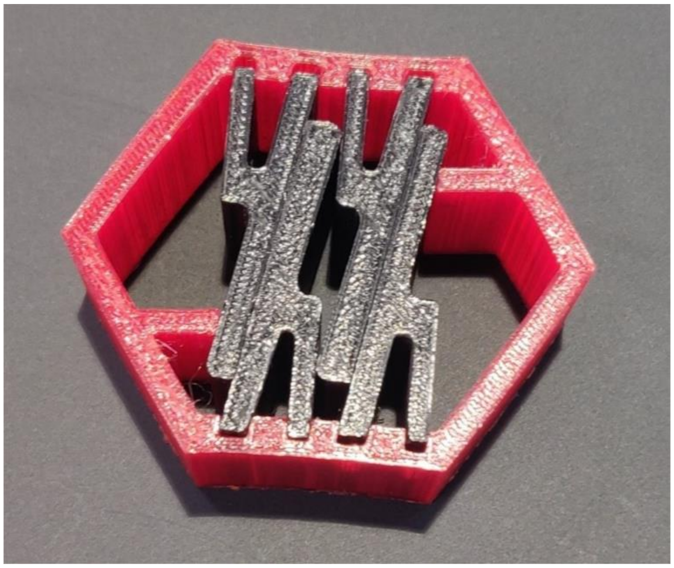


Figure 3: Downsized Unit Cell

Once the outer shape was finalized, the next step was to design a shape that would facilitate energy dissipation through friction, inside the frame. To maximize friction, the goal was to maximize surface contact. Therefore, two flat surfaces were chosen to maximize contact, with the idea of having two plates slide against each other. To ensure surface contact and prevent point contact, the plates were slightly curved, resulting in two versions:

one slider was slightly concave, and the other was slightly convex, both with a radius of curvature of 420mm. To maintain contact throughout the loading and unloading process, the top of the convex slider was made wider than its base, ensuring continuous contact with the flat concave slider. However, this proved insufficient, so lateral supports were added to prevent the top part of each slider from being pushed away and breaking contact (figure 4).

The assembly mechanism for the unit cell needed to be as simple and tool-less as possible. Therefore, grooves were designed within the hexagon to accommodate the sliders, which could be fitted in from the side. The tight fitting of the sliders in the grooves ensures contact and force transfer to the friction surfaces. The technical drawings with dimensions of the 3 parts of the unit cell are available in appendix.



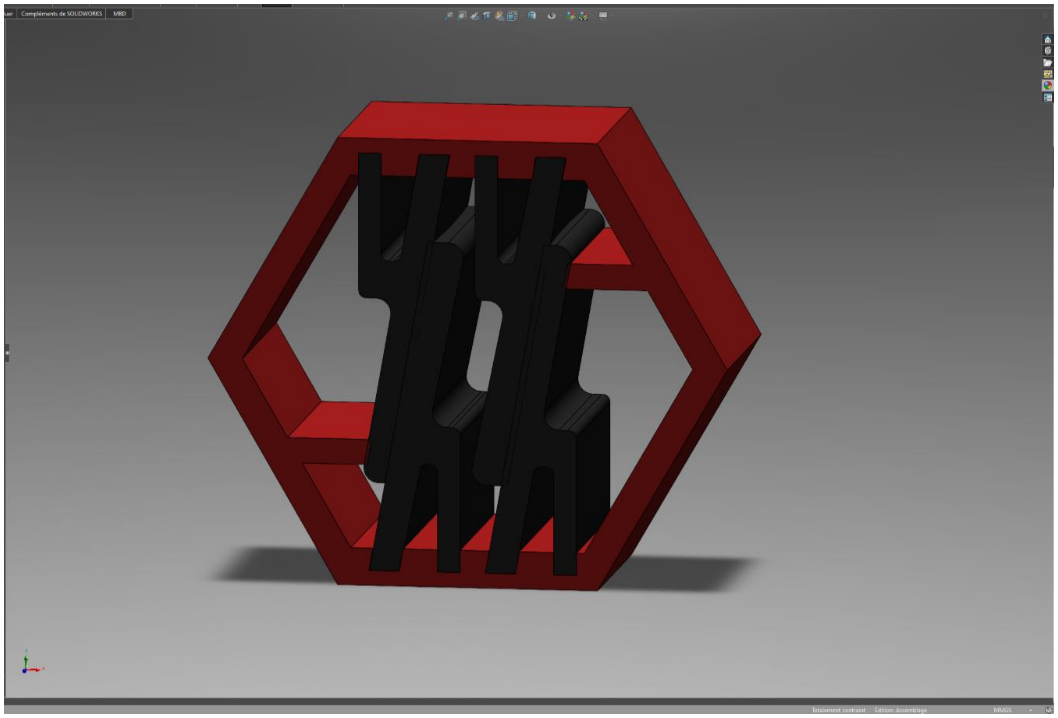


Figure 4: Finalized Design of the Unit Cell with lateral supports printed (top) and CAD (bottom)

3.2 3D Printing and Material Selection

With the design considerations established, the next step involved the practical implementation of the metamaterial through 3D printing. The material chosen for 3D printing was CPEHG100 due to its printability, availability in the lab, and suitability for friction applications, with a friction coefficient of 0.547. This coefficient is relatively high for plastics, which typically range between 0.1 and 0.7. CPEHG100 was also selected because it has been used in previous metamaterial designs, including those developed by Jeong et al. (2025), allowing for comparisons and building upon existing research. With a Young's modulus of 284.4 MPa, a density of 0.7783 g/cm^3, and a Poisson's ratio of 0.3, CPEHG100 is also suitable for withstanding compression tests and being easily manufacturable.

The 3D printing process was carried out using a Caribou MK3S 320 printer. The bed temperature was initially too low and was therefore increased to 90°C to ensure proper adhesion of the first layer. This is 10°C above the manufacturer's recommendations, but as the printing was done during the winter, the cold temperature in the lab may explain that the bed was too cold and therefore the prints were not adhering to it sufficiently. An 0.4 mm printing head was used, and the CAD files were sliced using Prusa Slicer software. An infill density of 50% was chosen to balance strength and precision with printing time, as well as to match previous models done in the same lab. The sliders' printing time was about 1 hour and 30 minutes, while the hexagonal frame took about 2 hours and 45 minutes. A compound printing file containing 6 sliders and 3 hexagons was used to reduce the total printing time to around 50 hours.

3.3 Computer Modeling

The Hexagonal frame was first designed using SolidWorks CAD software. The grooves and lateral supports were designed using a mirror and circular symmetry feature, ensuring that the sliders could fit whatever orientation of the frame.

ANSYS Structural Static was used to perform the Finite Element Analysis simulations. Total deformation and directional deformation calculations were used to generate force-displacement graphs. CPEHG100's properties were uploaded to the project based on previous research done in the lab [18]. This includes friction coefficient of 0.547, Young's Modulus of 284.4 MPa, density of 0.7783 g/cm^3 and Poisson's Ratio of 0.3. A loading and unloading cycle of 3 mm displacement was applied with the following boundary conditions: the top surface of the hexagon was selected as where the displacement would be applied, against a fixed surface defined as the bottom part of the frame. The meshing was refined to a level of 4 out of 7 to ensure accurate results without excessive computation time. Small sliding was turned off, since constant contact was assumed, and displacement was outside the range of small sliding. The material was assumed to be within its elastic deformation range. The contact between the plates was modeled as frictional, using the previously tested coefficient of 0.547.

To account for the tight fitting, a rough contact model was used between the lateral supports and the main sliders, the sliders in the grooves were assumed as bonded, and an additional frictional surface was set between the top and base of the inner plates. These assumptions aimed to accurately represent the tight fittings that hold the unit cell together. Similarly to [18], augmented Lagrange formulation was selected to better model contacts, and large deformation as well as the Newton–Raphson solver option were all used. This helped to take into account significant displacement and the coefficient of friction of 0.547, which is significant. Figure 5 shows a screenshot of the ANSYS model.

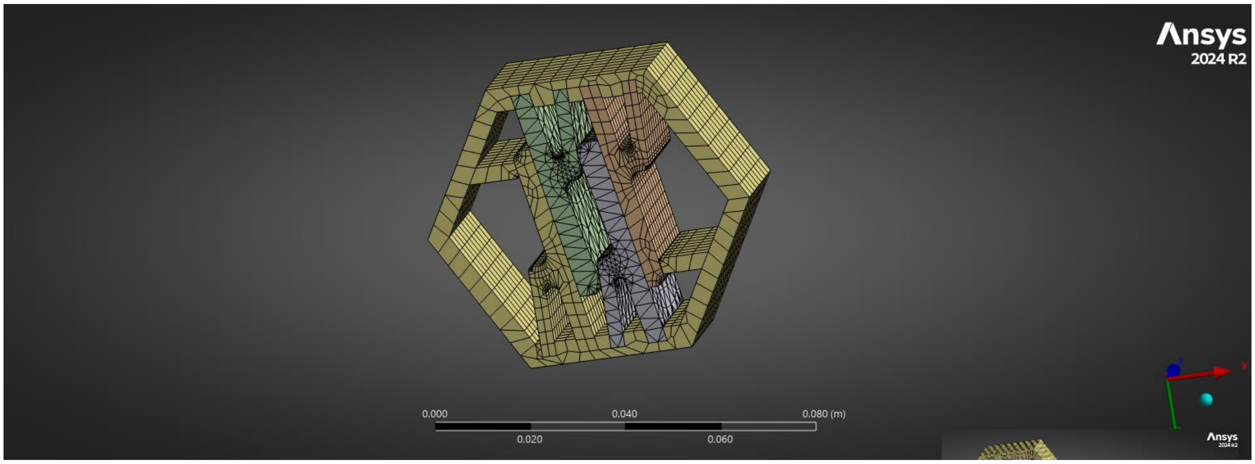
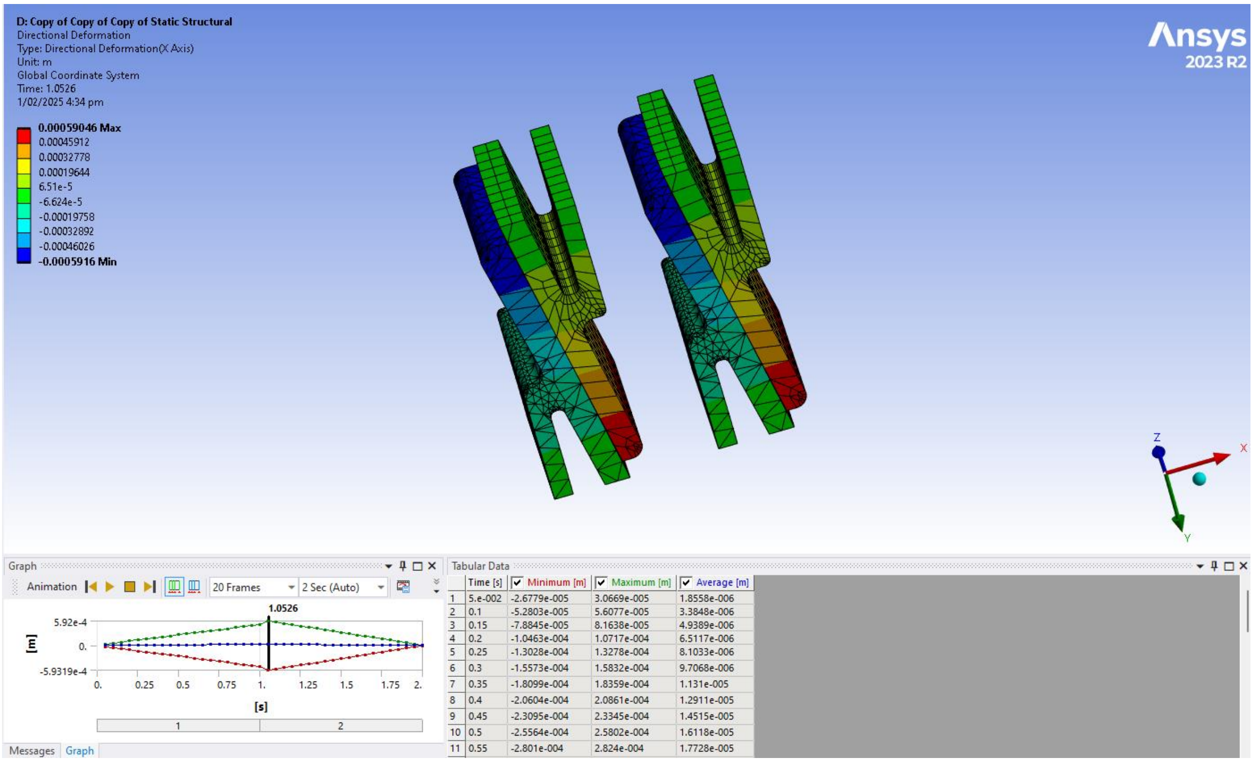


Figure 5: ANSYS Model with meshing

A simplified model was first tried with only two sets of sliders, as shown in figure 6. This further helped to validate the experimental models in ansys.



D: Copy of Copy of Copy of Static Structural
Directional Deformation
Type: Directional Deformation(X Axis)
Unit: m
Global Coordinate System
Time: 1.0526
1/02/2025 4:34 pm

	Time [s]	☑ Minimum [m]	☑ Maximum [m]	☑ Average [m]
1	5.e-002	-2.6779e-005	3.0669e-005	1.8558e-006
2	0.1	-5.2803e-005	5.6077e-005	3.3848e-006
3	0.15	-7.8845e-005	8.1638e-005	4.9389e-006
4	0.2	-1.0463e-004	1.0717e-004	6.5117e-006
5	0.25	-1.3028e-004	1.3278e-004	8.1033e-006
6	0.3	-1.5573e-004	1.5832e-004	9.7068e-006
7	0.35	-1.8099e-004	1.8359e-004	1.131e-005
8	0.4	-2.0604e-004	2.0861e-004	1.2911e-005
9	0.45	-2.3095e-004	2.3345e-004	1.4515e-005
10	0.5	-2.5564e-004	2.5802e-004	1.6118e-005
11	0.55	-2.801e-004	2.824e-004	1.7728e-005

Figure 6: Simplified ANSYS model without external hexagon frame.

3.4 Experimental Setup

The compression tests were conducted using a Hounsfield general test machine with a capacity of 5 metric tons of force (figure 7). The metamaterial was loaded between the two steel plates of the machine to optimize load distribution, and the machine was set to a displacement control of 3 mm at a speed of 3 mm/s. This ensured consistency with previous research conducted in the lab and provided control over the experiment, avoiding any dynamic loading shock.

Figure 7: Unit Cell Specimen loaded in compression machine

The machine automatically plotted and printed the displacement vs. force reaction curve. Data points were extracted visually from printed graphs, leading to slight approximation due to grid resolution and then transferred into an Excel sheet, with 42 coordinates. A standard trapezoidal integration method for hysteresis loop area calculation, the area between the loading and unloading curves, was calculated to determine the energy dissipated.

