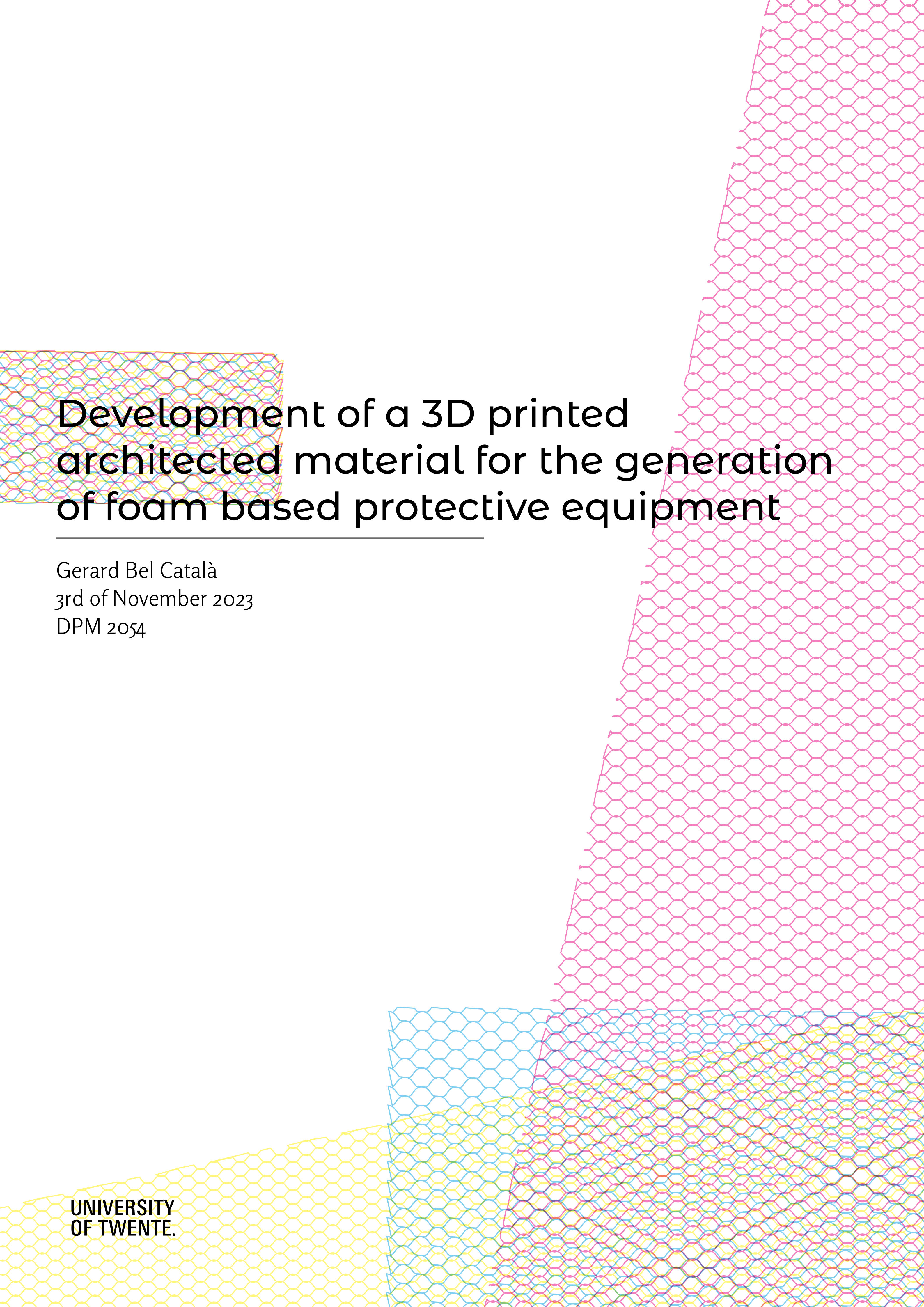

Development of a 3D printed architected material for the generation of foam based protective equipment

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Acknowledgments

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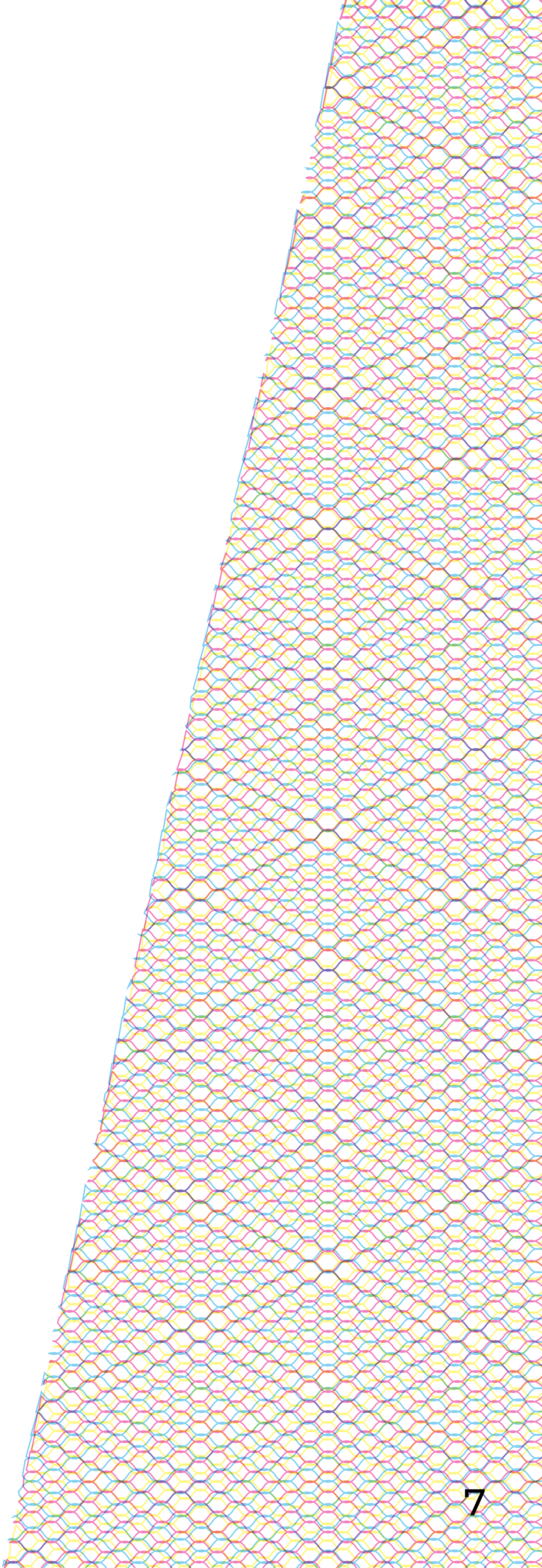


1. Introduction

Designing products intended for direct contact with the human body has long been a challenge. Initially due to the inherent variations found within the human population. This is solved by the generation of ergonomic studies which attempt to develop models of the human body that encompass the diverse range of gender, age, dimensions, and weight. However, relying on such generalised models often results in discomfort and dissatisfaction for users. The inability of mass-produced products to cater to individual needs can lead to issues such as skin irritation, inadequate fit, and compression due to inaccurate sizing.

While the concept of ultra customization has existed for some time, it has remained an exclusive luxury accessible only to those with the financial means to afford personalised products. The predominant manufacturing practices, driven by efficiency and cost-effectiveness, have limited the feasibility of creating custom moulds or patterns for each user. Consequently, mass production has become the standard approach for most consumer products. However, recent advancements in manufacturing methods, model generation techniques, and data collection have opened up new avenues for addressing this challenge effectively. By harnessing these technological advancements, it becomes increasingly feasible to overcome the limitations of mass production and provide ultra-customized protection products on a broader scale.

The initial objective of this research project was to design a 3D printed ski back protector, a product that plays a vital role in ensuring safety during skiing activities. However, as the project unfolded, it became evident that the primary prerequisite for creating any such protective gear is the development of a suitable material or 3D printed structure. This realisation prompted a shift in focus towards the creation of a versatile structure capable of altering its properties based on specific user requirements. By introducing intentional variations in certain qualities, this adaptable structure holds the potential to revolutionise the production of ultra-custom protection products.

The existence of such a structure, and the method of making it could significantly expedite the development of many personalised protective equipment products, transcending beyond the realm of ski back protectors.

1.1 Research Aim

The aim of this research is to investigate personal protectors used in sports, focusing on their functionality and the materials utilised, particularly the foam. It also aims to explore the process of generation of an architected material, with a focus centred on 3D printing, using affordable and accessible 3D printing methods, and Thermoplastic Polyurethane as its main material.

1.2 Scope and Objectives

1.2.1 Research Scope

This research project focuses on the development of a structure which can work within the domain of personal protectors, with a primary focus on substituting the foam materials integral to their construction. Additionally, it delves into the intricacies of the manufacturing process pertaining to the architected structure, with a specific emphasis on the utilisation of 3D printing.

For the production of the samples a production method selection will be done, based on the understanding and knowledge obtained from a study of the main methods, focusing on an easily and available method for us. Another important step is a small material study to select a suitable material for its production, this material selection will focus on also a material which is easily accessible.

A cornerstone of this research involves the examination of results from testing samples generated through the use of the structure developed. This testing should be done using comparable data from foams used in protective equipment, to understand what material or protection to use, and a basic understanding of foams used in the real world.

1.2.2 Research Objectives

Having successfully achieved the overarching research aim, the subsequent objectives within this research endeavour are poised to be realised, thereby propelling the project towards the crucial phases of matrix generation and testing. The specific objectives that constitute the next phase of this research are as follows:

1. Investigate the diverse foam materials that find application in sport-based personal protectors, understand how they work.
2. Select a proper 3D printing method which fits the requirements established for the project .
3. Acquire a comprehensive understanding of the distinctive properties and selection of the adequate material fitting the requirements.
4. Generating a viable structure and understanding the reasons for its viability,.
5. In the event of proven viability, advance towards the design and fabrication of a functional prototype.
6. Provide insightful recommendations and suggestions aimed at enhancing the design for future work.

The successful achievement of these objectives will contribute significantly to the field of highly customizable sports equipment. This material can potentially enable the design and manufacture of equipment in domestic settings, aligning with the increasing availability of 3D printers. Ultimately, these advancements in personalised protective gear have the potential to benefit athletes and sports enthusiasts alike.

By prioritising improvements in comfort, safety, and performance, this research aims to elevate the standards of sports equipment. This could herald a new era of tailored protection products that closely align with the specific needs of individual users.

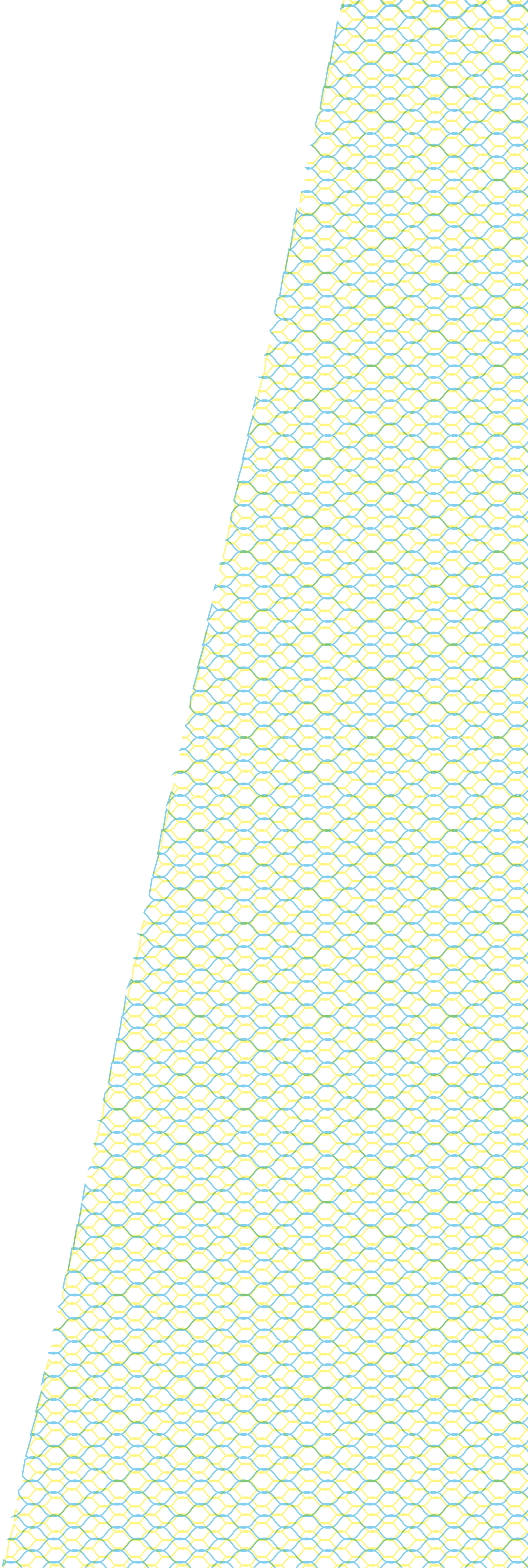
2. Inspiration Phase

2.1 Background on Sports Personal Protections

Sports personal protection equipment (PPE) has experienced significant evolution over time, playing a vital role in ensuring the safety of athletes during sporting activities. Sports personal protections.

The idea of safeguarding athletes from injuries through specialised equipment can be traced back to ancient times. Historical evidence suggests the use of basic protective gear like leather helmets and padded garments during physically demanding events[1]. However, it was only in the late 19th century that sports PPE began to gain recognition and systematic development, as sports organisations and public awareness of athlete safety increased[2].

Over time, sports PPE has undergone substantial advancements in materials, design, and technology, driven by the objective of injury prevention and performance enhancement. The introduction of innovative materials, such as impact-resistant plastics, lightweight fabrics, and shock-absorbing foams, revolutionised the field of sports PPE[3]. Some important milestones in this evolution include the introduction of American football helmets in the early 20th century[4], the invention of face masks for basketball and other high-impact sports, and the use of padding and reinforced structures in contact sports equipment. Today, sports PPE includes a wide range of equipment, including helmets, goggles, mouth guards, shin guards and body armour, tailored to the specific requirements of different sports and athletic activities.



2.1.1 What kinds

The categorization of sports protective equipment is multifaceted, with various classification approaches available. These categorizations can be based on the area of protection (such as limbs, joints, head, mouth, and face), their primary function (e.g., impact protection or thermal protection), or the level of protection they offer (ranging from high-level protection like helmets to lower-level protection as seen in padded shirts).

However, within the context of this thesis, the focus primarily revolves around the foam materials used in sports protective equipment. Therefore, the categorization of these foams will be contingent upon the qualities they exhibit based on their primary functions. Three primary categories will be considered:

- **Movement-Restricting Equipment:** These equipment are designed to limit or restrict the range of motion in specific body parts or joints. They prioritise stability and control, often used in protective gear where maintaining proper posture or preventing hyperextension is crucial.
- **Impact Protection Equipment:** Gear falling into this category are engineered to absorb and dissipate impact forces effectively. Their primary purpose is to provide cushioning and reduce the risk of injury from high-impact collisions or falls.
- **Combination Equipment:** This category encompasses foams that serve a dual purpose, offering both movement restriction and impact protection. They strike a balance between stability and cushioning, making them versatile options for various sports protective equipment.

By categorising foams based on their primary functions—movement-restricting, impact protection, or a combination thereof—this thesis aims to provide a focused and comprehensive examination of the foam materials crucial to the development of sports protective gear. This approach will enable a deeper exploration of the unique properties and characteristics of these foams and their suitability for specific applications within the realm of sports equipment design.

Motion Restricting

Movement-restricting protective gear, commonly referred to as braces, serves a crucial objective within the realm of sports and injury prevention. These protective devices are specifically designed to limit the range of motion of certain body parts and prevent them from bending or moving in undesirable ways. In doing so, they aim to enhance stability, provide support, and reduce the risk of injury during physical activities. The spectrum of movement-restricting protective gear is diverse, ranging from simple, yet effective techniques like taping to more complex braces with solid components and hinges.

Taping Techniques: Taping is a widely recognized and employed method of movement restriction. In sports like rugby, athletes often use taping to reinforce ligaments and tendons, particularly in joints prone to injury. Rugby players commonly employ techniques such as the "ankle tape" or "knee tape" to stabilise these vulnerable areas. The tape's primary function is to limit excessive joint movement, preventing hyperextension and promoting optimal joint alignment. It serves as a flexible and adaptable form of movement restriction, providing essential support without hindering overall mobility[5].

Joint Stabilisers: These braces focus on relieving pressure on joints while providing essential stabilisation. They are often used in sports where joint injuries are prevalent, such as basketball or volleyball. Patella stabilisers, for instance, are designed to support and stabilise the kneecap (patella). Some patella stabilisers incorporate solid plates and hinges to maintain proper alignment and prevent dislocation. Foam materials play a critical role in these braces by cushioning and distributing pressure to minimise discomfort caused by the solid components. By incorporating foam padding, these braces offer a balance between immobilisation and comfort, enabling athletes to perform optimally while safeguarding against injuries.

Elbow Braces: Elbow braces, including tennis elbow braces and golfer's elbow braces, are another category of movement-restricting protective gear. These braces aim to restrict the movement of the elbow joint, particularly during activities that involve repetitive arm motions. Foam inserts within these braces serve a dual purpose: they provide cushioning to reduce impact and prevent friction while maintaining the necessary level of immobility to protect the affected area[6].

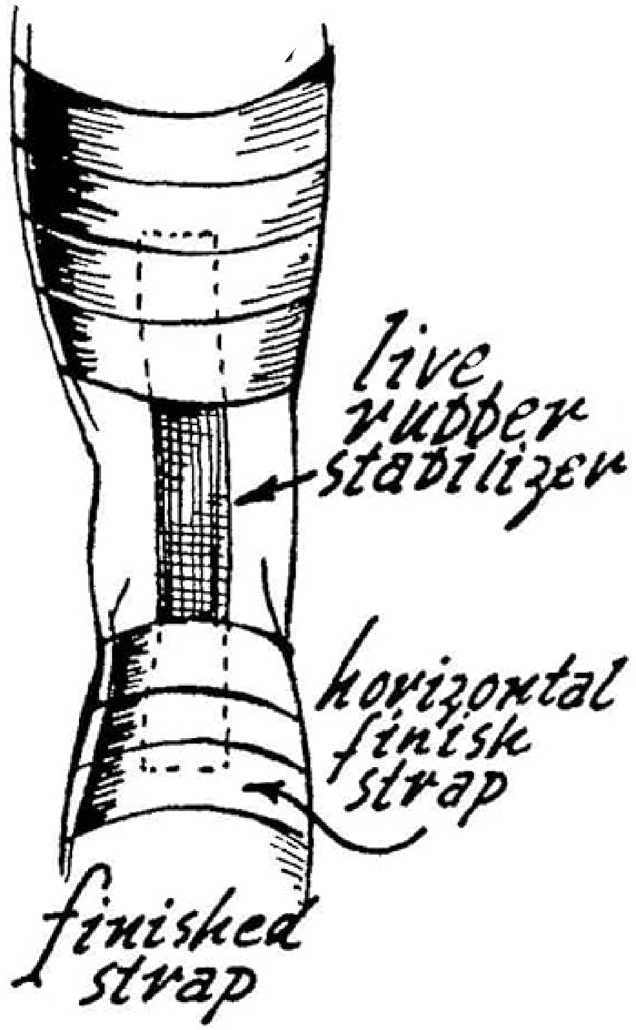


Figure 1: Strapping techniques for Mild Hamstring Strain

In summary, movement-restricting protective gear encompasses a wide range of devices and techniques, each tailored to address specific needs in various sports and activities. These protective measures prioritise stability and injury prevention by limiting excessive joint movement. Foam materials are integral components in many of these devices, not for impact protection but to ensure user comfort by preventing chafing or discomfort caused by solid components. Whether through taping techniques, joint stabilisers, or elbow braces, movement-restricting protective gear plays a vital role in enhancing athlete safety and performance.