3.5 Modular Assembly

The unit cells were designed to be modular and can be assembled into larger structures. The hexagonal shape of the unit cell lends itself well to modularity, allowing for the creation of various configurations, such as lattices or the hexagonal ring structure used in this research. The modularity of the design also opens possibilities for future research, such as incorporating Triboelectric Nanogenerators (TENGs) or creating other tile-like arrangements. The unit cells are assembled into a larger hexagon ring using two hexagon plates with a similar groove system. The plates have a 20% infill to reduce printing time, resulting in a printing time of only 3 hours and 30 minutes for the two hexagonal rings. The grooves are 3mm wide and 3mm deep, and the rings are 5mm thick. The grooves are printed directly onto the hexagons in the middle of the top and bottom sections, and in the middle of each of the 6 sides of the hexagonal ring, ensuring alignment of the setup. Figures 8,9 and 10 illustrate the modular setup.

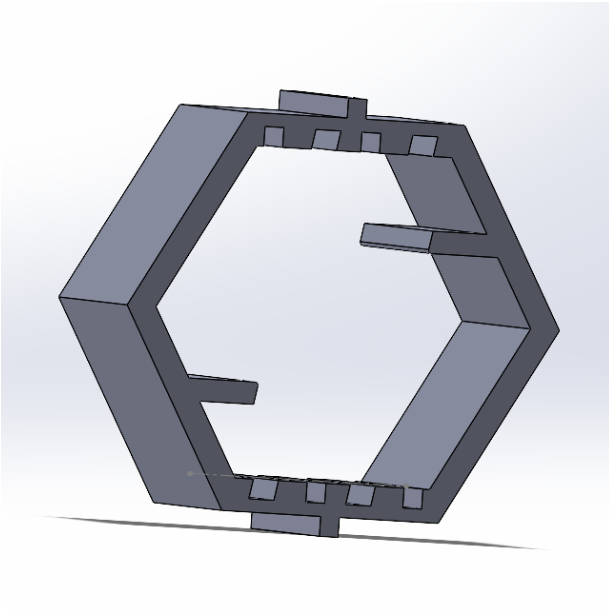


Figure 8: Hexagonal Frame with appendices for modular assembly

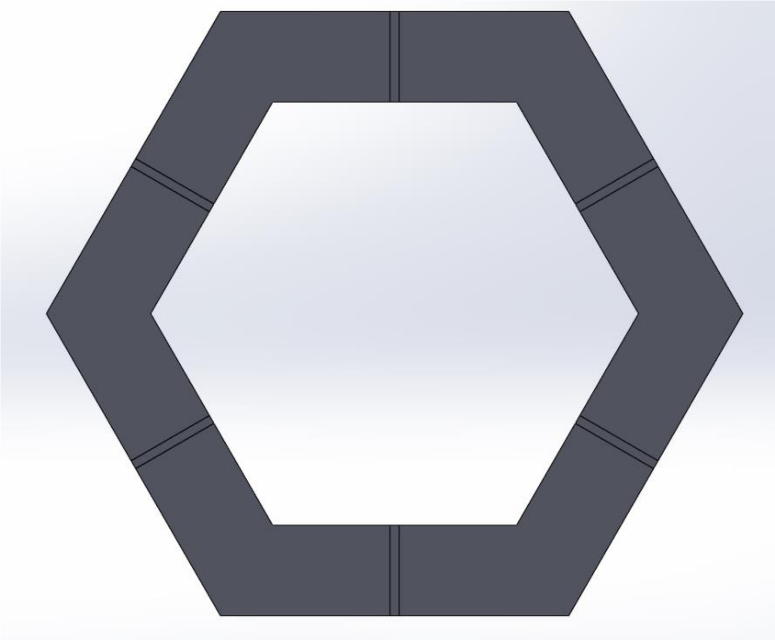
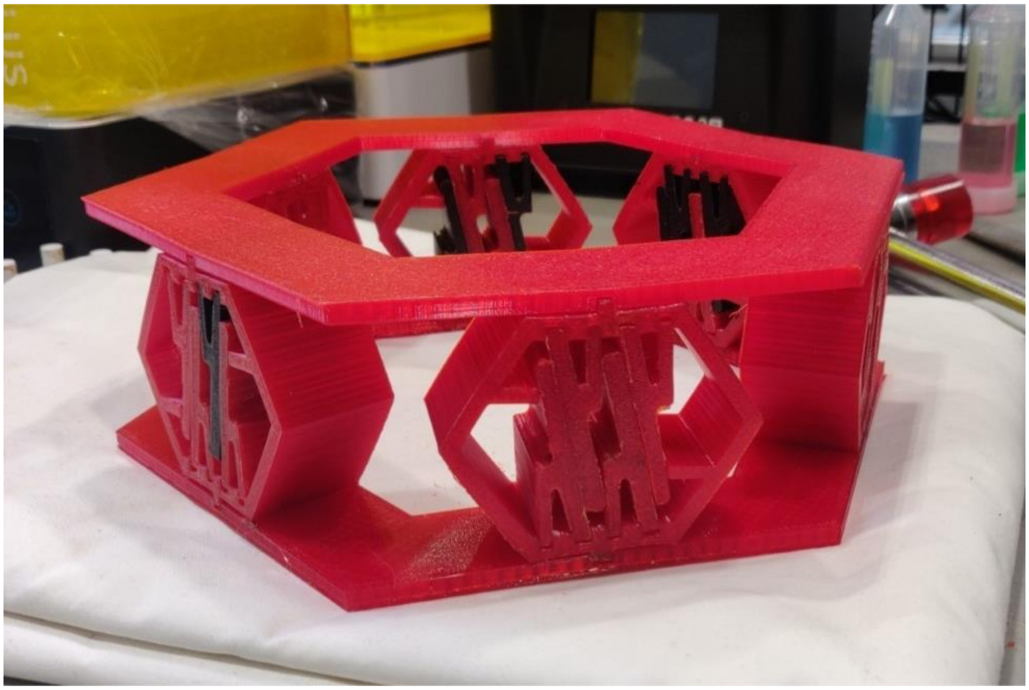


Figure 9: Top view of the hexagonal ring with grooves



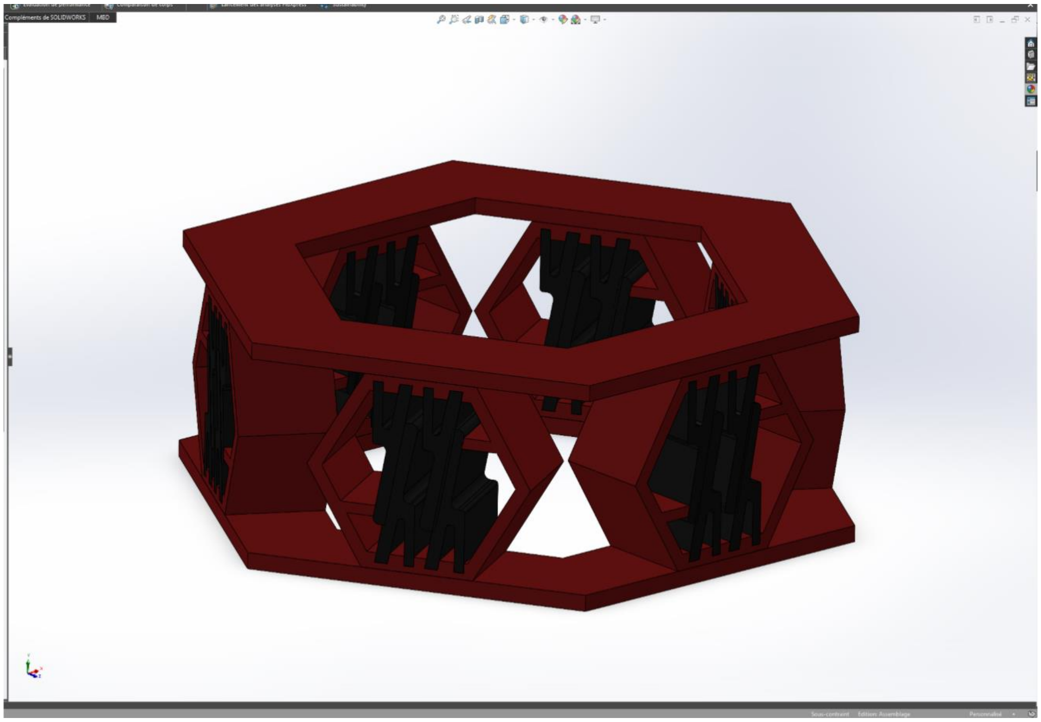


Figure 10: Final Modular Assembly Printed (top) and CAD (bottom)

The modular assembly was tested in the same fashion as the singular unit cell, both on ANSYS and under the compression machine. Larger steel plates were used to better distribute the load, as shown in figure 11. A bonded contact between the hex ring and the unit cells was assumed in the Ansys simulation.

Figure 11: Modular Assembly under compression test machine.

In conclusion, this chapter has meticulously detailed the methodology employed in this research, encompassing the design choices, 3D printing process, material selection, ANSYS simulations, experimental setup, and modular assembly of the metamaterial unit cell. The design process prioritized functionality, simplicity, scalability, manufacturability, and reusability, resulting in a hexagonal unit cell with central sliders optimized for surface contact and friction. The 3D printing process was carefully controlled to ensure the accurate fabrication of the unit cell using CPEHG100, a material selected for its printability, availability, and suitability for friction applications. ANSYS simulations were conducted to analyze the metamaterial's behavior under compression, providing insights into its deformation and energy dissipation characteristics. The experimental setup involved compression tests using a Hounsfield general test machine, allowing for the evaluation of the metamaterial's energy dissipation performance. The modular design of the unit cell enables the assembly of larger structures, offering potential for future research and applications. With the methodology clearly defined, the following chapter will present the key findings from the simulations and experiments, highlighting the energy dissipation capabilities of the metamaterial and its potential for various engineering applications.

Results

Following the detailed methodology outlined in the previous chapter, this section presents the key findings from the simulations and experiments conducted on the metamaterial unit cell. The results are systematically organized to highlight the performance of the metamaterial in terms of energy dissipation, structural integrity, and repeatability under loading and unloading cycles. By analyzing the data obtained from both the ANSYS simulations and the experimental tests, this chapter aims to provide a comprehensive understanding of the metamaterial's behavior and its effectiveness in achieving the research objectives. The findings will be discussed in the context of the design parameters, material properties, and experimental conditions, offering valuable insights into the potential applications and limitations of the proposed metamaterial design. Focus is given to the relationship between deformation behavior, failure modes, and energy dissipation.

4.1 Simulation Results

The ANSYS simulations provided valuable insights into the metamaterial's behavior under compression. Energy dissipation is the difference between the energy accumulated by the model or specimen during loading and the energy released during unloading. Effectively it is the area between the top and bottom curves of the hysteresis loops.

The key findings are as follows:

- The unit cell dissipated 225 mJ of energy when subjected to a 3 mm displacement, indicating its capacity for energy absorption.
- The lateral supports lost contact with the back of the sliders upon deformation, but the two sliders maintained contact throughout the loading and unloading process, ensuring consistent friction and energy dissipation.

- The hexagonal frame did not buckle under the applied load, demonstrating its structural integrity.

The average energy dissipated in the simulations was 225 mJ. Figure 1 shows the unit cell under 3 mm of displacement, with the surfaces colored according to their deformation. The lateral supports can be seen losing contact with the sliders, which was not seen experimentally. Figure 2 shows the unit cell before displacement is applied.

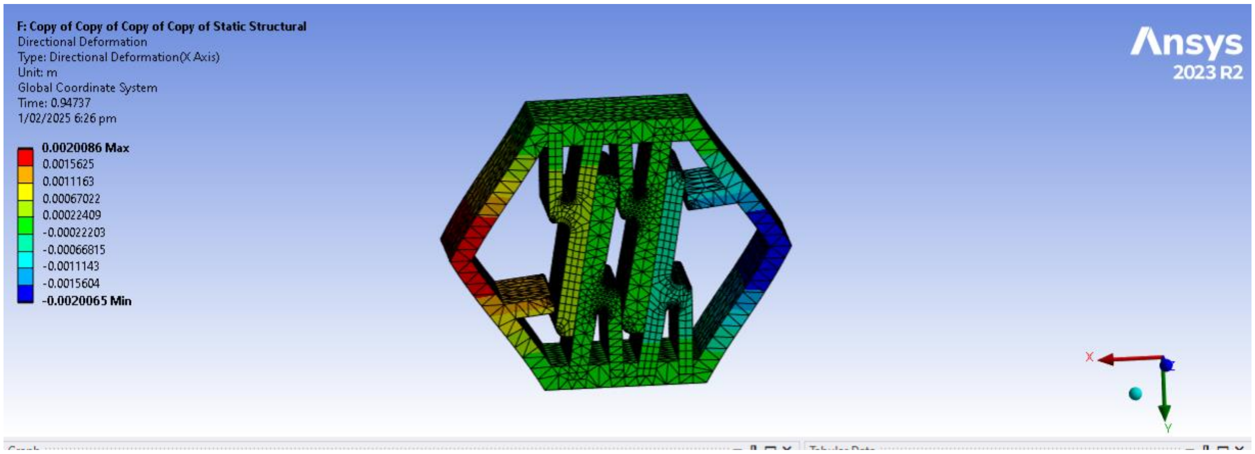


Figure 1: Ansys simulation model under maximum deflection.

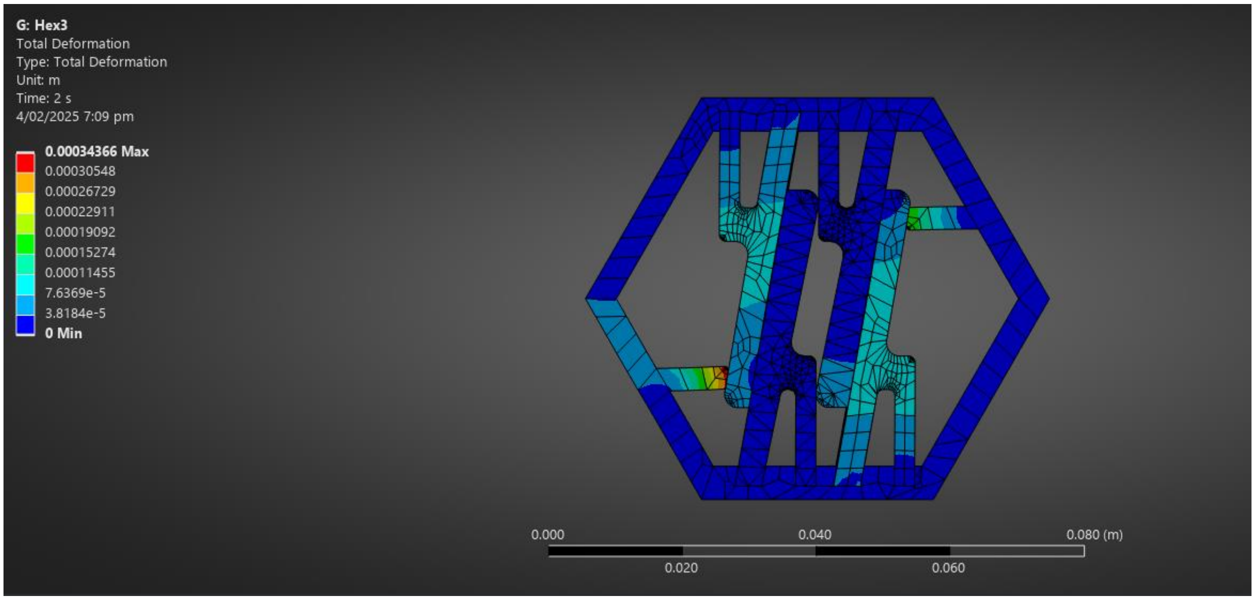


Figure 2: Ansys simulation model under minimum deflection.