Impact absorbing

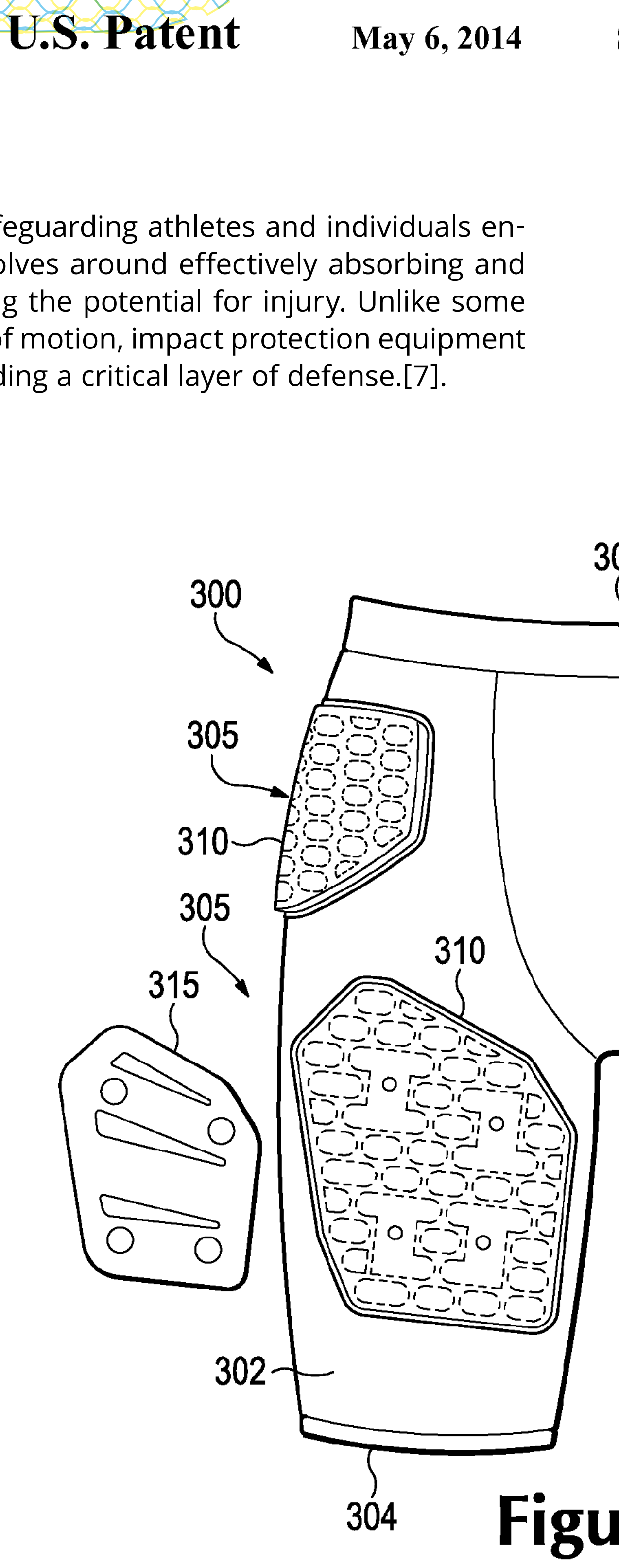
Impact protection equipment serves a paramount role in safeguarding athletes and individuals engaged in various physical activities. Its primary function revolves around effectively absorbing and dispersing the force generated by impacts, thereby mitigating the potential for injury. Unlike some forms of protective gear that may restrict the wearer's range of motion, impact protection equipment is engineered to prioritise freedom of movement while providing a critical layer of defense.[7].

Mouthguards: While not visibly extensive, mouthguards are essential for impact protection in contact sports such as rugby, boxing, and martial arts. These custom-fitted or boil-and-bite guards are composed of shock-absorbing materials that cushion the teeth, gums, and jaws, reducing the risk of dental injuries and concussions.[8]

Protective Padding in Apparel: Many sports and activities integrate impact protection directly into clothing. For instance, cycling shorts may include padded inserts to safeguard the hips and tailbone during falls. Similarly, snowboarders and skateboarders often wear impact shorts with strategically positioned foam padding to absorb shocks in case of tumbles.[9]

Knee Pads: certain sport players rely on knee pads made with impact-absorbing foam to protect their knees during dives and falls on hard surfaces, ensuring they can perform at their best without fear of injury.

In each of these examples, impact protection equipment is designed not only to offer superior safeguarding but also to allow users to perform at their peak by minimising the hindrance to their natural range of motion. By effectively absorbing and distributing the force of impacts, these specialised protective gear pieces enable athletes and enthusiasts to pursue their passions with confidence and safety.



Hard Shell

In certain instances, sports protective equipment employs the use of a hard shell component as an integral part of its design. These hard shells serve a crucial purpose by providing a robust barrier against high-impact forces, particularly in localised areas. The incorporation of hard shells is motivated by the need to prevent overloading the absorption capacities of the softer materials in specific regions. Additionally, hard shells can act as formidable guards against any external objects or elements that may attempt to penetrate the protective layer.

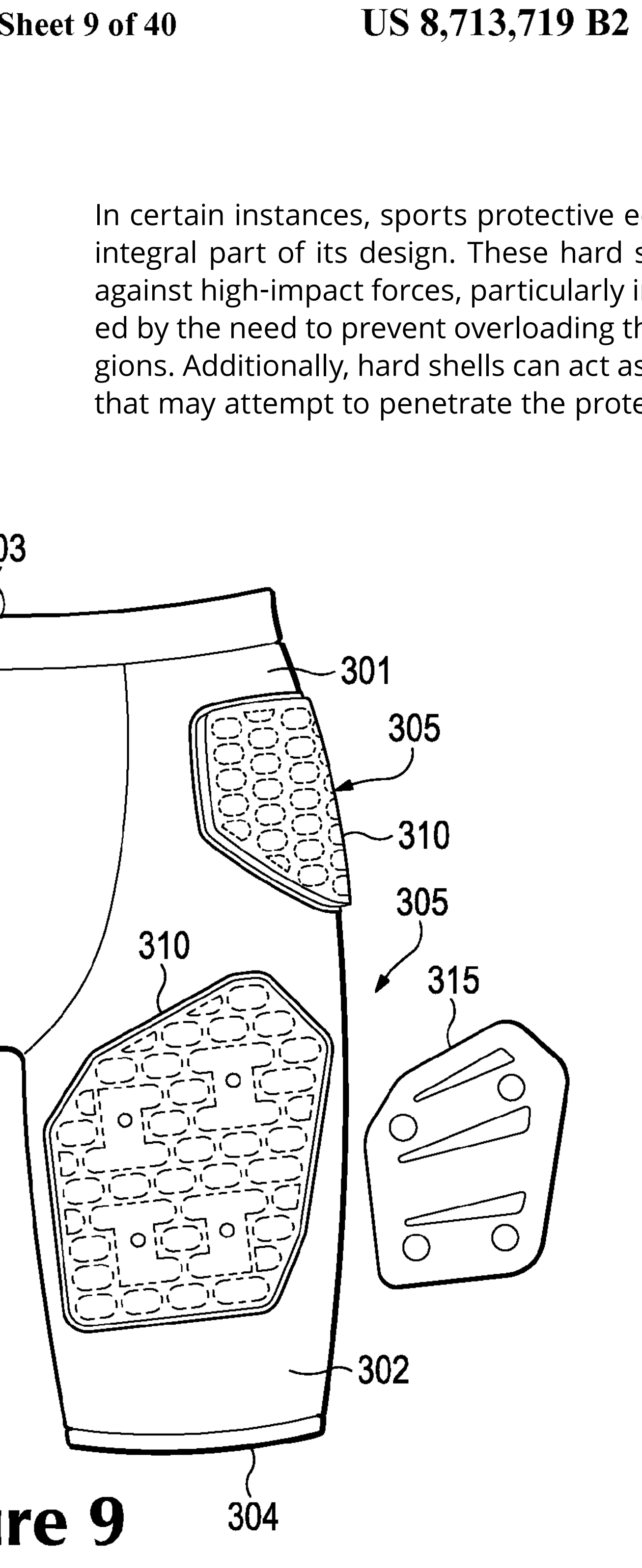


Figure 2: Exploded front elevational view of the inner garment
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Helmets: This hard shell not only enhances the helmet's structural integrity but also helps disperse the force of impact in the event of a crash, reducing the risk of head injury.

Gloves: Gloves often feature hard-shell components on the knuckles and fingers. These hard shells protect the hands from collisions with hard surfaces, such as ski poles, branches and even the ground in case of a crash.

Motocross Chest Protectors: Chest protectors for motocross riders frequently incorporate hard shells on the chest and back regions. These hard shells safeguard vital organs from high-velocity impacts and potential penetration from debris encountered during off-road riding.