4.2 Experimental Results

The experimental tests further elucidated the metamaterial's behavior under compression. The key findings are as follows:

- The metamaterial withstood repeated loading and unloading cycles, demonstrating its reusability and potential for applications requiring multiple compression cycles. Figure 3 shows the experimental specimen under maximum displacement. It is noteworthy to see that the lateral supports are still in contact with the sliders.

Figure 3: Experimental specimen under max displacement

- Failure modes, such as fracture or buckling, appeared after 7 mm of displacement, indicating the limits of the metamaterial's elastic deformation range. Figure 4 shows a fracture failure example:

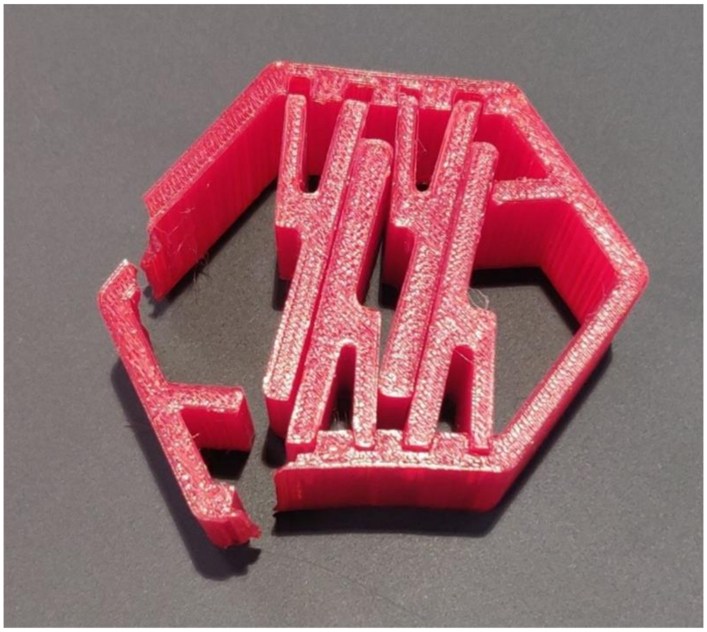


Figure 4: Fracture failure after 7mm

- At 3 mm of displacement, the loading and unloading behavior was not smoothed, as can be seen in the jagged lines of the raw data (in appendix). This is due to the tight fitting of the unit cell.
- The energy dissipation was 270 mJ.
- The energy dissipation values for 1 mm, 2 mm, and 4 mm of displacement were 120 mJ, 135 mJ, and 550 mJ, respectively, showing a non-linear increase in energy dissipation with increasing displacement, as shown in Figure 5:

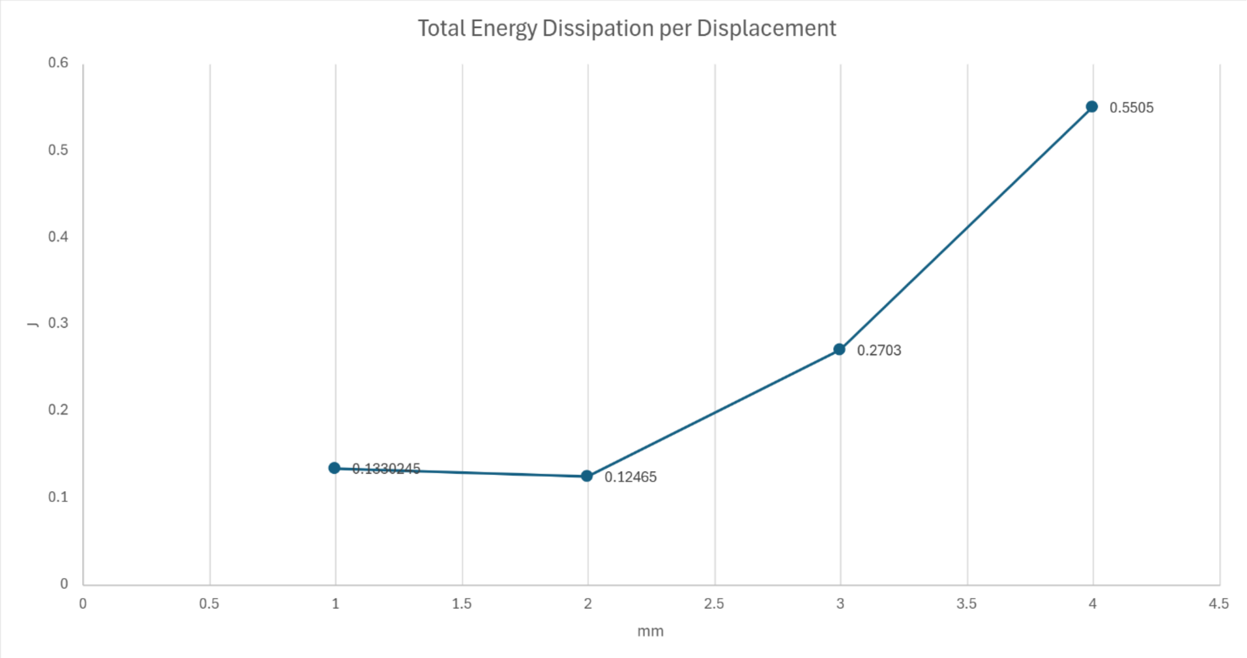


Figure 5: Experimental results for Total Energy Dissipation for 1, 2, 3 and 4mm of displacement

4.3.1 Comparison of Simulation and Experimental Results

A side-by-side comparison of the hysteresis loops obtained from the simulations and experiments is shown in figure 6. As a reminder, the experimental unit cell dissipated 270mJ and the simulated unit cell dissipated 225mJ. In Figure 6, the red curve represents the simulation results, while the blue curve represents the experimental results.

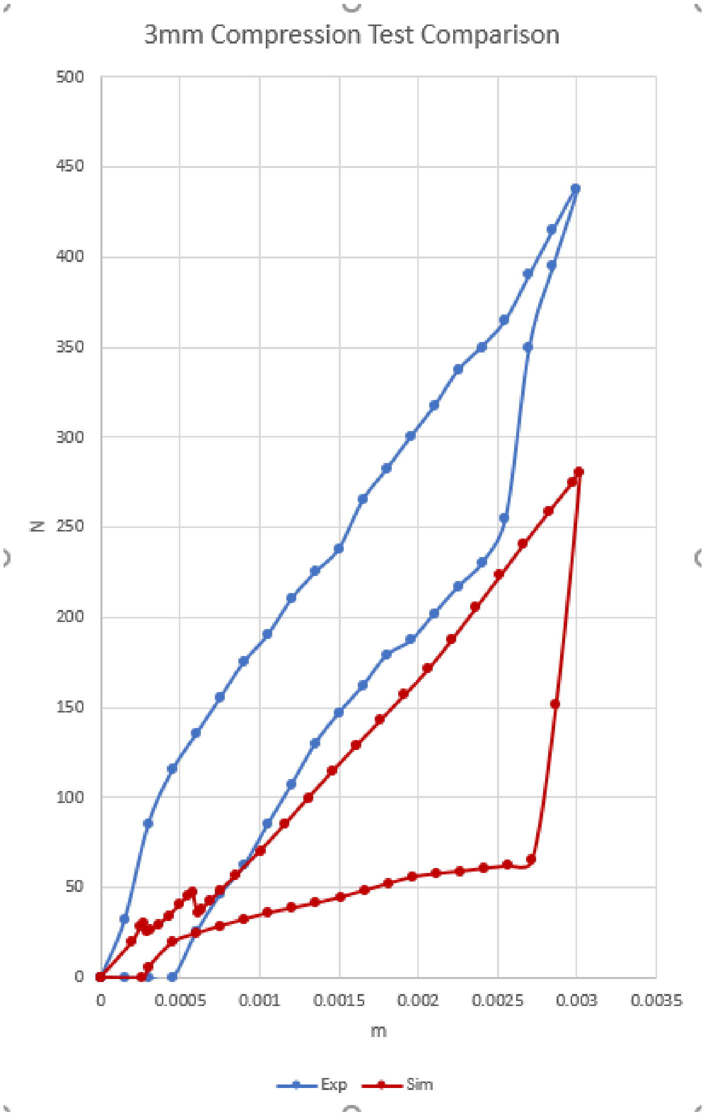


Figure 6: Experimental vs Simulation Force v Displacement graphs.

Figure 7 presents total energy dissipation values by displacement applied.

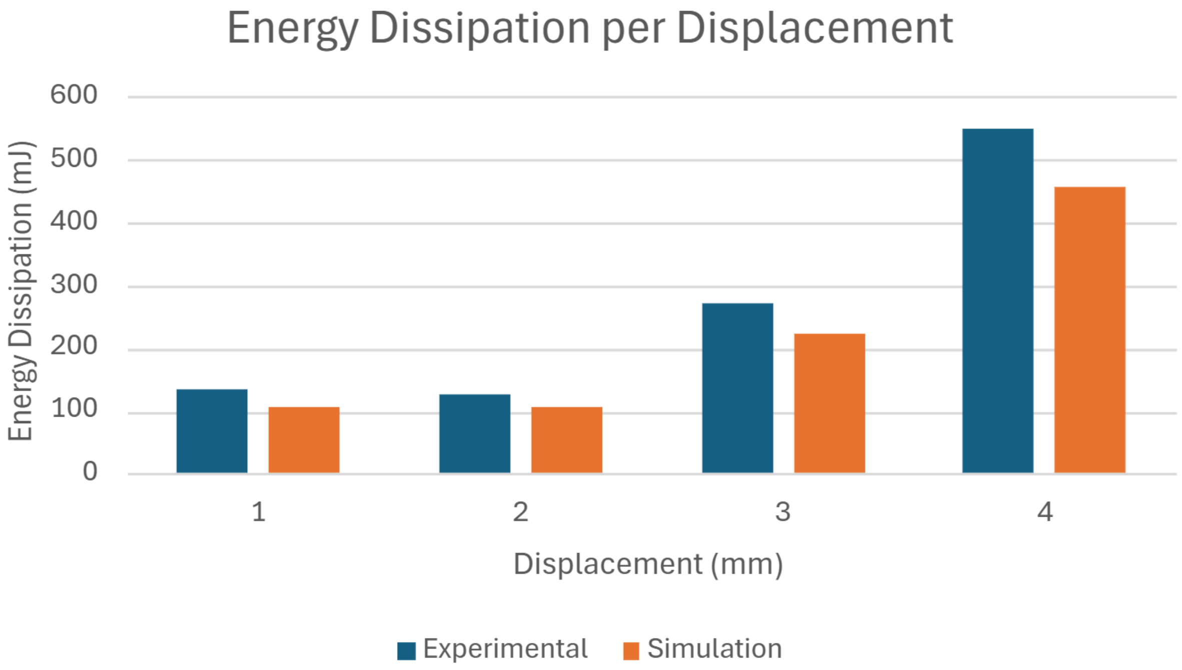


Figure 7: Comparison of Total Energy Dissipation values for different applied displacements

The comparison reveals the following:

- The simulation and experimental results differed by approximately 20%, indicating a reasonable agreement between the two. This discrepancy can be attributed to the tight-fitting nature of the design, where the hexagonal frame was constrained by the sliders in the grooves before compression, and the contact between the sliders and lateral supports involved slight penetration. These factors were not fully captured in the simulation, leading to a slight underestimation of the energy dissipation.
- The experimental force-displacement curve exhibited a steeper gradient and was less wide compared to the simulation curve, suggesting a greater stiffness in the experimental setup. This difference in stiffness can be attributed to the inherent

variability in 3D-printed parts and the assumptions made in the simulation regarding material properties and contact behavior.

- Unexpectedly, the hexagonal frame buckled slightly in the experiments, while the lateral supports maintained contact, a behavior not observed in the simulations. This discrepancy highlights the limitations of the simulation in fully capturing the complex deformation behavior of the metamaterial, particularly under tight-fitting conditions.
- The energy dissipation performance remained consistent under different loading conditions and after repeated cycles, demonstrating the robustness and reliability of the metamaterial. This is shown by the total energy dissipation discrepancies being consistent in Figure 7.

4.3.2 Key Observations

The key observations from the simulations and experiments are summarized as follows:

- The metamaterial design effectively dissipates energy through friction, as demonstrated by both the simulation and experimental results.
- The tight-fitting nature of the design and the variability in 3D-printed parts may contribute to the discrepancies observed between the simulation and experimental results. This is further explored in the next section.
- The metamaterial exhibits consistent energy dissipation performance under different loading conditions and after repeated cycles, highlighting its potential for various applications. All of the experimental results are available in the appendix.

Overall, the results demonstrate the effectiveness of the metamaterial design in achieving its intended purpose of energy dissipation through friction. The insights gained from the simulations and experiments provide a solid foundation for further analysis and discussion for the modular assembly.

4.4 Modular Assembly

Indeed, in a similar manner, the modular 6-unit assembly was tested under the exact same conditions both experimentally and using FEA:

4.4.1 Simulation Results

The ANSYS simulations were conducted in the exact same manner as for the singular unit cell. The key findings are as follows:

- The unit cells acted individually in the same manner they did during the single unit test. No buckling of the hexagonal frame was seen, and no deformation of the hexagonal rings either.
- The modular assembly dissipated 1265mJ at 3mm of displacement.

4.4.2 Experimental Results

The modular assembly was tested in the exact same manner as the single unit cell. The key findings are as follows:

- The metamaterial withstood repeated loading and unloading cycles, including in varying speeds of compression (3 and 5mm/s), demonstrating consistent results, available in appendix. Figure 8 shows the experimental assembly ready for testing. Due to the tight fitting in the unit cell, the rings and the unit cells were not perfectly in flat contact at the grooves.

Figure 8: Modular Assembly before compression test

- At 3 mm of displacement, the loading and unloading behavior was similar, although smoother than the singular unit cell, and the energy dissipation was 1656mJ.

4.4.3 Comparison of Simulation and Experimental Results

A side-by-side comparison of the hysteresis loops obtained from the simulations and experiments for the modular assembly is shown in figure 9. The green curve represents the simulation results, while the purple curve represents the experimental results.