Inline Skating Knee Pads: Knee pads designed for inline skating and skateboarding can include hard caps on the front. These caps provide a shield against abrasions and impacts when skaters fall or collide with obstacles.

It's essential to note that while hard shells play a pivotal role in specific protective equipment, there are numerous sports protective gear items that do not utilise hard shells. These products rely primarily on the cushioning and shock-absorbing properties of foam materials to provide adequate protection. In such cases, the design emphasis is on optimising the foam's qualities, such as impact absorption, flexibility, and comfort, without the added rigidity of a hard shell.

2.2 Background on Foams

2.2.1 Definition

Foam is, under physical chemistry, a dispersion of particles in a continuous medium, or also called a colloidal system, in which the particles are gas bubbles and the medium is a liquid, this term is also often used for spongy or rigid materials.[10] Foamed plastics are a solidification of the previous chemical phenomena, this is achieved by having the continuous medium be a polymeric material and the particles a gas. This means its porosity is variable, and can be controlled, resulting in different and specific properties[11]. When the right conditions and processes are applied, almost any thermosetting or thermoplastic can be converted into a foam. Plastic foams can be separated in three groups, Open cell, closed cell and reticulated foam which are made through different process and achieve different properties.[12]

- **Open cell foams** are those which are produced through the dispersion of high pressure gases, during the curing process of the thermoset plastic, the pressure is dropped, forcing the gas to expand, and pop, thus creating the open cells. This type of foams do not have sealed cells which allow air and other fluids to move through, or soak them. This ability for air and fluids to move through allows the foam to easily compress and then, naturally, return back to its original shape[13].
- **Closed cell foams** are those which due to the manufacturing process the gas bubbles do not pop, thus remaining isolated one from another. This is achieved through the use of foaming agents, which when activated, this being a chemical reaction, or a thermal activation, degrade, generating a certain amount of gas, which is not enough to generate large cavities and pop but, it is enough to generate an increase in volume [14]. Closed cell foams do not allow air or other fluids to move through, thus they do not compress as much and do not absorb any sort of liquid or even moisture.
- **Reticulated foams** are a mixture of the first two groups, a closed cell foam is thermally/physically treated to break the walls of the bubbles, leaving behind only the vertices. Such method allows the production of very low density foams while maintaining high mechanical properties.[11]

Recyclability of foams is very dependent on the type of foam and materials used. But the recycling of foamed plastics has always been an issue, recycling facilities require special equipment, and due to foams having a large ratio of air, the transport and storage is not cost efficient, making the whole process more expensive.[15]

Other issues are due to their properties, such as being good at absorbing fluids, which means, foams are harder to fully clean of the materials that can degrade the properties of recycled plastics, such as oils or other chemicals[16].

2.2.2 Common Foams

This brief selection of foams represents some of those found in many protections and everyday objects. Specific foams, blends, or commercial names generated by different brands have not been thoroughly studied. Not all of these foams are used in protective equipment, that is due to their mechanical and physical properties.

Polypropylene foam (EPP)

Polypropylene is a thermoplastic hydrocarbon from the group known as polyolefins, in its non foamed state it is already the lowest density plastic from the thermoplastics family, it offers a versatile range of properties that make it an attractive material for various applications, from great resistance to UV rays and to high temperatures. In its solid state, polypropylene exhibits toughness and durability, although it can lack flexibility[18]. Through the process of foaming, polypropylene becomes a lightweight material, which balances rigidity and flexibility, with excellent resistance to moisture and chemicals[11].

The creation of polypropylene foam involves introducing a gas or a chemical blowing agent into the polymer matrix, this mixture is typically foamed in a specialised extrusion or moulding process. As the blowing agent expands due to heat or pressure, the polymer matrix stretches and forms a multitude of interconnected cells. This structure results in lower density, and a higher degree of impact resistance[19]. Other characteristics of polypropylene foam include its resistance to compression and impact absorption, making it a favoured choice for protective gear and cushioning applications. Additionally, its inherent resistance to moisture and temperature broadens its suitability across various environments and conditions[20] .

While recycling of both solid polypropylene and polypropylene foam is feasible, polypropylene faces challenges in terms of collection, transport, and proper recycling infrastructure. Despite its recyclable nature, the lightweight nature of the foam and the economics of recycling can sometimes deter efficient processing[21]. This concern over mismanagement has led to instances of polypropylene foam finding its way into the environment, with potential adverse impacts. In response, regulatory measures have been considered to mitigate these environmental risks[22]

Polyurethane foam (PU-PUF)

Polyurethane is the result of the synthesis of organic units joined through the use of urethane links. This is accomplished through polyaddition[27]. This polymer encompasses more than 6% of all polymers produced in 2021, at around 24.7 million metric tons[28]. Out of this amount, over 60% is produced in its foamed state[29]

Polyurethane foam's versatility stems from its ability to exist in various forms, including flexible and rigid versions. Flexible polyurethane foam is valued for its comfort and cushioning properties, seen in mattresses and upholstery due to its breathable structure. On the other hand, rigid polyurethane foam excels in insulation, offering strength and thermal resistance for applications like construction and appliances[30].

The manufacturing of polyurethane foam involves precise control of isocyanate-polyol reactions, resulting in a wide spectrum of foam types. Recycling initiatives target waste reduction. Mechanical recycling grinds used foam into particles for new products, while chemical methods break it down into components for processing. Innovations focus on sustainability, incorporating bio-based materials like plant-derived polyols to reduce reliance on petroleum[31].

Expanded Polystyrene (EPS)

Polystyrene is the polymerization of the aromatic hydrocarbon styrene, a clear liquid which in certain conditions becomes a hard odourless resin [23]. This polymer can be used in its rigid format or foamed, when rigid it offers clear and hard properties, although it is brittle and offers a poor barrier to oxygen and humidity. It is a low cost material, and it has a low melting point [24].

Expanded polystyrene is produced through the impregnation of virgin polystyrene beads with a blowing agent, usually pentane. This impregnation is achieved through placing the beads in an agitated, pressurised container. Once the beads are fully soaked, the beads can be expanded using heat, by placing the beads in a sealed mould, and heating said mould, they expand filling the entirety of the volume, thus resulting in a finished, closed cell product [25].

Once expanded this foam benefits from a very low density, up to 98% of its volume being gas, while still having semi rigid properties. Its technical characteristics are easily moulded, easily cut, great resistance to compression, good impact absorption on the first impact, the reason why many helmets use it, high resistance to humidity, and temperature [11].

Recycling Polystyrene and Expanded Polystyrene is not only feasible, but a high studied concept, with many low cost solutions. Even under these circumstances its high volume to weight ratio and the lack of incentives for the recycling meant it was not being processed properly, Some studies suggest the collection and transport outweigh any potential environmental benefit [16]. This misuse meant it was found in marine ecosystems, and in 2019 the European Union banned the use of Expanded polystyrene in single use products [26].

Polyethylene foam (PE, EPE)

Polyethylene is one of the most, if not the most, commonly used plastics[17]. It is commonly used in the packaging sector, it is a material that is not recommended to be used when high precision is required or under high heat conditions. There are many categories of Polyethylene, many do not enter the subset of foams, as a foam it can be divided into two groups:

Non reticulated

To obtain this kind of foam the method of production relies on a gas, usually Isobutane, which maintains the chemical structure of polyethylene, it has great capabilities of returning back to its original shape after impacts,(quality that makes it very useful for packaging)., it is flexible, easily shaped or made into any shape, has great anti-vibratory, impact resistance, anti-static and even flame retardant qualities

Reticulated

These kinds of polyethylene foam are produced through chemical reactions using catalysts or even exposing the materia to high doses of Gamma rays. These processes generate a foam that has small closed cells, this kind of foam has good resistance to heat and even UV rays, although they become harder to recycle.

This foam is adequate for uses that require a certain level of watertightness, and for the production of thermoformed parts, they have low toxicity which allows for their use in many fields, such as medicine , toys, sports equipment...

Ethylene-vinyl acetate foam (EVA)

Ethylene-vinyl acetate (EVA) is a versatile copolymer known for its adaptability and unique properties. This foam is created by introducing a chemical blowing agent into the EVA polymer matrix, resulting in a cellular structure upon expansion[32]. EVA foam strikes a balance between softness and durability, making it an excellent choice for various applications. Its cushion-like feel and impact-absorbing qualities make it a popular material for shoe insoles, sports equipment, and protective gear. Moreover, EVA foam's ability to be easily shaped and moulded adds to its appeal, enabling it to conform to specific designs and contours[11].

EVA foam's inherent resistance to water, UV radiation, and chemicals enhances its utility across different environments. This resilience makes it a preferred option for water-related activities and outdoor equipment. The foam's closed-cell structure also contributes to its buoyancy, rendering it valuable in products like flotation devices and aquatic gear. Its lightweight composition and ease of processing have led to its usage in crafts, hobbies, and DIY projects. EVA foam's range of densities offers flexibility in tailoring its characteristics to match specific project requirements[11].

As the use of EVA foam grows, so does the concern about its recycling. While EVA is recyclable, the infrastructure for its proper recycling is still developing. Efforts are being made to repurpose EVA foam waste into new products such as flooring and padding for playgrounds, and even footwear[33]. Researchers continue to explore efficient recycling methods, including chemical processes, to address the challenges associated with managing EVA foam waste. As the industry focuses on sustainability, the attention given to the recycling of EVA foam becomes increasingly vital for a greener future.