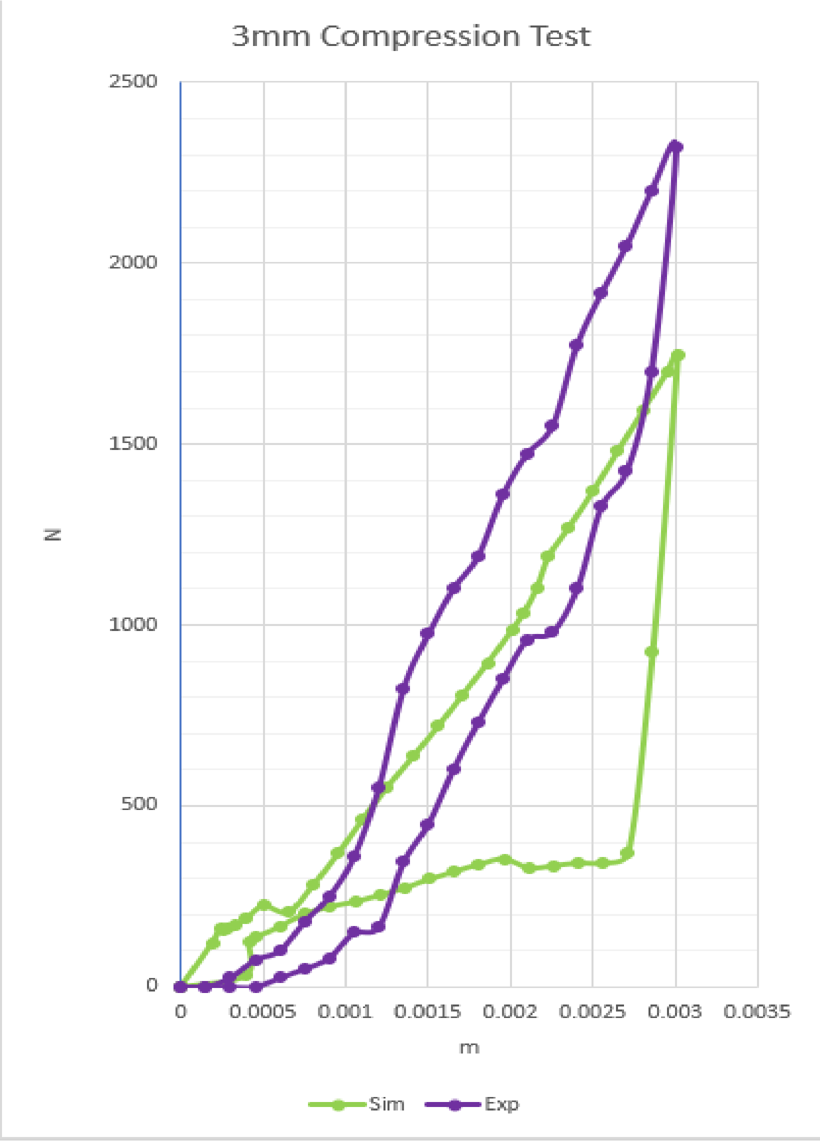


Figure 9: Experimental vs Simulation Force v Displacement graphs (modular assembly).

The comparison reveals the following:

- The simulation and experimental results differed by approximately 25%, which is consistent with the singular unit cell test. This discrepancy may be attributed to the same factors as the singular unit cell, aggravated by the number of unit cells and uncertainty points.
- The two curves are closer than those of the singular unit cell.

4.4.4 Key Observations

The key observations from the simulations and experiments of the assembly are:

- The two results are very close (90-93%) to 6 times the energy dissipation of the singular unit cells, showing consistency in the modeling and experimental setups.
- The same discrepancies that explain the variation in results may explain, albeit in a multiplied manner, the discrepancies in the modular assembly results.

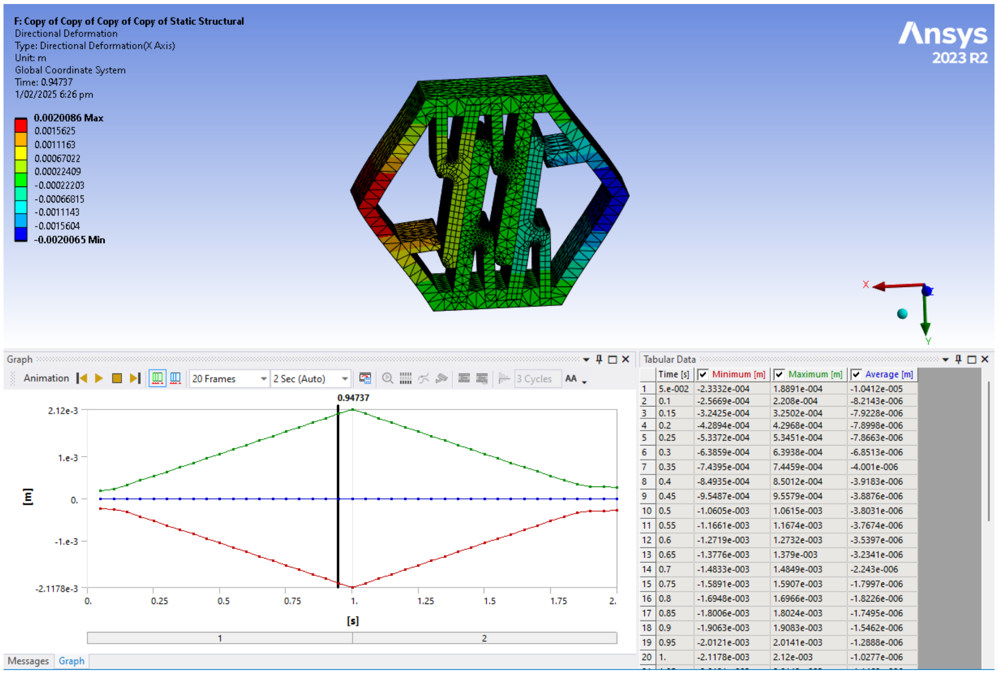
In conclusion, this chapter has presented the key findings from the simulations and experiments conducted on the metamaterial unit cell. The results demonstrate the effectiveness of the design in achieving its energy dissipation objectives. The simulations and experiments revealed the metamaterial's ability to withstand repeated loading and unloading cycles, dissipate energy through friction, and maintain its structural integrity within a certain range of deformation. The discrepancies observed between the simulation and experimental results highlight the challenges in accurately modeling the tight-fitting and contact behavior of the metamaterial, suggesting areas for future refinement. The next chapter will delve deeper into these findings, discussing their implications and comparing them with existing research in the field.

Discussion

Building on the key findings presented in the results section, this chapter delves deeper into the implications of the research outcomes, comparing them with existing studies in the field of metamaterials. The discussion will explore the significance of the observed energy dissipation capabilities, the suitability and benefits of this design as a novel metamaterial, and the discrepancies between simulation and experimental results. By critically analyzing these aspects, this chapter aims to provide a nuanced understanding of the metamaterial's performance, identify areas for improvement, and suggest directions for future research. The insights gained from this discussion will contribute to the broader knowledge base of frictional metamaterials and their potential engineering applications.

5.1 Comparing Simulation and Experimental Results

5.1.1 FEA Visualizations and Stress Analysis



F: Copy of Copy of Copy of Copy of Static Structural
Directional Deformation
Type: Directional Deformation(X Axis)
Unit: m
Global Coordinate System
Time: 0.94737
1/02/2025 6:26 pm

	Time [s]	☑ Minimum [m]	☑ Maximum [m]	☑ Average [m]
1	5.e-002	-2.3332e-004	1.8891e-004	-1.0412e-005
2	0.1	-2.5669e-004	2.208e-004	-8.2143e-006
3	0.15	-3.2425e-004	3.2502e-004	-7.9228e-006
4	0.2	-4.2894e-004	4.2968e-004	-7.8998e-006
5	0.25	-5.3372e-004	5.3451e-004	-7.8663e-006
6	0.3	-6.3859e-004	6.3938e-004	-6.8513e-006
7	0.35	-7.4395e-004	7.4459e-004	-4.001e-006
8	0.4	-8.4935e-004	8.5012e-004	-3.9183e-006
9	0.45	-9.5487e-004	9.5579e-004	-3.8876e-006
10	0.5	-1.0605e-003	1.0615e-003	-3.8031e-006
11	0.55	-1.1661e-003	1.1674e-003	-3.7674e-006
12	0.6	-1.2719e-003	1.2732e-003	-3.5397e-006
13	0.65	-1.3776e-003	1.379e-003	-3.2341e-006
14	0.7	-1.4833e-003	1.4849e-003	-2.243e-006
15	0.75	-1.5891e-003	1.5907e-003	-1.7997e-006
16	0.8	-1.6948e-003	1.6966e-003	-1.8226e-006
17	0.85	-1.8006e-003	1.8024e-003	-1.7495e-006
18	0.9	-1.9063e-003	1.9083e-003	-1.5462e-006
19	0.95	-2.0121e-003	2.0141e-003	-1.2888e-006
20	1.	-2.1178e-003	2.12e-003	-1.0277e-006

Figure 1: FEA Contours at Maximum Displacement (3mm)

The FEA provided substantial insight on the stress distribution in the unit cell at peak compression. Figure 1 illustrates this. As evident by the color contouring, stress concentrations are primarily located at the side tips of the hexagonal frame, and on the lateral supports within the frame. These areas of high stress are expected due to the orientation of the compression on the hexagonal frame. Furthermore, failure modes shown in the previous chapter confirm this as the side tip is where the model broke under too much compression. To minimize this during the design phase, fillets were added to the inner edges of the hexagon.

Figure 2: Experimental Specimen after failure

Figure 2 provides additional insight on the FEA visualization. Figure 2 shows the printed specimen right after failure. The side tips of the hexagon are broken as expected, and the lateral inner supports also loose contact with the sliders, which was not seen during the 3mm displacement tests. This may show that the phenomenon is observed, but at much higher compressions than what the simulation predicts.

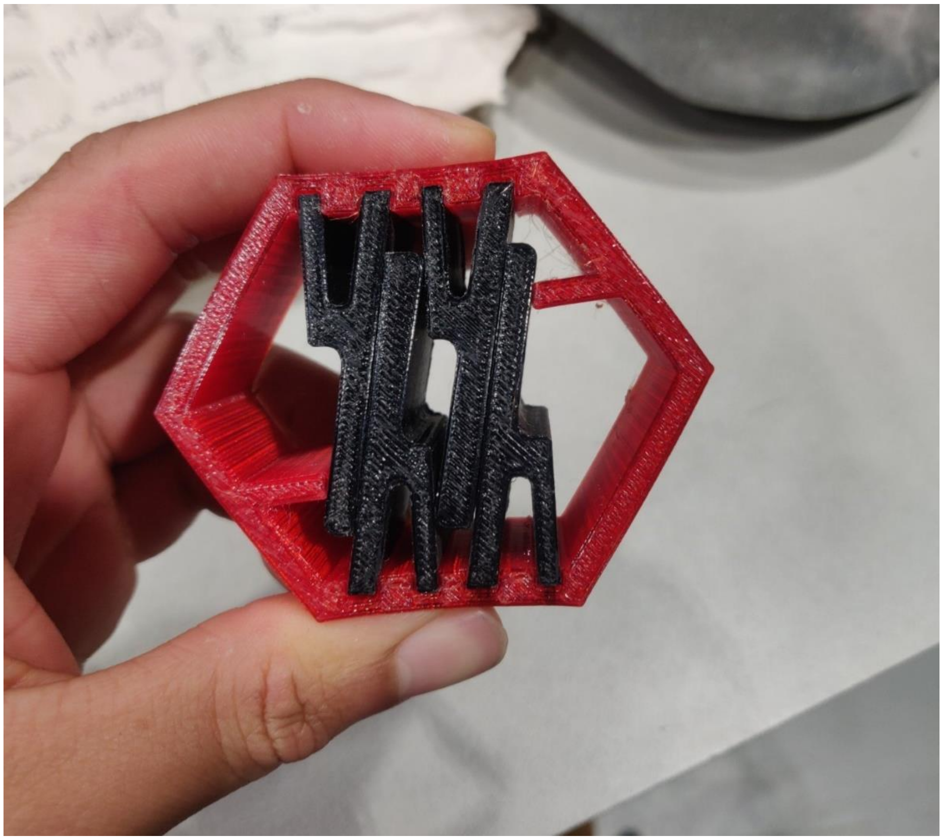


Figure 3: Printed Specimen under minimal load, showing buckling

Finally, Figure 3 shows a crucial difference between the FEA model and the actual experimental model. The hexagon can be seen slightly buckling on the top and bottom surfaces near the fingers. This is most probably due to the inner forces on the tight fittings with the sliders and was not shown in the FEA. The buckling and tight fittings may explain the discrepancies later found between experimental and simulation results.

5.1.2 Energy Dissipation Values Discussion: Single Unit Cell

	Simulation	Experimental	Discrepancy
Energy Dissipated by 1 Unit Cell after a 3mm displacement	225 mJ	270mJ	17%

Table 1: Energy Dissipation Values and Discrepancy

The simulation and experimental results showed a reasonable agreement, with the energy dissipation values differing by 17%, as shown in table 1. However, some discrepancies were also observed. The experimental force-displacement curve exhibited a steeper gradient and was less wide compared to the simulation curve, suggesting a greater stiffness in the experimental setup. However, the maximum of the loop is high on the experimental curve compared to the simulated curve. This difference can be attributed to the tight-fitting nature of the design, which was not fully captured in the simulation. The tight-fitting resulted in the hexagonal frame being constrained by the sliders in the grooves before compression, and the contact between the sliders and lateral supports involved slight penetration. These factors led to a greater stiffness in the experimental setup compared to the simulation and could have led to a stick-slip phenomenon at a micro level.

Furthermore, during the raw experimental data shows a jagged hysteresis loop, indicating stick and slip rather than smooth continuous friction in the experiments. Stick-slip friction is characterized by alternating periods of 'sticking' where surfaces momentarily adhere and resist motion, followed by 'slipping' where the built-up force overcomes static friction, resulting in sudden, jerky movements. This phenomenon is typical of frictional interfaces where surface roughness and adhesion forces dominate and can be seen in the raw data in appendix.

The jaggedness in the experimental curves implies that the frictional energy dissipation is not a smooth, continuous process but rather occurs in discrete bursts of energy release during the 'slip' phases. This contrasts with the smoother hysteresis loops obtained in the simulations, suggesting that the FEA model, in its current form, may not fully capture the stick-slip behavior occurring at the micro-contact level within the physical metamaterial.

Another discrepancy was the unexpected buckling of the hexagonal frame in the experiments, which was not observed in the simulations. This highlights the limitations of the simulation in fully capturing the complex deformation behavior of the metamaterial, particularly under tight-fitting conditions. The simulation assumed ideal contact conditions and did not account for the forces exerted by the tight fittings and the inner tensions on the frame. This may have contributed to the buckling behavior in the experiments. This suggests another area where both the simulated and the experimental model can be refined to find a better middle ground.

Indeed, overall, the discrepancies between the simulation and experimental results can be attributed to the challenges in accurately modeling the tight-fitting and contact behavior of the metamaterial. Future research could explore refining the simulation model by incorporating more realistic contact conditions and considering the potential for micro-scale interactions. This would allow for the simulation to accurately model the lateral supports keeping contact with the sliders for example. Additionally, reprinting the model with looser fits in the grooves could help to reduce the tight-fitting effects and improve the agreement between the simulation and experimental results. Improving printing quality by using a more precise printer head or refining the slicing in the software could also lead to more precise and accurate data. In short, discrepancies can be attributed to the quality of the printing and its variability, especially regarding surface roughness and induced stick-slip phenomena as well as computer modeling of the tight fits and contacts that need to be refined.

5.1.3 Energy Dissipation Values Discussion: Modular Assembly

The modular design showed consistent results with the singular unit cell. The discrepancy between simulation and experimental data is 24%. The total energy dissipation, both measured experimentally and in the software total more than 90% of the addition of 6 singular unit cell tests, shown in table 2:

	Energy Dissipated For 1 Unit Cell (mJ)	Theoretical Energy Dissipation for 6 units cells (1 unit multiplied by 6)	Measured Energy Dissipation for Modular Assembly (mJ)	Similarity
Simulation	225	1350	1265	94%
Experimental	270	1620	1656	98%

Table 2: Modular Assembly Energy Results and Similarity to Theoretical Results

This demonstrates consistency between the tests conducted on individual unit cells and the modular assembly, indicating a linear behavior of the assembly. The increased discrepancy observed between the simulation and experimental results for the modular assembly can be attributed to the accumulation of divergent points within the assembly, as it consists of six individual unit cells.

The force v displacement curves for the 6-unit cell assembly shown in the previous chapter show a closer similarity between experimental and simulated graphs. The hysteresis loop for the experimental model still has a steeper gradient and the raw data (available in appendix) also shows a jagged nature, although to a lesser extent than the singular unit cell. The experimental graph also has a higher maximum and is narrower. This further proves the consistency between the singular unit cell and the 6-unit assembly results. This reinforces the modularity and scalability of the design.

5.2 Looking to the future

This research contributes significantly to the expanding field of frictional metamaterials for energy dissipation. Compared to existing designs, the proposed metamaterial offers several advantages, including simplicity, ease of manufacturing, and modularity. While other designs may achieve higher energy dissipation values, they often involve complex geometries that are challenging to manufacture. The simplicity and manufacturability of the proposed design make it a promising candidate for practical applications.

Furthermore, the modularity of the design allows for the assembly of larger structures with varying configurations, providing flexibility and adaptability for different applications. The flat surfaces of the metamaterial also offer opportunities for further modifications, such as textured metasurfaces or the addition of triboelectric nanogenerators (TENGs), to enhance dissipation capabilities and explore energy conversion. Given the relatively wide and flat contact friction surfaces, further research could easily incorporate skin-like improvements to test either triboelectric nanogenerators or metasurfaces. Metasurfaces could improve energy dissipation properties by increasing surface contact.

Concerning TENG, these can convert mechanical energy into electrical energy through friction, offering a promising approach for self-powered devices and systems [29,30]. The modular assembly could facilitate the use of TENGs by positioning the electrical connections and wires in the middle of the ring, aiding in measurements. However, this would require an additional testing machine that the lab currently lacks. This machine would need to apply the same force as a compression machine but at a lower frequency than a fatigue test machine. The testing parameters would also need to be automated and controlled to ensure experimental accuracy. This experimental setup would need to be custom-made or adapted from other setups used for TENG testing, as referenced in (insert reference). A simulation model of TENG could also be explored, although it is rarely seen in the literature and would demand more complexity. Testing a TENG assembly on this metamaterial would give valuable insight on the correlation between energy dissipation and energy generation, and could be compared with existing literature (add reference).

In the future, this metamaterial example could be miniaturized, woven in textile and used in shock absorbing materials for crash boxes, seismic engineering or even better disc brakes. As explained in the literature review, the applications for tribological metamaterials are as vast as the field of tribology, which touches almost every part of industry. First, attempts should be made to miniaturize both the unit cell and then the modular assembly by another third, down to about 2cm high. This would allow then for the assembly to be manufactured into a plate or brick and used as building blocks for larger structures like planks or beams for example. If adapted to a TENG setup, this metamaterial could lead to self-powering devices, or devices converting mechanical into electrical energy through the intrinsic property of their material. Finally, exploring real-world applications of this metamaterial in applications such as seismic engineering, shock absorption, and crash boxes could lead to the development of innovative solutions for energy dissipation and impact protection.

This study has some limitations. Only one material, CPEHG100, was tested with one machine, limiting the generalizability of the findings. Future research could explore alternative materials such as nonlinear or hyper elastic plastics, or other 3D printing techniques such as selective laser sintering. This would enable investigating their effects on energy dissipation performance.
Additionally, the design was not subjected to fatigue tests, so its long-term durability remains unknown. Future studies could assess the fatigue life of the metamaterial under cyclic loading conditions to evaluate its suitability for real-world applications. Indeed, the validity of the unit cell as well as its potential application in industry depend on its lifetime. This could take the form of cyclic testing using fatigue test machines readily available in the

lab and subjecting the model to repeated load-unload cycles under different displacement as well as until failure. This would allow to characterize the lifetime of the model as well as its performance over the course of said lifetime.
Also, future studies could study the economic viability of the model, taking into account CPEHG100 prices and manufacturing costs dependant on the energy consumption of each 3D printer.

Overall, this research provides a valuable contribution to the field of frictional metamaterials for energy dissipation. The proposed design's simplicity, ease of manufacturing, and modularity make it a promising candidate for various applications. Future research can build upon these findings to further enhance the metamaterial's performance and explore its potential in diverse fields.

This chapter has provided a comprehensive discussion of the research findings, comparing them with existing literature and highlighting the contributions and limitations of the study. The discrepancies between the simulation and experimental results have been analyzed, suggesting potential areas for improvement in the modeling and design of the metamaterial. The research has been contextualized within the broader field of frictional metamaterials, emphasizing its advantages and potential applications. Finally, several promising future research directions have been identified, including the integration of triboelectric nanogenerators, the exploration of alternative materials and 3D printing techniques, and the investigation of real-world applications. The following chapter will conclude the thesis by summarizing the key findings and their implications, highlighting the significance of the research, and providing recommendations for future work.

Conclusion

6.1 Summary of Key Findings

This thesis developed and presented a functional design for a mechanical metamaterial for energy dissipation. The design developed is simple, scalable, easily manufacturable, modular and adapted to future developments. The model was designed using CAD software, printed using a slicing software and a TPU Caribou 3D printer, then subjected to compression tests in the lab. The model was also implemented in an FEA simulation in ANSYS and subjected to the same trials numerically. The data was then compared between experimental and simulation results and discussed. The model was built into a 6-unit modular assembly and tested again.

The energy dissipation of the singular unit cell under 3mm of displacement was measured at 225mJ numerically and 270mJ experimentally. The discrepancy between the two results is therefore 17%, and such discrepancy is observed consistently even when different displacements are applied. The modular 6-unit assembly dissipated 1265mJ numerically and 1656 mJ experimentally. The discrepancy is therefore 24%, and the similarity to a theoretical result of 6 times the singular unit cell's dissipation is more than 94%. Again, these results are consistent through several tests and simulations.

6.2 Contribution to the Field, implications and applications

This research contributes to the field of friction-based metamaterials by demonstrating a successful design and fabrication process for a unit cell with energy dissipation capabilities. The simplicity and modularity of the design make it a promising candidate for various applications, and its adaptability opens possibilities for further improvements and modifications. The proposed design provides a solid foundation for future research and development, paving the way for the creation of new and improved metamaterials with enhanced energy dissipation capabilities.

Through its simple design and ease of manufacture, the design acts as a building block for future research and real-world applications. Indeed, the design could be beneficial in the development of new materials to manufacture products such as:

- Seismic engineering products, to protect buildings from earthquakes and natural disasters by dampening the movements of the buildings under the forces of nature and dissipating the energy through friction
- Shock absorbing products, like helmets, vehicle dampeners or crash boxes. By dissipating more energy from impacts, the benefit for human safety could be substantial. Such products made from efficient energy dissipating metamaterials could prevent injury.

6.3 Limitations and Challenges

This research has limitations and faced some challenges. By not subjecting the model to endurance and fatigue tests, the long-term durability of the design is unknown. Also, future research could explore the impact of alternative material selection and additive manufacturing techniques. Different modular layouts could also be tested to better suit different applications.

The discrepancies encountered between simulation and numerical model have been addressed and could be solved through two directions. On one hand, the model could be refined to better represent the tight fittings that characterize the experimental specimen. Contact models could be refined, including allowing for some degree of penetration. This would help better represent the stick and slip phenomena that could happen at a micro-level. The lateral supports and related contacts could be better modeled to ensure constant contact with the sliders, as observed experimentally. On the other hand, the experimental specimen could be upgraded, through more precise and better-quality printing, as well as looser fits to lessen the tension that causes the buckling of the frame. By working on these two aspects, the model and the experimental specimen could be harmonized, and the force-displacement curves could be similar.

6.4 Future Research Directions

This thesis could be used by future research as a solid basis to pursue the exploration of frictional metamaterials. Several aspects can keep the research going. First, alternate plastics could be used with the same 3D printer, or the model could be manufactured with a different technique such as powder bed fusion for example. Alternatively, the metamaterial could also be manufactured with metal 3D printing and tested; The model should also be subjected to fatigue tests to characterize its durability. New failure modes could then be found, analyzed and corrected.

Research could also be pushed further into enhancing the energy dissipation capabilities through metasurfaces. The metasurfaces could easily be placed on the flat surfaces of the sliders. These could potentially increase surface contact and energy dissipation. Future research could quantify this. Also, energy harvesting could be achieved through the use of TENG to convert the frictional energy into electricity. The flat surfaces are suitable for skin-like improvements like these, and the modular design could be well adapted to a TENG experimental setup. As discussed, this would however require an experimental setup not currently found in the lab.

To bring the lab research to real world applications, the metamaterial or its assembly could be manufactured into bricks, planks or even textile fibers and then used to make the products previously listed as potential applications. Tests for large-scale manufacturing and industrialization could also be made.

6.5 Final Remarks and Broader Impact

Overall, this research demonstrates the potential of friction-based metamaterials for energy absorption applications. Beyond the specific findings of this thesis, there is significance in demonstrating a pathway for the practical design and manufacturing of frictional metamaterials. By prioritizing simplicity, modularity, and feasibility, this research moves beyond proof-of-concept demonstrations. It offers a readily adaptable building block for future lab improvements and perhaps real-world energy dissipation solutions. The inherent adaptability of the design to incorporate future advancements, such as metasurfaces and energy harvesting components, promises new research. The scalability of the design, validated through modular assembly testing, suggests a possibility for integrating these metamaterials into diverse applications. From enhancing protective gear to creating earthquake-resilient building elements, the design's inherent accessibility could democratize the application of new mechanical metamaterial. This thesis, therefore, will hopefully help translating laboratory innovation into impactful engineering solutions for a safer and more sustainable future.

References

1. Barchiesi, E., Spagnuolo, M., & Placidi, L. (2019). Mechanical metamaterials: a state of the art. Mathematics and Mechanics of Solids, 24(1), 212-234. doi:10.1177/1081286517735695

2. McCrary, A., Hashemi, M. S., & Sheidaei, A. (2022). Programmable bidirectional mechanical metamaterial with tunable stiffness and frictional energy dissipation. Advanced Materials, 34(5), e2107789. https://doi.org/10.1002/adma.202107789

3. Vulliez, M., Catapane, G., Guy, M.-A., Kesour, K., Marquis, J.-C. G., Jeanvoine, R., La Madeleine, F., Verdière, K., Petrone, G., & Robin, O. (2025). Design and laboratory validation of multistructured acoustic resonators for the attenuation of airborne machinery noise in ships. Ocean Engineering, 322, 120515. https://doi.org/10.1016/j.oceaneng.2025.120515

4. Del Vescovo, D., & Giorgio, I. (2023). Dynamic problems for metamaterials: Review of existing models and ideas for further research. Journal of Applied Mechanics, 90(4), 041006. htt ps://doi.org/10.1115/1.4096859

5. Surjadi, J.U., Gao, L., Du, H., Li, X., Xiong, X., Fang, N.X. and Lu, Y. (2019), Mechanical Metamaterials and Their Engineering Applications. Adv. Eng. Mater., 21: 1800864. https://doi.org/10.1002/adem.201800864

6. Wang, J., Shan, S., & McKnight, G. P. (2018). Energy absorption and large deformation of 3D printed polymer lattice structures. Materials & Design, 143, 156-165. doi: 10.1016/j.matdes.2018.01.042

7. Bastiaan Florijn*, Corentin Coulais†, and Martin van Hecke‡. Programmable Mechanical Metamaterials. DOI: https://doi.org/10.1103/PhysRevLett.113.175503

8. Melchels, F. P. W., Domingos, M. A. N., Bertoldi, K., & Leeflang, M. A. (2012). Additive manufacturing of tissue scaffolds for skeletal regeneration. Biomaterials, 33(12), 2213-2230. doi: 10.1016/j.biomaterials.2011.11.078

9. Zheng, X., Lee, H., Weisgraber, T. H., Shusteff, M., DeOtte, J., Duoss, E. B., ... & Spadaccini, J. L. (2014). Ultralight, ultrastiff mechanical metamaterials. Science,344(6190), 1373-1377. doi: 10.1126/science.1252291

10. Qian, X., & Wang, Q. (2021). Frictional Metamaterials: Design, Fabrication, and Applications. Advanced Functional Materials, 31(46), 2104425. doi: 10.1002/adfm.202104425

11. Bertoldi, K., Boyce, M. C., & Mullin, T. (2011). Mechanics of deformation-triggered pattern transformations and superelastic behavior in periodic elastomeric structures. Journal of the Mechanics and Physics of Solids, 59(9), 1797-1810. doi: 10.1016/j.jmps.2011.06.001

12. S. Yuan, C. K. Chua, K. Zhou, Adv. Mater. Technol. 2019, 4, 1800419. https://doi.org/10.1002/admt.201800419

13. Garland, A. P., Adstedt, K. M., Casias, Z. J., et al. (2021). Coulombic friction in metamaterials to dissipate mechanical energy. Advanced Materials, 33(37), e2101476. https://doi.org/10.1002/adma.202101476

14. Bauer, J., & Schmiedmayer, G. (2011). Shape memory polymers for smart metamaterials. Smart Materials and Structures, 20(7), 075014. doi: 10.1088/0964-1726/20/7/075014

15. Hedayati, R., & De Clercq, J. (2017). 3D printing of shape memory polymer composite cellular structures. Materials & Design, 122, 165-174. doi: 10.1016/j.matdes.2017.03.072

16. Wu, L., Yao, S., Chen, L., & Jiang, H. (2020). Design and 3D printing of multi-stable mechanical metamaterials for energy absorption. Materials & Design, 193, 108785. doi: 10.1016/j.matdes.2020.108785

17. Dionisio Del Vescovo, Ivan Giorgio, Dynamic problems for metamaterials: Review of existing models and ideas for further research, International Journal of Engineering Science, Volume 80, 2014, Pages 153-172, ISSN 0020-7225, https://doi.org/10.1016/j.ijengsci.2014.02.022.

18. Jeong, E., Calius, E., & Ramezani, M. (2024). Design and analysis of a 3D frictional mechanical metamaterial for efficient energy dissipation. Advanced Materials Technologies.

19. Kumar, S. (2018). Additive manufacturing of metals: a review. Materials & Manufacturing Processes, 33(1), 1-20. doi: 10.1080/10426914.2017.1294077

20. Gibson, I., Rosen, D. W., & Stucker, B. (2014). Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. Springer Science & Business Media.

21. Bourell, D. L., Kruth, J. P., Leu, M. C., Levy, G. N., Rosen, D. W., Shimada, S., & Suh, N. P. (2009). Roadmap for additive manufacturing: Identifying opportunities and challenges. Solid Freeform Fabrication Symposium Proceedings, 2009, 1-10.