Polyvinyl Chloride foam (PVC)

Polyvinyl Chloride (PVC) foam stands as a versatile material with a diverse range of applications. The creation of PVC comes from the polymerization of different vinyl halides[34] once done, this can be foamed by introducing a blowing agent into the polymer matrix, resulting in the formation of a cellular structure upon expansion. This foam exhibits a balance between lightweight flexibility and durability, making it suitable for various uses[11].

PVC foam's adaptability stems from its ability to exist in different forms, including rigid and flexible variations. Flexible PVC foam is recognized for its softness and cushioning properties, often seen in upholstery and padding applications. On the other hand, rigid PVC foam offers structural integrity and insulation capabilities, making it an excellent choice for construction and signage. This duality of characteristics positions PVC foam as a sought-after material for both comfort-focused and utility-driven applications[11].

PVC foam is known for its resistance to moisture, chemicals, and weathering, contributing to its durability in various conditions. The foam's closed-cell structure enhances its buoyancy, making it valuable in marine-related applications such as flotation devices. While PVC foam offers unique benefits, its environmental impact has been a subject of discussion. The production and disposal of PVC have raised concerns due to the release of potentially harmful substances[35]. Efforts to mitigate these concerns include exploring alternative formulations and recycling methods to reduce the material's environmental footprint.

2.3 Additive Manufacturing

2.3.1 Brief definition and history

Additive manufacturing is the term given to what is generally known as 3D printing. This way of manufacturing used to receive the name of rapid prototyping as this was its main purpose when it was first developed. It allowed the generation of reproductions before their final form was made, and put into production[36]. The concept of Rapid prototyping emerged in 1987 with the first commercial Stereolithography printer, created by 3D Systems[37]. The concept of rapid prototyping stayed relevant until the late 90's, where due to the changes in precision, and the lower prices, some products started to be wholly fabricated using 3d Printing processes, the term of rapid prototyping was no longer representative.

Additive manufacturing is a process where a file of a 3D model generated using Computer Aided Design is processed so a machine can fabricate the geometry into a real part[38]. This does not differ much from other processes such as CNC milling, which can also take a computer generated model/file and produce a part. The main difference with additive manufacturing is the parts are made through the addition of material in a layered way[36], instead of the subtraction of said material (fig3).

Working by adding material following the CAD model it allows for more intricate and complex geometries, even some that would, otherwise, be impossible to manufacture using other methods[39]. Advancements in additive manufacturing also mean a wide range of materials can be "printed", from materials like thermoplastics, resins and such to glass, ceramics, concrete and even a wide variety of metals, in some other cases, even food has been printed[40]. This capacity to print such a wide variety of materials, even in some cases mixing them, is thanks to the different methods and processes that are encompassed by the term Additive Manufacturing. In the next section the seven most important ones[41] will be briefly explained.

Figure 3: Additive manufacturing vs Subtractive manufacturing
Own work

2.3.2 Additive Manufacturing methods

Vat Photopolymerization

This method was the first to be developed in the world of Additive manufacturing, and the first commercially available system, known at the time as Stereolithography Apparatus (SLA)[37]. This method uses photocurable resins, which when exposed under a specific wavelength, usually UV light, supplies the energy needed to form the links between the molecules, thus curing the resin, and becoming a polymer[42].

To achieve this photopolymerization, as said before, the right wavelength of light needs to be applied. If what is desired is to generate a 3d model, this application of lights needs to be controlled, there are different methods of controlling/delivering the light, Laser based, Mask based, Volumetric Additive Manufacturing;

Laser based systems use a UV laser to cure the resin, this laser is controlled through the use of mirrors to aim it to the desired point, in the case of “2 Photon Systems” the laser is focused, as it would not carry enough energy when parallel[43]. Using lasers allows for very high quality prints, it also allows for large print areas, although in that case the quality is lower.[44] Although using a laser brings some benefits, the laser has to move to the different areas where a solid part is desired, this can result in slower prints.

In the case of Mask based the UV light is displayed to the resin using a technology very similar to Projectors and screens, in the case of the projectors a DMD (Digital Micromirror Device) is used to direct the light, some use LCD (Liquid Crystal Display) to mask the areas where light should not reach. This method exposes the entire layer at the same time, thus achieving faster print times[43]. Using this method can have lower quality prints, there are DMD chips and LCD screens which can achieve very high resolutions, due to the system using Pixel based technologies. To have the highest quality possible, the print area is greatly reduced[45].

One way used to even reach faster print times is through the use of CLIP (Continuous Liquid Interface Production). This technology uses a liquid interface, also called a dead layer, this layer allows for the continuous movement of the platform, as it is not required to separate the part from the vat, and move the resin to the now empty section[43].

The last method is Volumetric Additive Manufacturing, a much more experimental method where, with the aim of reaching higher speeds, the vat of transparent resin is exposed from multiple angles to the pertaining view of the model. The concept works thanks to having higher energy concentrations where multiple light sources collide[46].

Figure 4: Carbon SLS 3D printer

Material Extrusion

Material Extrusion, also referred to as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF), constitutes another prominent Additive Manufacturing technique. This approach involves layer-by-layer material deposition, akin to the gradual assembly of intricate structures. A thermoplastic filament, frequently wound on spools, serves as the primary material.

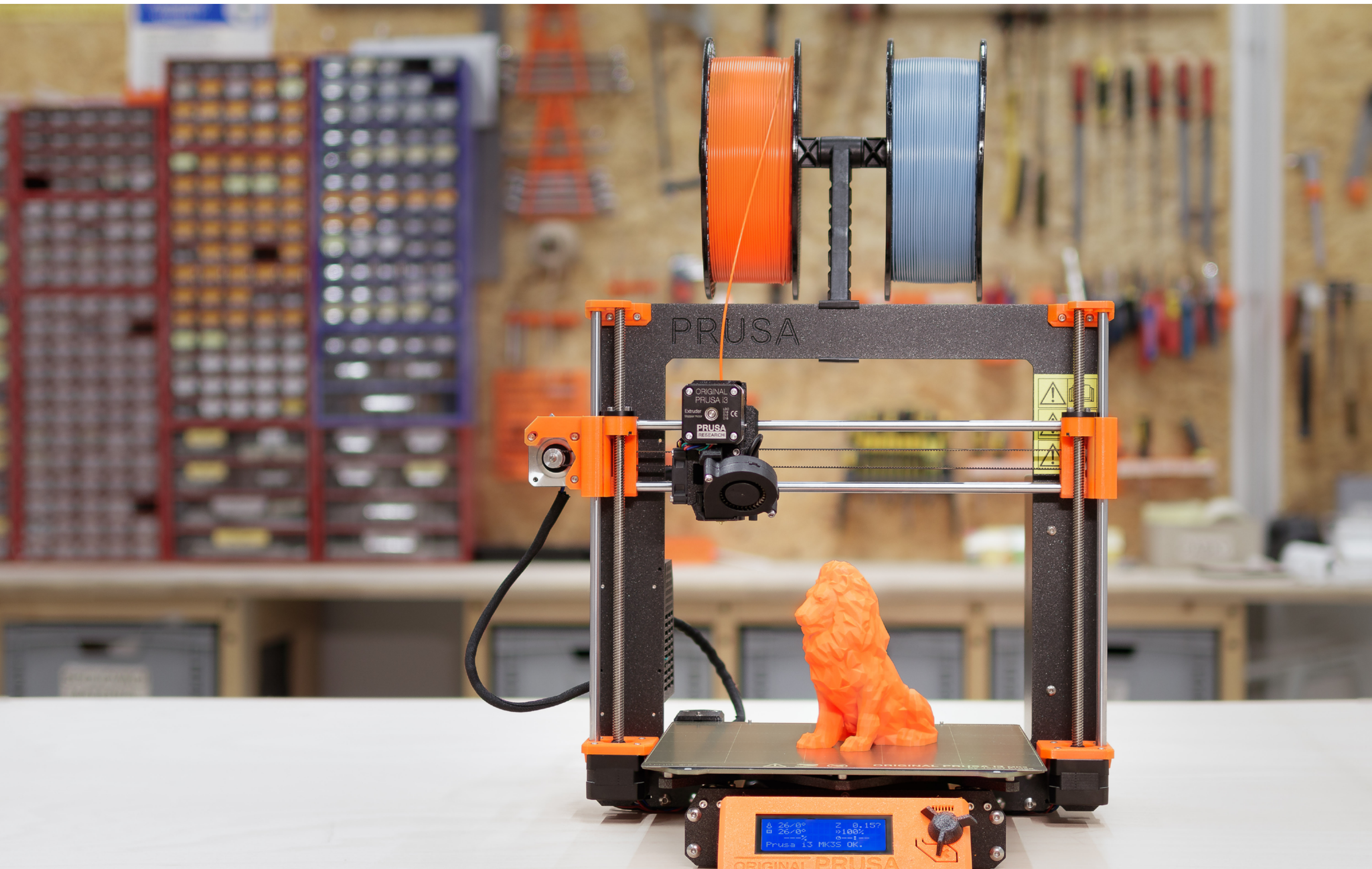
The extrusion process unfolds as follows: The filament is guided through a heated nozzle, where it softens and becomes pliable. The nozzle deposits the softened material in precise paths, tracing the design's contours. As the material exits the nozzle, it rapidly cools and solidifies, resulting in layer formation. This cycle recurs until the entire model emerges[61].

Material Extrusion supports an array of thermoplastics, encompassing ABS, PLA, PETG, and more[62]. Each thermoplastic variant presents unique properties, influencing factors like strength, flexibility, and temperature resistance. While diverse materials offer versatility, the underlying technique remains consistent.

Limitations of Material Extrusion are primarily attributed to layering, resulting in visible lines and anisotropic mechanical properties[63]. However, advancements like finer nozzles and refined slicing software have mitigated these concerns, enhancing surface finish and mechanical integrity.