22. Kumar, A., & Clausen, P. (2017). Energy absorption in mechanical metamaterials. Composites Part B: Engineering, 113, 240-254. doi: 10.1016/j.compositesb.2017.02.002

23. Herzog, D., Wohlers, T., & Diegel, O. (2016). Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. Hanser Publications.

24. Maniatty, A., & Jin, H. (2015). Designing and fabricating metamaterials. International Journal of Smart and Nano Materials, 6(1), 1-32. doi: 10.1080/19475411.2014.997148

25. Ye M, Gao L, Wang F, Li H. A Novel Design Method for Energy Absorption Property of Chiral Mechanical Metamaterials. Materials. 2021; 14(18):5386. https://doi.org/10.3390/ma14185386

26. Hamzehei, & Bodaghi. (2023). Parrot Beak-Inspired Metamaterials with Friction and Interlocking Mechanisms 3D/4D Printed in Micro and Macro Scales for Supreme Energy Absorption/Dissipation. Materials Today, 45, 189-197. https://doi.org/10.1016/j.mattod.2023.04.012

27. Gong, X., & Chou, K. (2015). Additive manufacturing of metamaterials: A review. International Journal of Advanced Manufacturing Technology, 76, 2059-2074. doi: 10.1007/s00170-014-6257-z

28. Tan, J., Yao, H., Liu, L., & Chen, Y. (2020). A review of energy absorption of mechanical metamaterials. Composite Structures, 234, 111689. doi: 10.1016/j.compstruct.2019.111689

29. Wang, Z. L., & Song, J. (2006). Piezoelectric nanogenerators based on zinc oxide nanowire arrays. Science, 312(5771), 242-246. doi: 10.1126/science.1124005

30. Fan, F. R., Tian, Z. Q., & Wang, Z. L. (2012). Flexible triboelectric generator. Nano Energy, 1(2), 328-334. doi: 10.1016/j.nanoen.2012.01.004

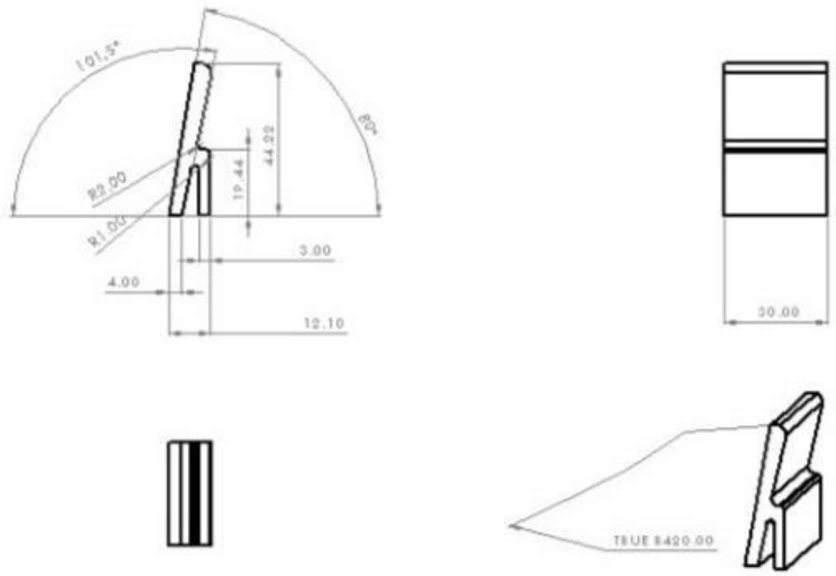
31. Surjadi, J. U., Aymon, B. F. G., Carton, M., & Portela, C. M. (2024). Double-network-inspired mechanical metamaterials. *arXiv preprint arXiv:2409.01533*. https://doi.org/10.48550/arXiv.2409.01533

32. Razavi, S. M. J., Yazdani, M. A., Rezaei, A. H., Nasihatkhah, P., & Ahmadi, M. (2025). Modeling, Design, and Laboratory Testing of a Passive Friction Seismic Metamaterial Base Isolator (PFSMBI). *Materials, 18*(2), 527. doi: 10.3390/ma18020527

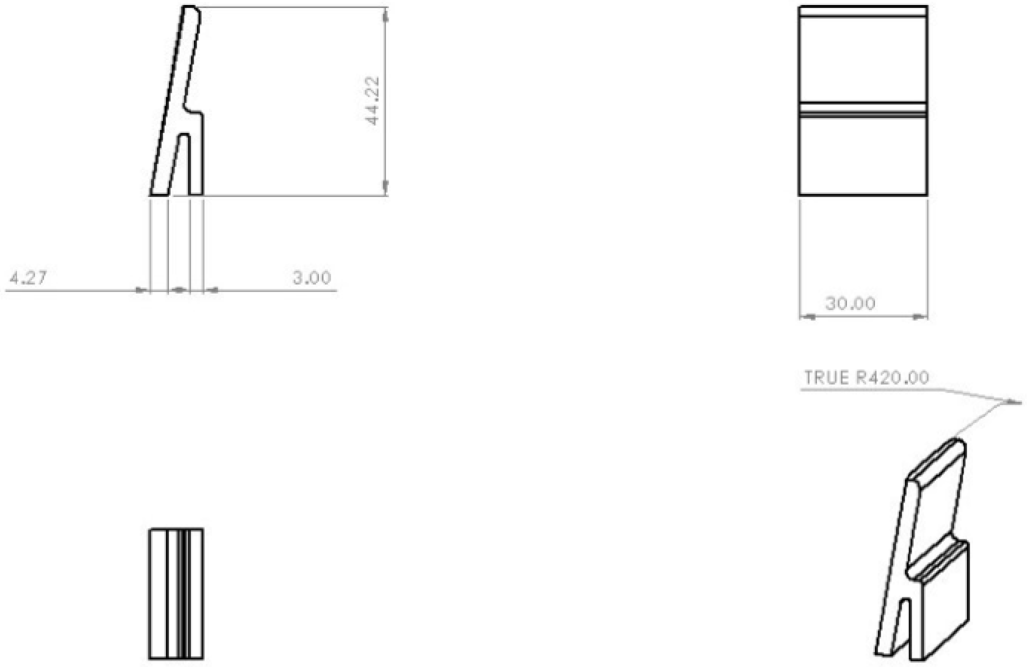
33. Huijing Xiang et al. Triboelectric nanogenerator for high-entropy energy, self-powered sensors, and popular education.Sci. Adv.10,eads2291(2024).DOI:10.1126/sciadv.ads2291

Appendix

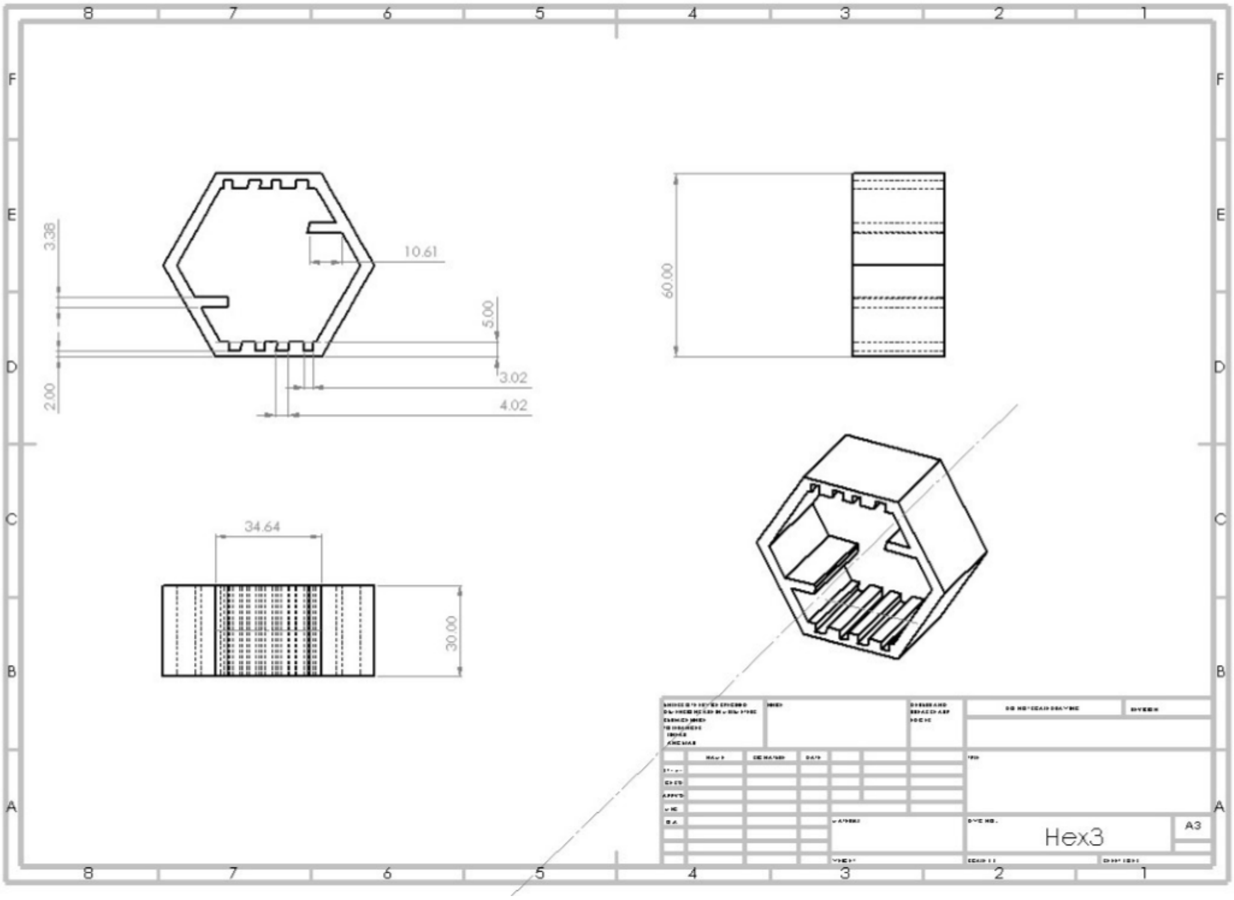
Appendix A: Technical Drawings of the three parts of the Unit Cell