This technique's accessibility and versatility render it a staple in various fields, from rapid prototyping to hobbyist creations. Though not as intricate as some other methods, Material Extrusion thrives in scenarios prioritising speed, cost-efficiency, and ease of use.

Figure 5: Prusa mks3+ FDM 3D printer



Binder Jetting

Binder Jetting has a similar functioning principle as Powder Bed Fusion, it does not use a beam to shape the powder into a final shape. What it does use is a powder bed where, layer by layer, a binder liquid is spread to the desired parts, then a new powder layer is placed on top. This process is repeated until the model is finished[54].

This method also uses a wide array of materials, at its beginnings the powder used was starch based, another powder used, as plaster based, bothe materials, which where used by the two forefront companies, used water based binders[54]. Soon after the patents expired, other companies took the process and developed other systems to print with different materials and binders[55]. The first materials used allowed for the production of models and volumetric prototypes, these parts, has limited structural integrity, and to achieve better properties, mainly to enhance the durability, the parts where soaked in resins, such as wood hardeners[56].

The newly developed mix of binders and powders, allowed companies to use materials such as PMMA as a powder and a liquid binder that chemically reacts with the PMMA, another option is the use of a wax based binder for parts used to fabricate casting moulds using the method known as Lost Wax Casting[54]. Another material used for the fabrication of moulds and cores is a mix of Silica Sand and a two part binder, this method outputs moulds for the fabrication of parts using the method of Sand Casting, which uses sand to shape the metal, once cold, the sand can be safely removed from the finished part.

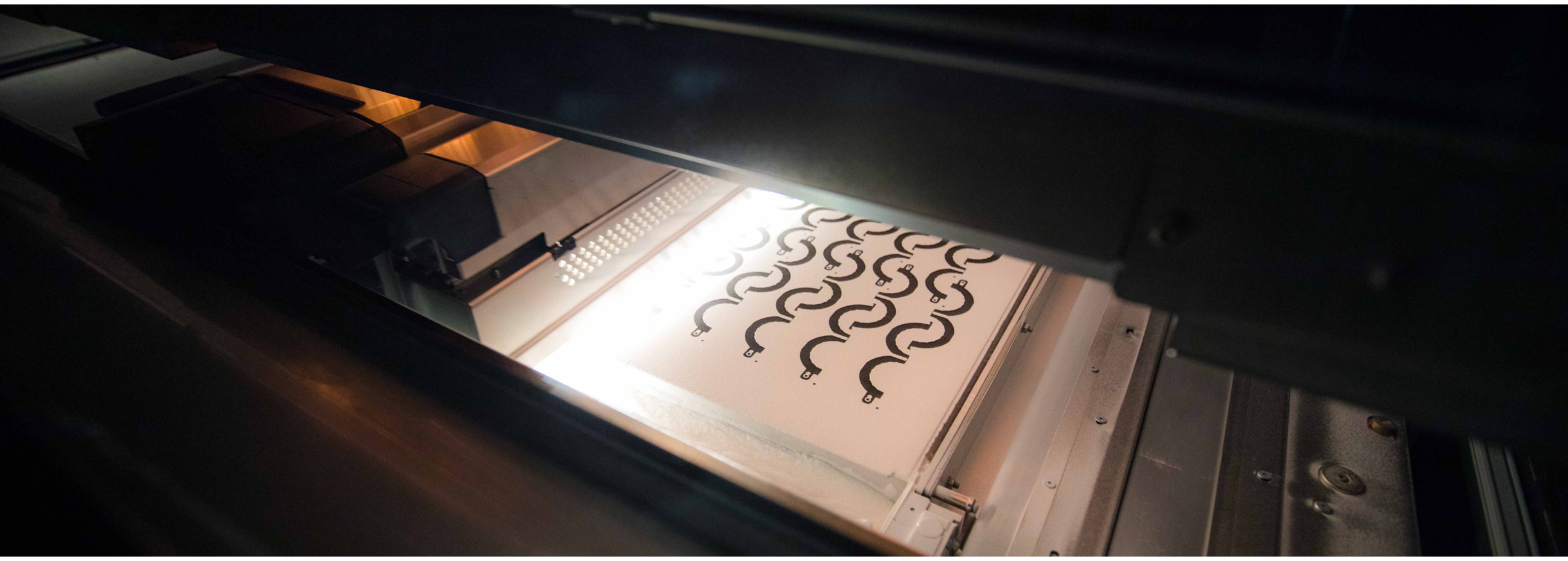
Other materials used are metal powders. This form of metallurgy allows the fabrication of geometrically complex parts which do not suffer from the mechanical issues found in sintered metals. This is achieved by using high melting metals as a powder, which are binded through the use of polymeric liquid binders, once the part is finished, the binders are burned off in an oven , following a gradual process, which ensures the metal powder remains stuck together once the binder is gone, finally the part is heated to a temperature right below the melting point of the powder used, together with another metal which has a lower melting point. This method ensures the second metal is liquified, which then infiltrates the model. A commonly used metal powder is steel, and the second metal used to infiltrate the part is bronze[56].

A similar process is used to create metal ceramic mixes, this is a more experimental method but it has been used to create composites for the fabrication of cutting inserts and highly technical models, in this case the final product is post processed using Hot Isostatic Pressing to achieve the best mechanical properties[56].

Some of the previous methods have had variations which allow for a wide range of requirements, the use of Local Composition Control allows the supply of different binders to the model to obtain tailored properties. From full colour prints using CYMK inks in the binder liquids, to customised metallic and magnetic properties. [56]

Powder Bed Fusion

Figure 6: Protolabs MJF 3D printer



Powder bed fusion uses a similar method as Vat photopolymerization, a laser is used to energise the medium which will be transformed into the 3D model. In this case, the way it is done is not through photopolymerization of a liquid resin, but through melting or partially melting a powder.

A laser system scans the areas which have been determined to generate the final volume, this laser heats up and fuses the powder to generate a solid layer. Once done, the bed lowers the amount defined by the layer thickness, and a system spreads and levels a new layer of powder. This process is done for each layer until the model is finished[47].

Powder bed fusion can be used to 3D print a large range of materials, from metals and ceramics, to polymers, and even natural materials, composites and glass[36][37]. While on paper the process can use a wide range of materials, one machine cannot do all of them, each set of materials, polymers, metals, ceramics, have different requirements which mean specialised machines must be used for each group[50].

Powder bed fusion can be divided into multiple sub processes, these have variations make them more suitable for different materials, results , and precision, Selective Laser Sintering (SLS) is one of the most commonly known processes, this method, heats up the particles below their melting point, which allows them to fuse together, it is used with some metals, alloys, and plastics[48]. This fusion can also be achieved chemically, the laser induces a chemical reaction between particles. This method uses lower temperatures, it is commonly used with ceramics, and a post treatment is used to increase the mechanical properties of the finished part[51].

When the method instead of heating the particles below their melting point, aims to melt them, it is called Selective Laser Melting (SLM). This process is commonly used with metals as it can achieve better mechanical properties through the melting of the powder. This process in some cases is used in a controlled atmosphere to reduce the oxidation of the materials[52]. It is also commonly post-processed through heat treating to achieve better mechanical properties and to reduce the mechanical stress induced by the temperatures[53].

Other variations of Powder Bed Fusion include Electron Beam Method (EBM) abd Direct Laser Metal Sintering (DLMS) each with its differences, does a similar work than the two previously described processes, EBM as its name suggest, does not use a Laser but a beam of electrons, controlled not by mirror but magnets.

Sheet Lamination

Sheet Lamination emerges as another facet in the realm of Additive Manufacturing, characterised by its distinct layering approach. Unlike previous methods, it employs sheets of material rather than liquid resins or powders. The method encompasses two notable techniques: Laminated Object Manufacturing (LOM) and Ultrasonic Additive Manufacturing (UAM).

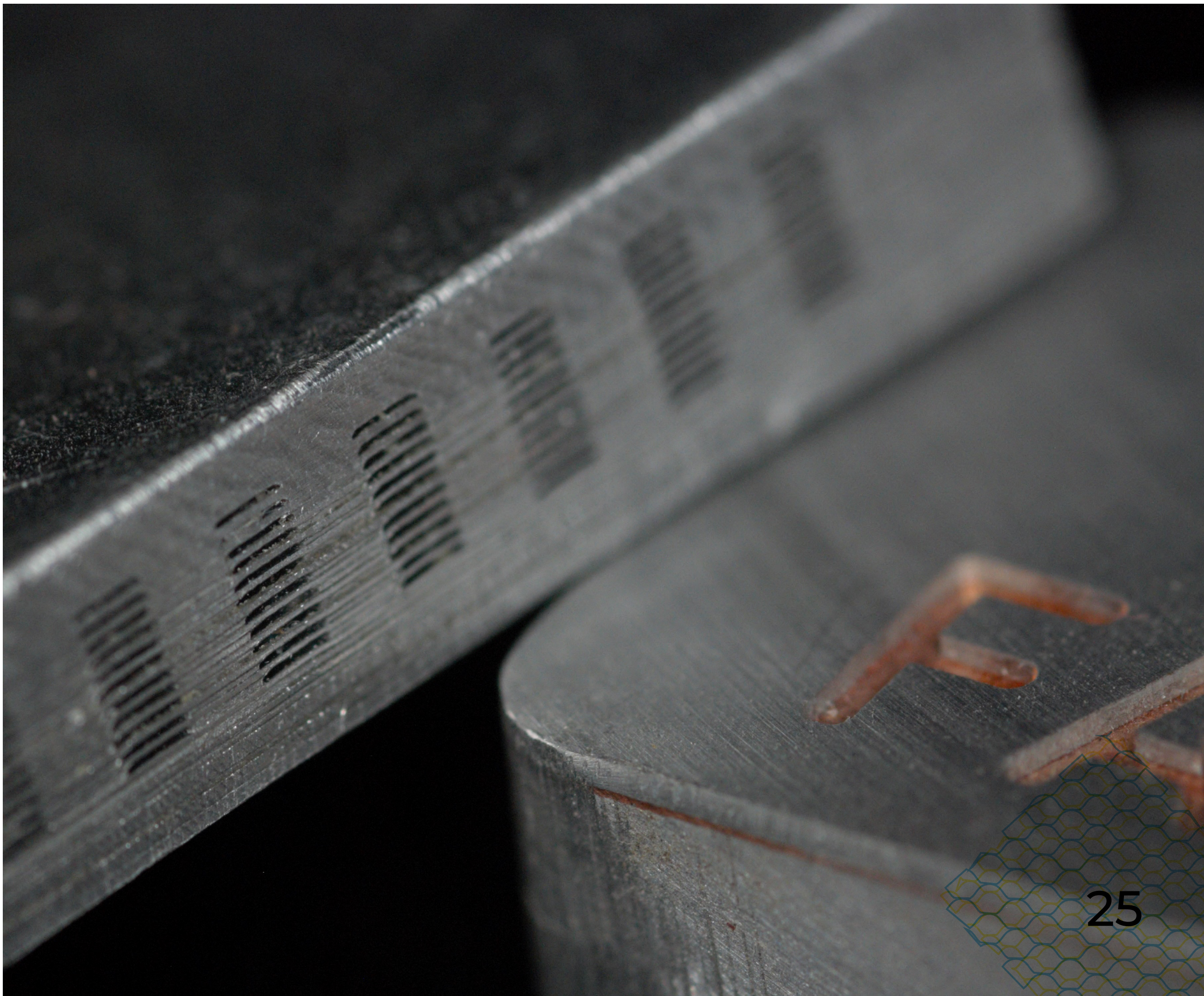
Laminated Object Manufacturing (LOM) orchestrates the creation of objects layer by layer through the assembly of sheets. Each sheet consists of material such as paper or plastic, which is then adhered using heat or adhesive. A laser or knife traces the design onto the top sheet, cutting out the desired shape. Once a layer is complete, a fresh sheet is added, and the process iterates until the object forms[67].

Ultrasonic Additive Manufacturing (UAM) employs ultrasonic vibrations to bond thin sheets of metal. These sheets are layered atop each other, and where welding is required, ultrasonic energy fuses the materials. The process is dynamic, permitting the inclusion of embedded components. These components are placed within the sheets before the ultrasonic bonding takes place, allowing for intricate designs[68].

Both LOM and UAM cater to unique applications. LOM primarily suits prototypes, models, and patterns due to its reliance on paper or plastic sheets[69]. UAM, on the other hand, finds its niche in metal fabrication, producing parts with exceptional mechanical properties and structural integrity[68].

In conclusion, Sheet Lamination provides a distinctive layer-by-layer approach, offering LOM for paper and plastic creations and UAM for robust metal components. Each technique serves a specific purpose, contributing to the diverse landscape of Additive Manufacturing.

Figure 7: Fabrisonic- **Ultrasonic Additive Manufacturing** Sheet lamination



Directed Energy Deposition

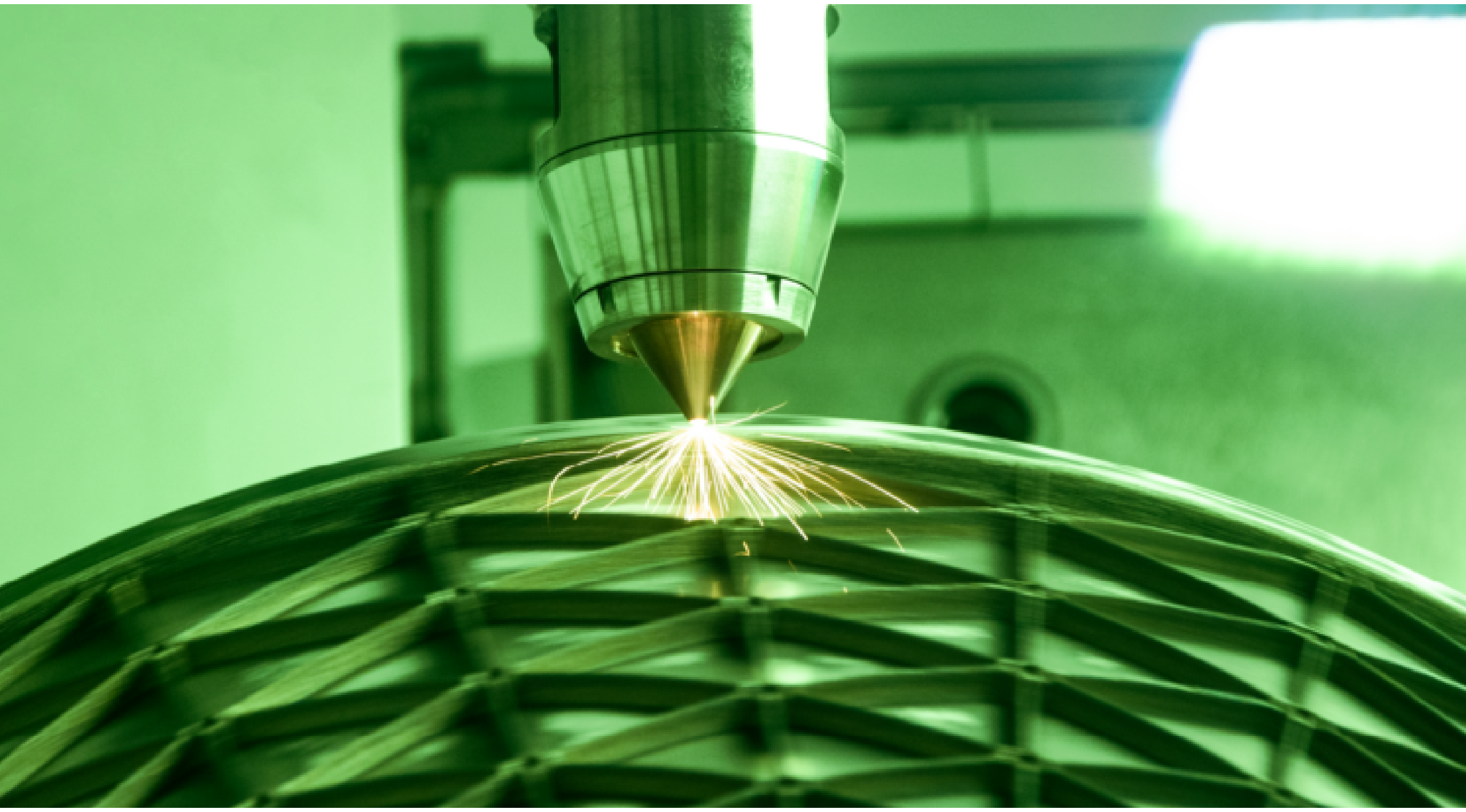


Figure 8: AddUp - Directed Energy Deposition

Directed Energy Deposition, or DED, emerges as another significant technique in Additive Manufacturing. DED involves depositing material layer by layer, guided by focused thermal energy sources. This versatile method caters to various applications, spanning prototyping to repair and production.

In DED, a material feedstock, usually in the form of powder or wire, is melted or sintered atop an existing substrate. Diverse energy sources fuel the process, such as lasers, electron beams, or plasma arcs. This technique stands distinguished by its adaptability to numerous materials, including metals, alloys, ceramics, and even composites[64].

Laser-based DED utilises laser beams to melt the feedstock material as it's added. This precise control allows intricate geometries and minimal material waste. Conversely, electron beam DED employs electron beams to achieve similar effects, often in high-vacuum environments. Both methods can fabricate large-scale components or repair damaged parts, exhibiting remarkable potential for aerospace and industrial sectors[65].

The benefits of DED include rapid build rates and minimal material waste, making it a cost-effective solution for certain applications. Complex, near-net-shape components are achievable, followed by secondary machining for precise tolerances[66]. Post-processing steps like heat treatments can further enhance material properties.

Moreover, DED finds usage in hybrid manufacturing, where additive and subtractive processes converge. This synergy leverages the strengths of each method, allowing intricate and functional end products. However, challenges persist in achieving consistent material properties, managing residual stresses, and optimising deposition strategies.

Material Jetting

Material Jetting constitutes another notable Additive Manufacturing method. This approach parallels Inkjet printing technology, depositing droplets of material onto successive layers to craft the final object. This technique offers exceptional accuracy and the potential for diverse materials, akin to Vat Photopolymerization and Powder Bed Fusion[41, p. 7].

In Material Jetting, print heads disperse liquid material in controlled patterns, layer by layer. These droplets solidify rapidly, fostering layer bonding. Unlike other methods, Material Jetting permits the use of multiple materials within a single print, enhancing versatility.

One prominent aspect of Material Jetting is its ability to produce intricate models with minute details. The fine resolution is attributed to the small droplet size achievable through modern print heads. The method can create objects with varying material properties, such as rigid and flexible segments within the same part, granting functional diversity[57].

Furthermore, Material Jetting facilitates the production of full-colour models. By integrating pigments into the liquid materials, the printing process incorporates vibrant colours directly, eliminating the need for post-processing painting. This is particularly beneficial for architectural models, product prototypes, and other visually intricate applications.

One challenge posed by Material Jetting is the requirement for material compatibility with the printhead and nozzle. Materials must flow consistently and not clog the nozzles to ensure smooth operation. Even with such restrictions there are multiple materials that have been able to be printed, from a variety of polymers to ceramics[58], [59]. Moreover, the need for support structures during printing to counteract overhanging features can increase material consumption and post-processing effort.