Convex Slider



Concave Slider



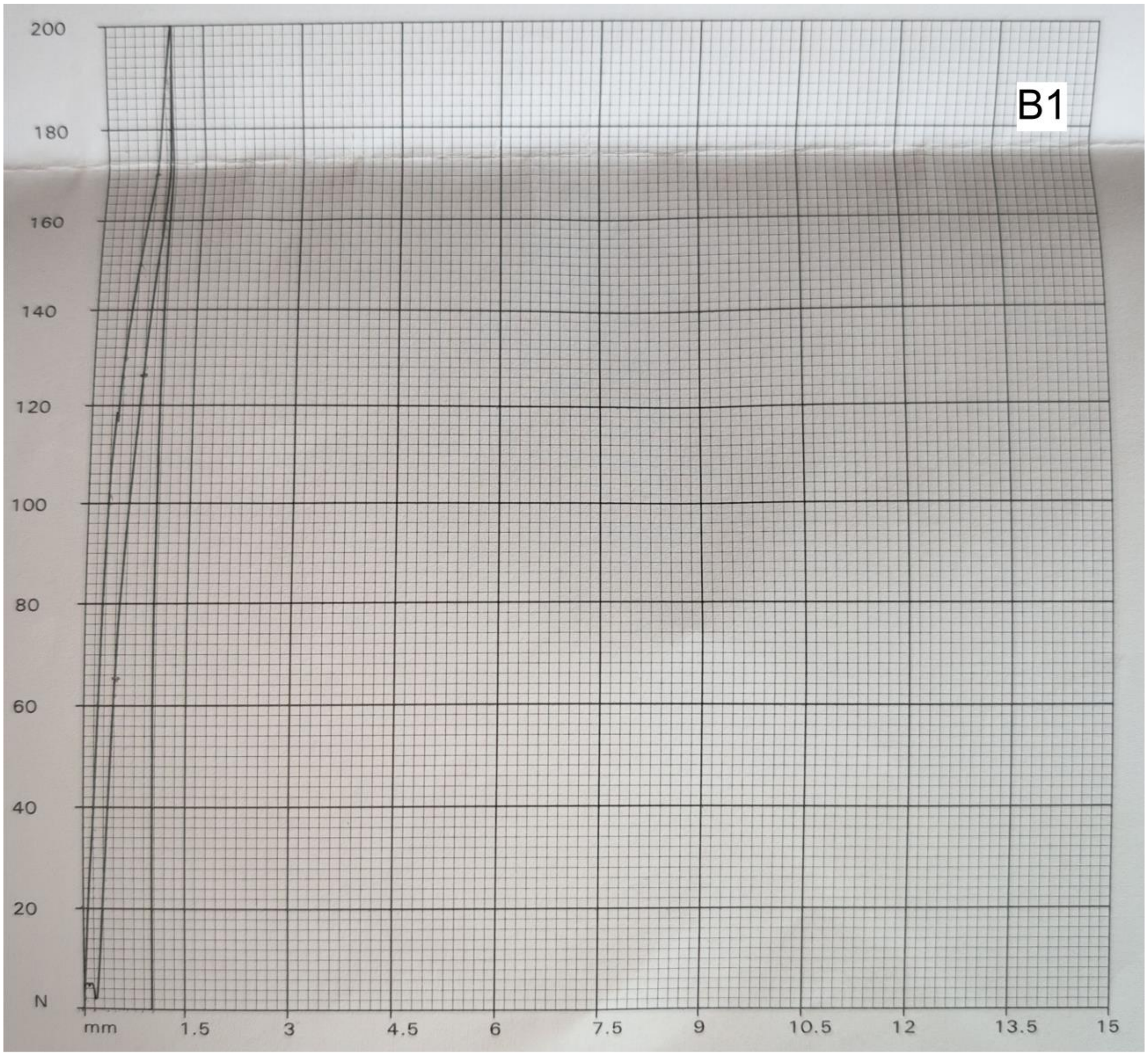
Hexagonal Frame

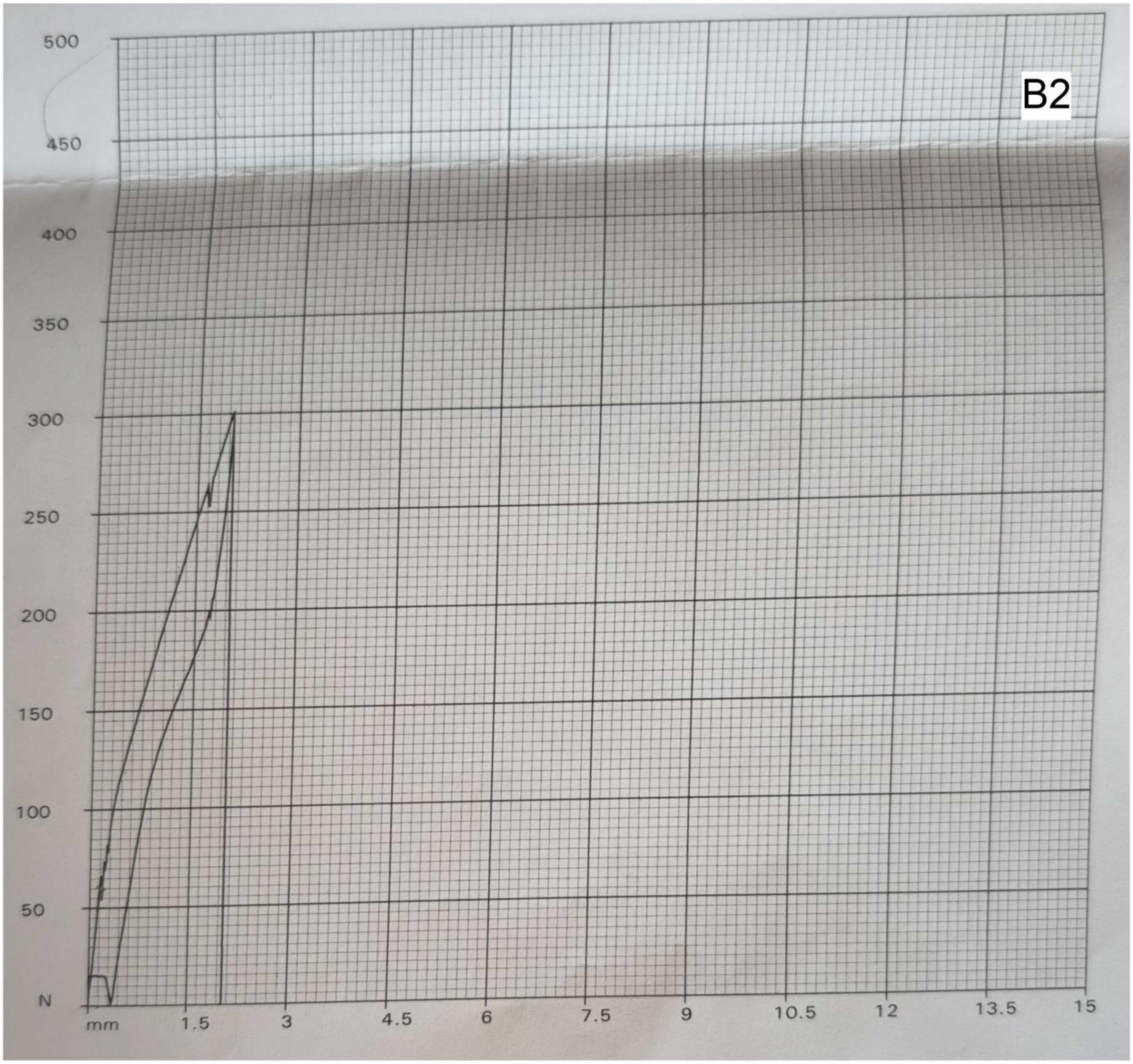
Appendix B: Raw Experimental Data of Singular Unit Cell Compression Tests

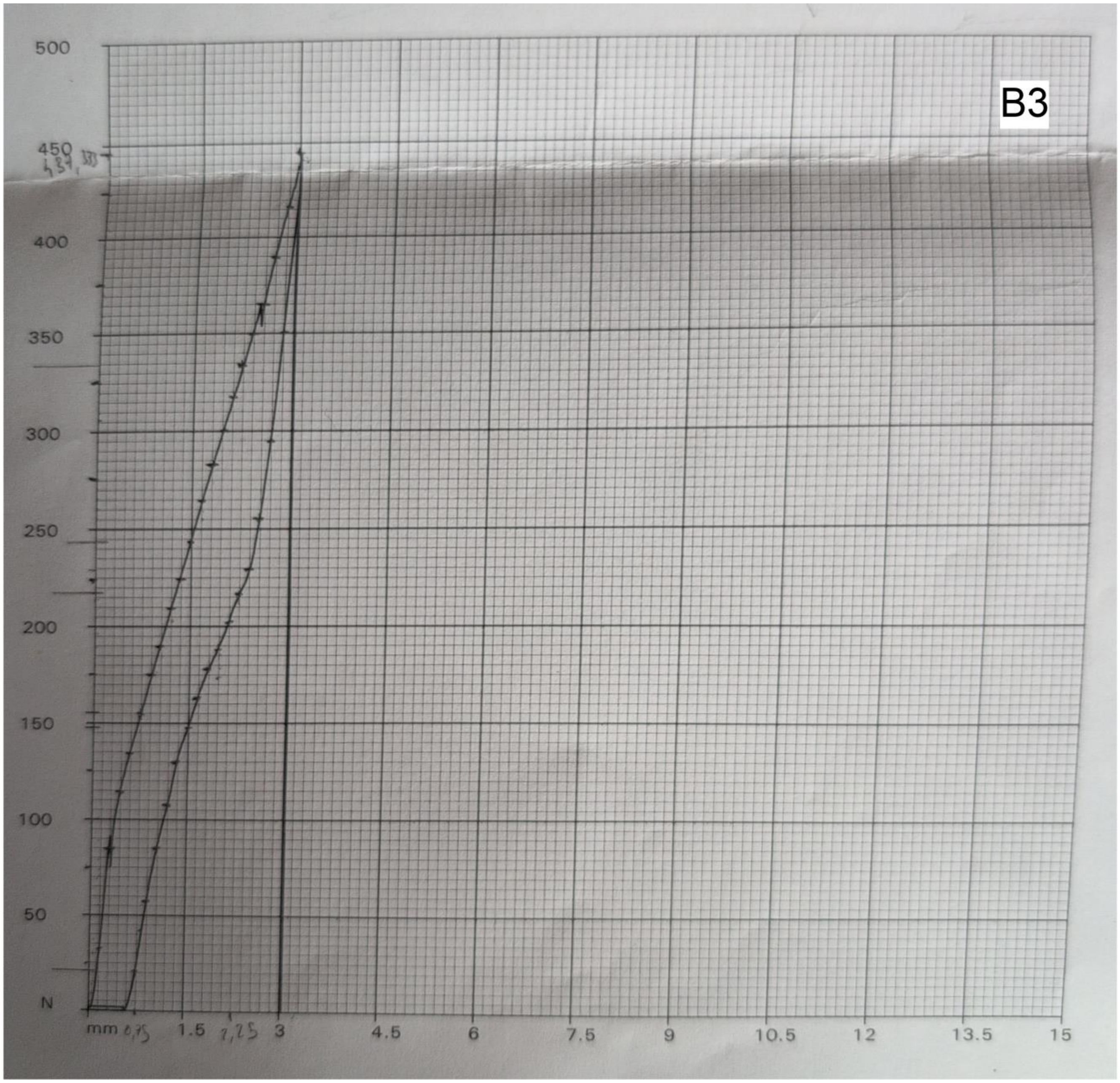
B1	B2	B3	B4	B5
1mm	2mm	3mm	4mm	7mm (failure)

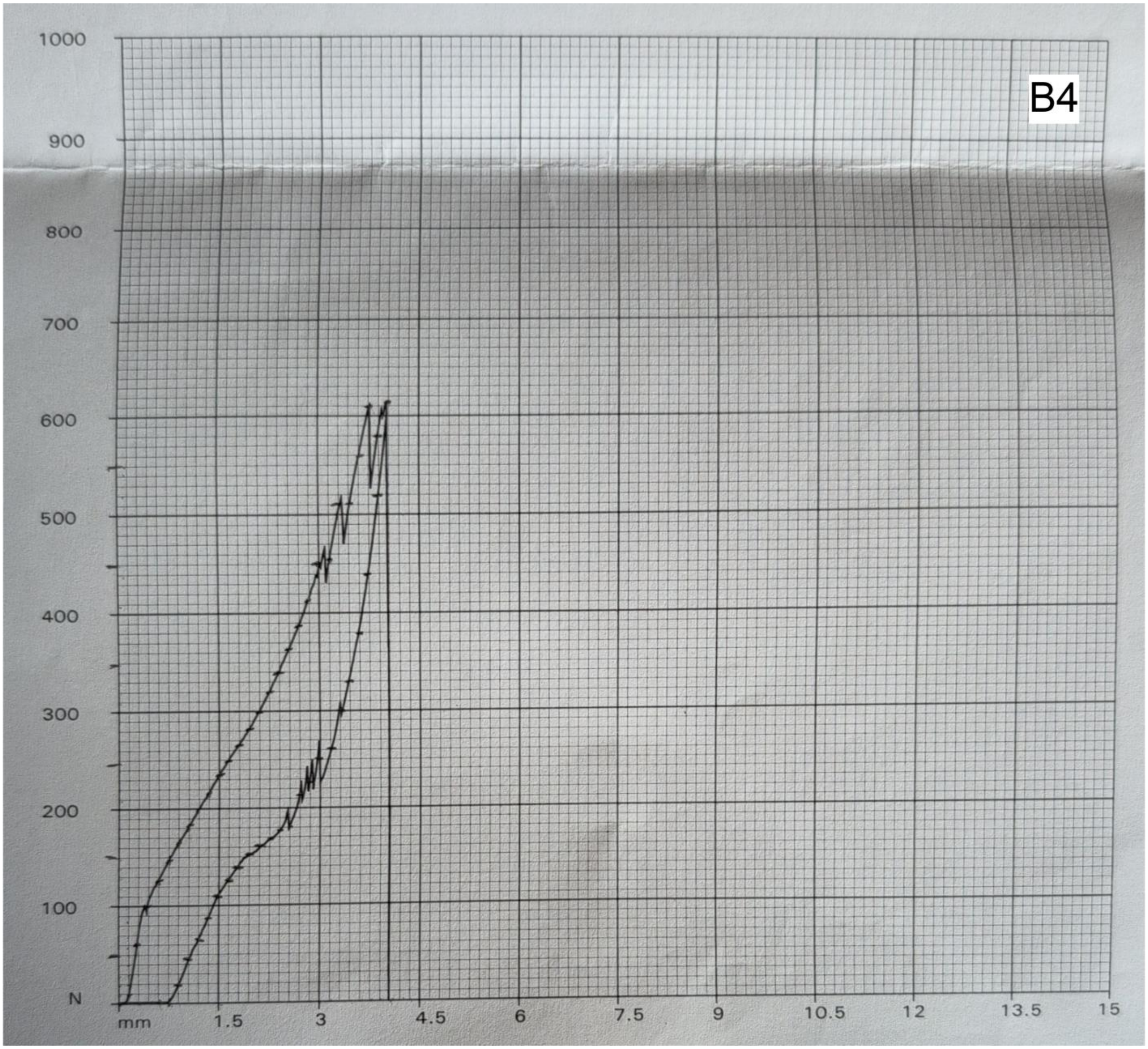
Appendix C: Raw Experimental Data of 6 Unit Assembly Compression Tests

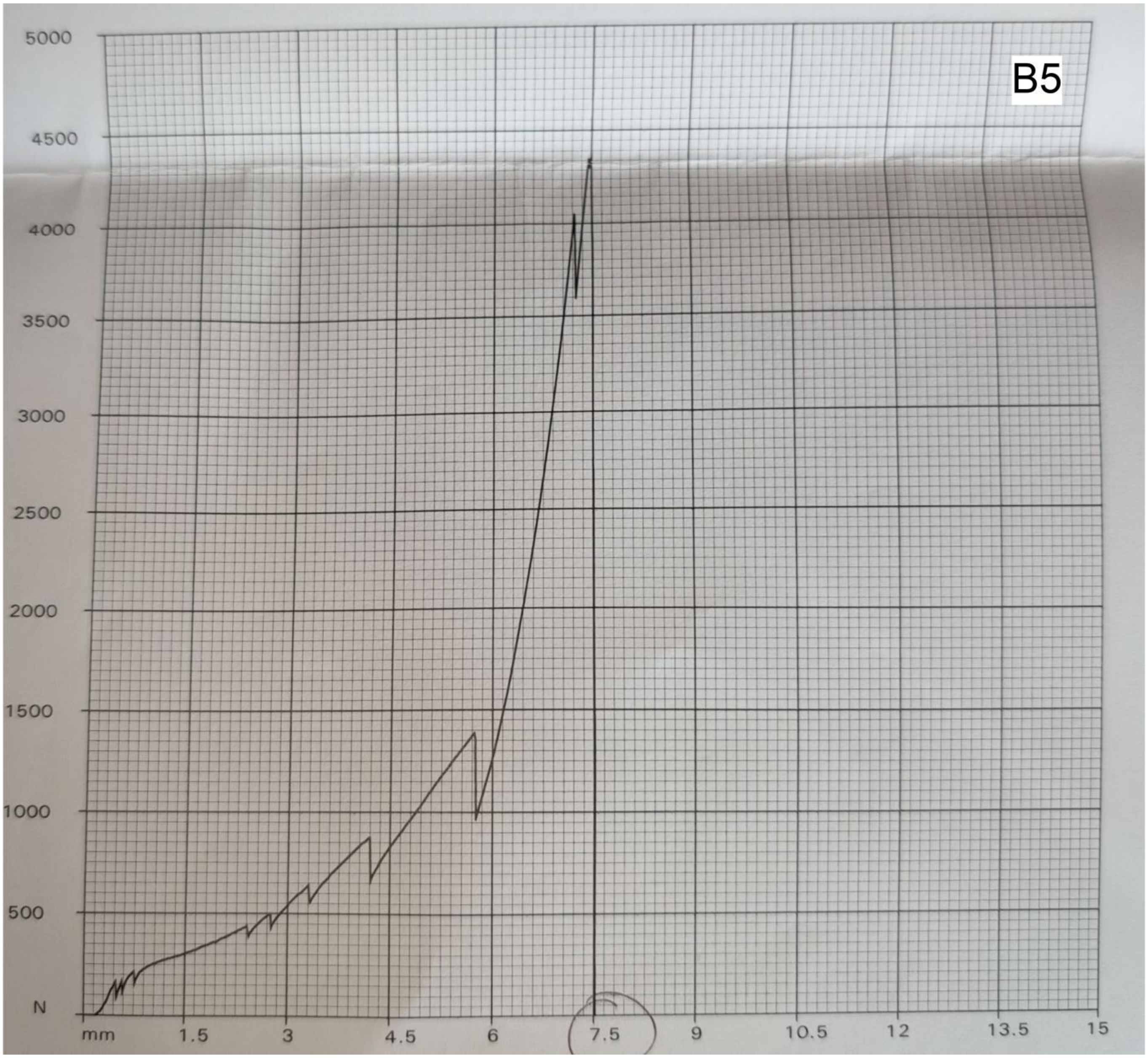
C1	C2	C3	C4
1mm	2mm	3mm	4mm

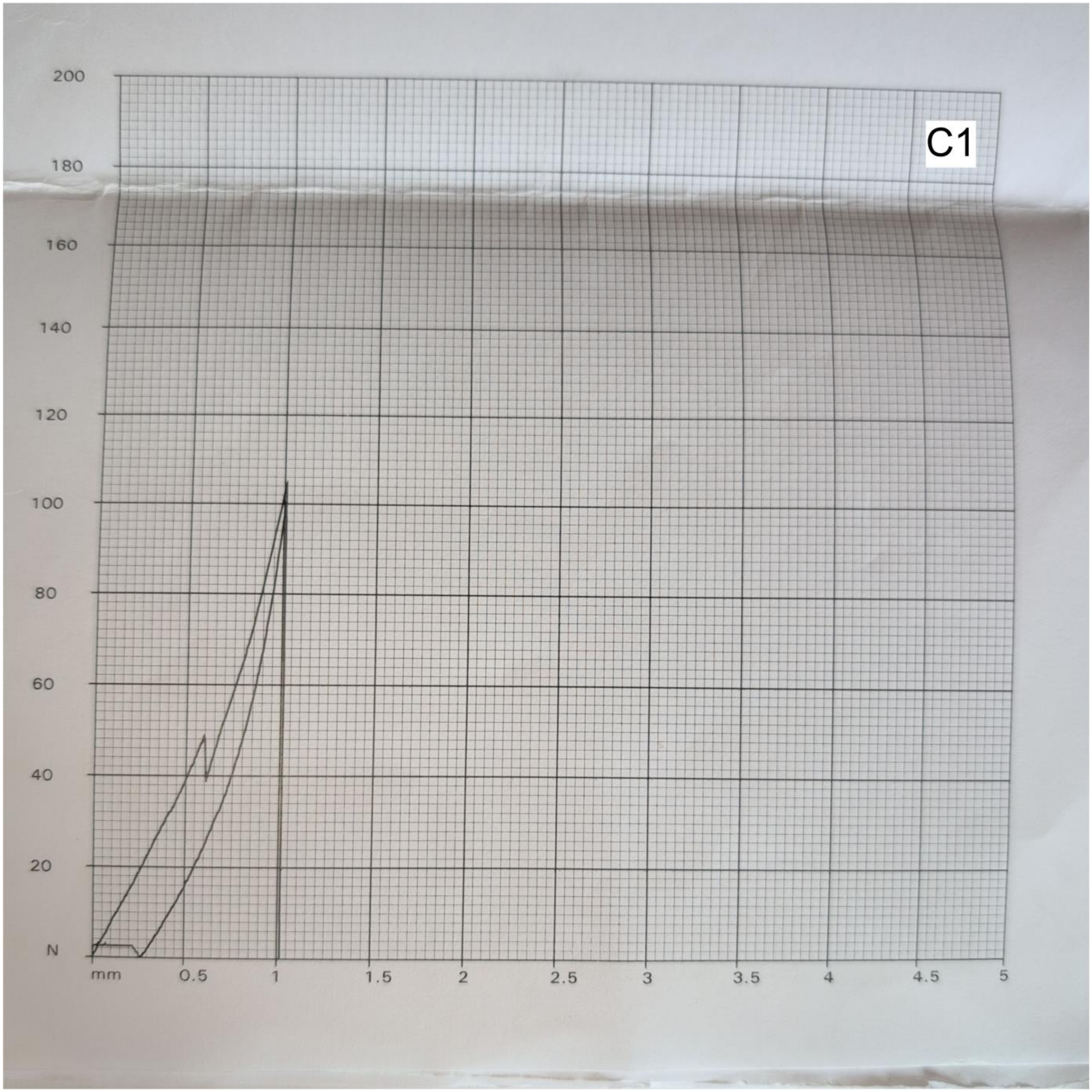

B1
200
180
160
140
120
100
80
60
40
20
N
mm
1.5
3
4.5
6
7.5
9
10.5
12
13.5
15

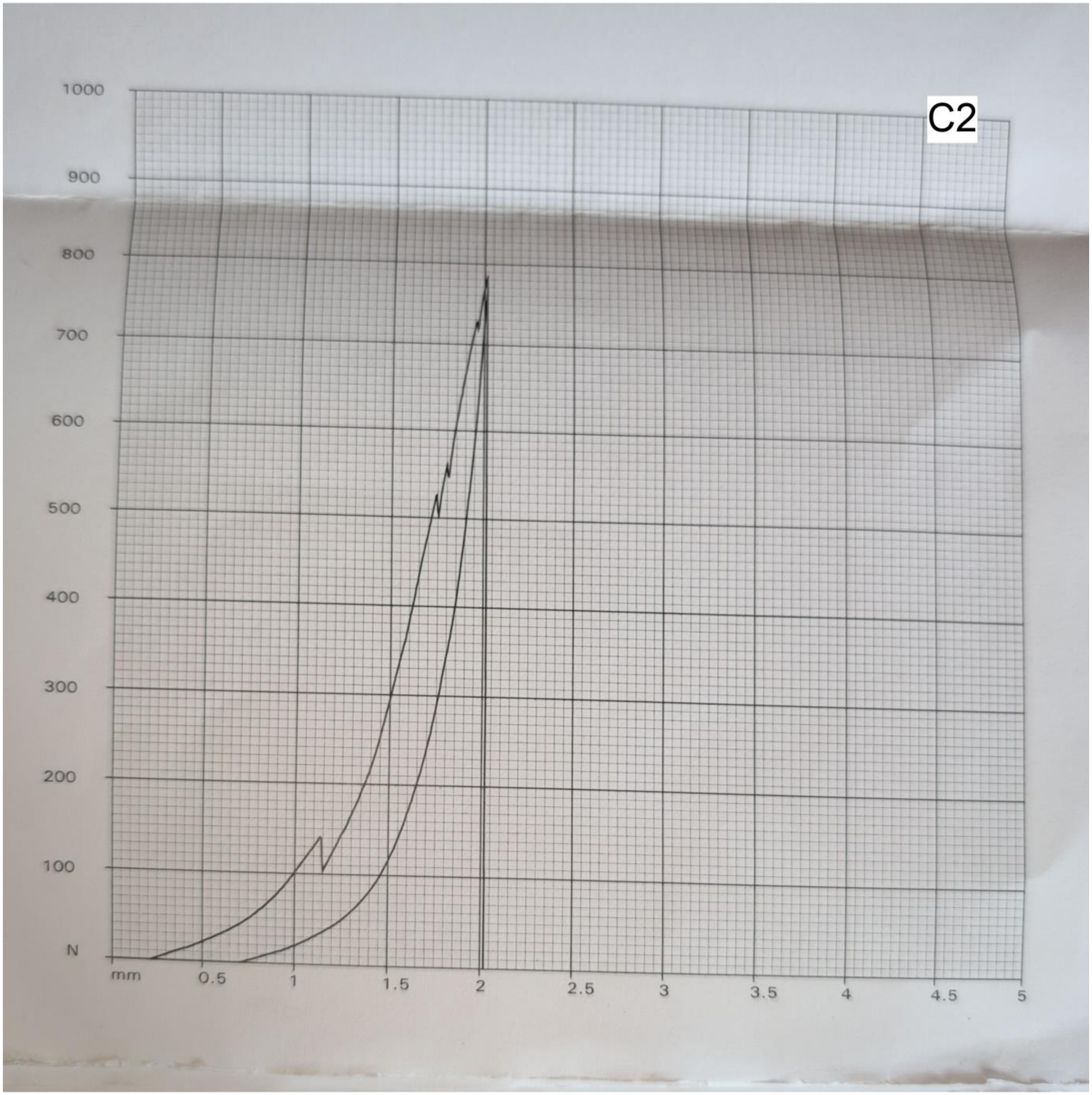

B2
500
450
400
350
300
250
200
150
100
50
N
mm
1.5
3
4.5
6
7.5
9
10.5
12
13.5
15

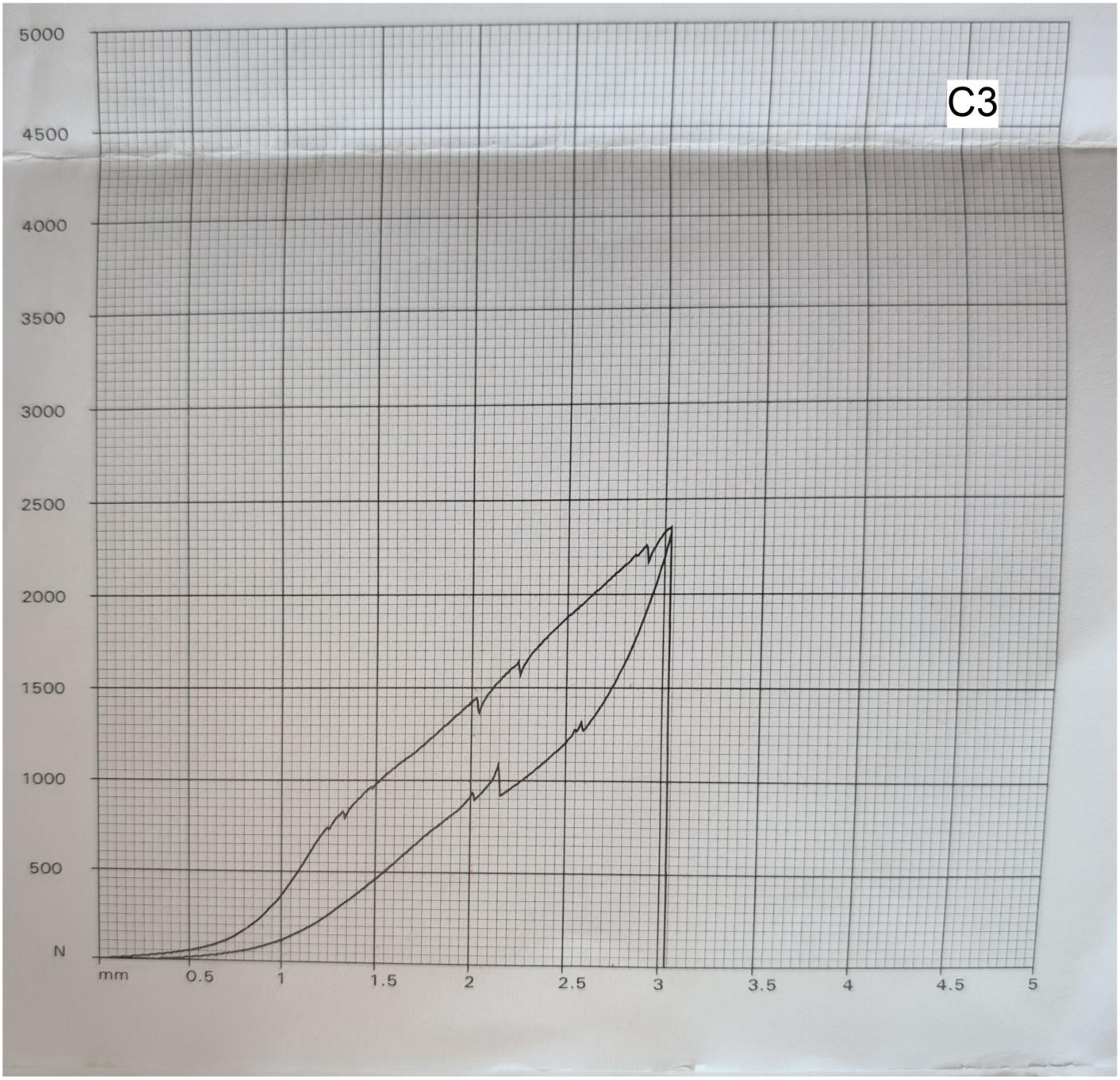

B3
500
450
437,333
400
350
300
250
200
150
100
50
N
mm
0,75
1.5
2,25
3
4.5
6
7.5
9
10.5
12
13.5
15

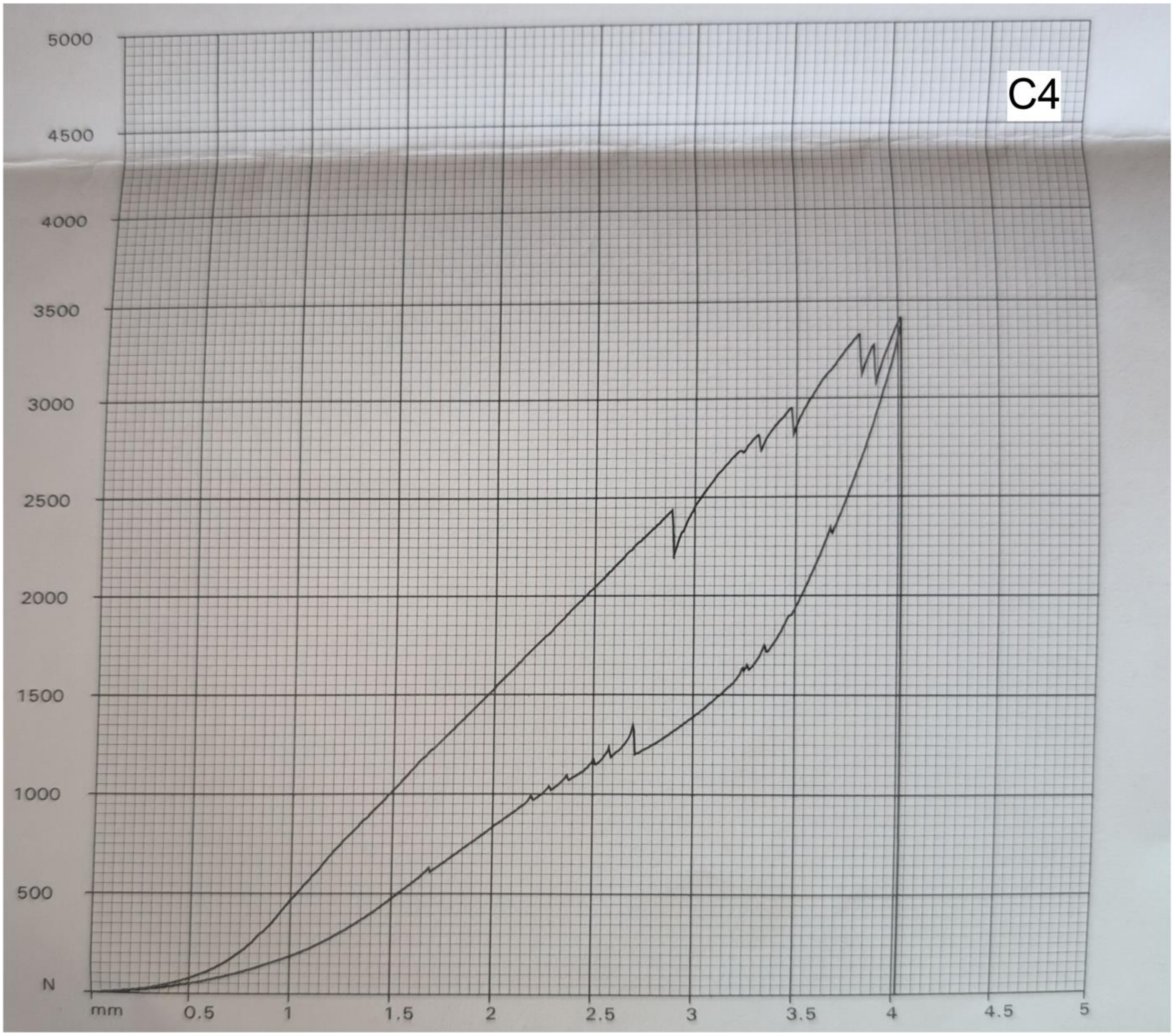

B4
1000
900
800
700
600
500
400
300
200
100
N
mm
1.5
3
4.5
6
7.5
9
10.5
12
13.5
15


B5
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
N
mm
1.5
3
4.5
6
7.5
9
10.5
12
13.5
15


C1
200
180
160
140
120
100
80
60
40
20
N
mm
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


C2
1000
900
800
700
600
500
400
300
200
100
N
mm
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


5000
4500
4000
3500
3000
2500
2000
1500
1000
500
N
mm
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
C3


C4
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
N
mm
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5