Despite its capabilities, Material Jetting may involve longer print times compared to some other methods due to the layer-by-layer deposition of droplets. This can be mitigated by using multiple print heads working in tandem to expedite the process[60].

In conclusion, Material Jetting stands as a precise and versatile Additive Manufacturing method, enabling the creation of intricate, multi-material, and full-colour objects. Its technology continues to evolve, enhancing its potential across various industries, from design and prototyping to production of complex functional components.

2.3.3 Method selection

Material extrusion, often referred to as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF), has been chosen as the manufacturing process for several compelling reasons. These considerations stem from both project constraints and the notable advantages associated with this method.

Accessibility: FDM printers are exceptionally accessible, with a broad range of options available, spanning from entry-level machines to more advanced models. This high degree of accessibility renders FDM technology an attractive choice, particularly among hobbyists and enthusiasts.

Cost-Effectiveness: FDM printers are renowned for their cost-effectiveness. Their relatively affordable price points make them a practical and financially viable option for individuals exploring the realm of 3D printing as a hobby or for prototyping purposes.

Materials Variety: FDM technology boasts a remarkable versatility in supporting a wide array of thermoplastic materials. This flexibility empowers hobbyists and creators to experiment with various material properties, colors, and finishes, thereby expanding the creative possibilities.

Ease of Use: FDM technology is lauded for its user-friendly nature. Operating FDM printers does not necessitate extensive technical expertise, and many of these printers come equipped with intuitive and user-friendly software, streamlining the printing process.

Versatility: While FDM may have certain limitations in terms of surface finish and mechanical properties when compared to other advanced manufacturing methods, it still offers a remarkable degree of versatility. This adaptability enables the creation of functional and aesthetically pleasing objects, which is especially advantageous for prototyping and personalization.

Online Community and Resources: The widespread popularity of FDM has cultivated a thriving online community. This vibrant community serves as a valuable resource, offering a plethora of tutorials, pre-designed models, and troubleshooting advice. It fosters a collaborative environment in which hobbyists can exchange knowledge and expertise.

This collection of benefits underscores the democratic nature of FDM technology, enabling individuals of varying skill levels and backgrounds to engage in the process of creating protective gear, from the initial prototyping phase to the final product. The feasibility of printing protective gear using hobby-level machines has the potential to revolutionise the industry. It paves the way for an innovative concept where consumers may not purchase ready-made protective gear, but rather acquire the digital blueprints for personalised protection. This paradigm shift can usher in a new era of online services that empower users to generate highly customised protective gear, which they can then print and assemble themselves. Such an approach holds the promise of reducing steps in the supply chain, including international transportation, and fostering a culture of self-sufficiency and personalization in protective gear manufacturing.

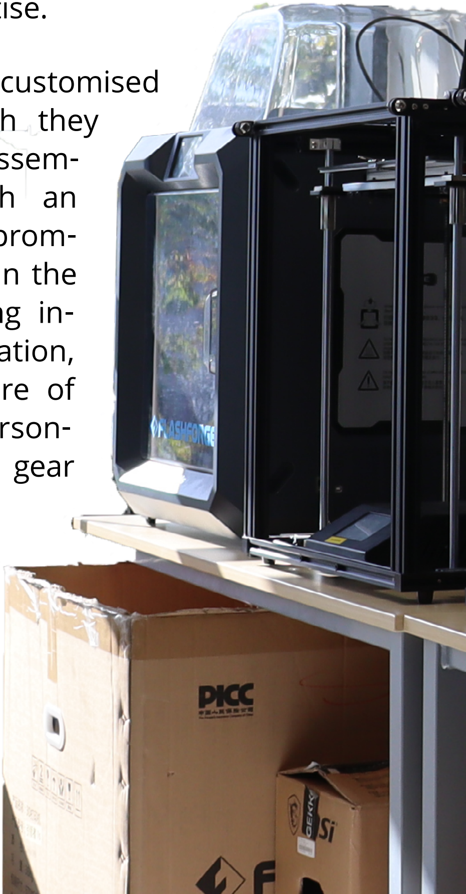
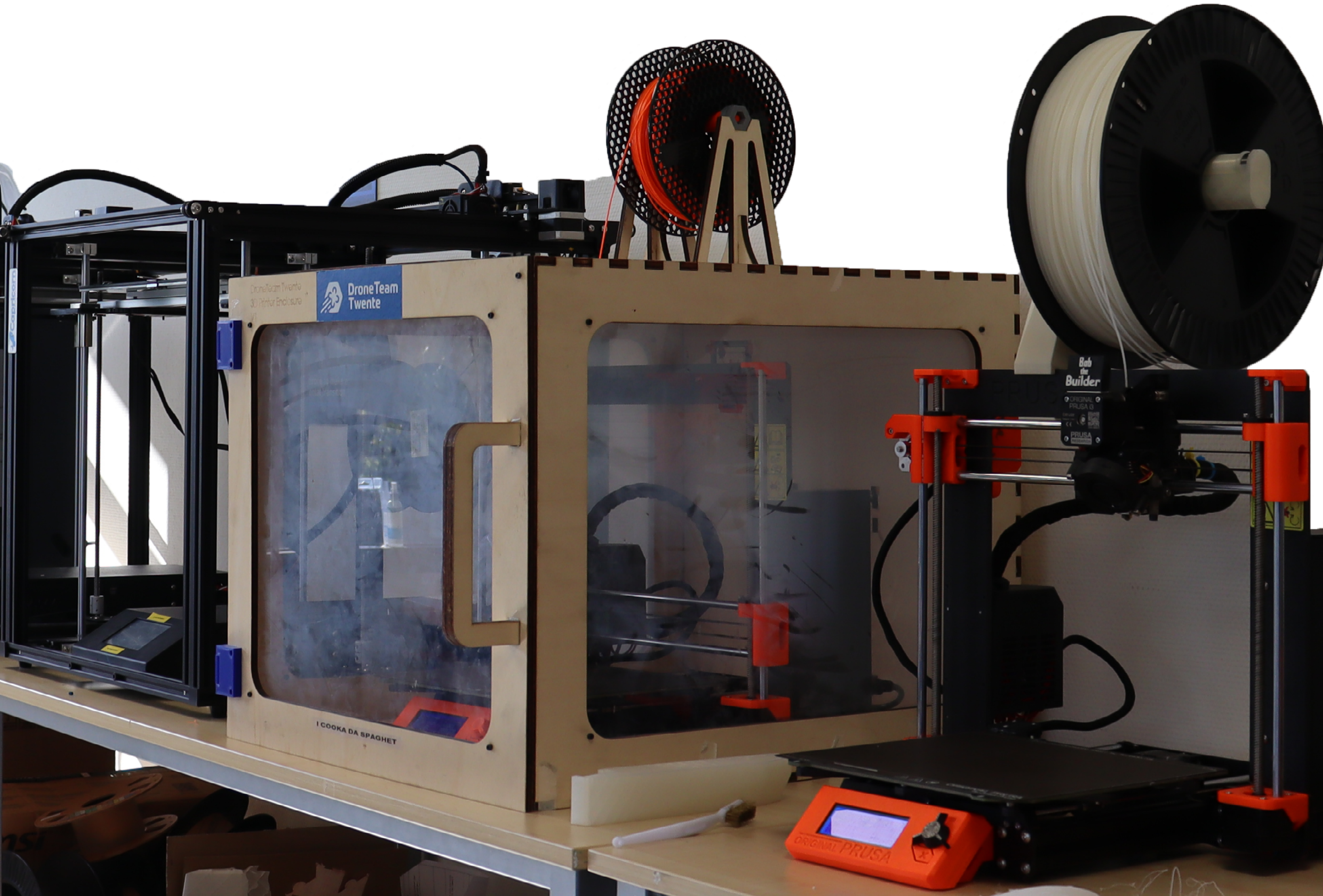


Figure 9: Drone Team Twente's printer Farm
Own work


DroneTeam Twente
I COOKA DA SPAGHET
Bob the Builder
ORIGINAL PRUSA

2.3.4 Material

After selecting the method of production, the available quantity of usable materials has been reduced. Not only are there material constraints due to the project's objectives, but there are also process-related constraints. The materials under analysis will be those suitable for filament format, designed for extrusion.

This analysis will focus on various flexible materials. It's essential to note that brands may include certain additives to alter colour or improve printability. The analysis will provide insights into each material, along with a brief list of leading brands and the price per kilogram of filament as of August 2023.

TPEs are a class of polymers that blend the characteristics of rubber with those of thermoplastics, thus theri name of **Thermoplastic Elastomer**. They are renowned for their flexibility, elasticity, and soft texture. TPE filaments are ideal for creating objects requiring both durability and flexibility, such as phone cases, shoe soles, gaskets, and grips. Many online 3D printing shops may market various materials like TPU, TPC, TPS, etc., alongside TPE, even though TPE represents the material family.

TPC filament is made out of **Thermoplastic Copolyester**, this thermoplastic offers a balance between flexibility and strength thanks to its Copolymeric build[70]. They are often used in applications where toughness and chemical resistance are important, as it shows great resistance to oils and other chemicals[71]. TPC filaments can be used to print parts for automotive components, industrial equipment, and consumer products. However, TPC is considered an engineering material[72], which means it is not very common in shops and the amount of information available to solve any issues while printing is rather lacking. Another issue with engineering materials is their price, a 0.5kg roll of TPU can sell from around 30€[73] to over 65€[74].

TPU filament,made of **Thermoplastic Polyurethane** is a flexible and elastic material with excellent wear and tear resistance[75]. It is widely used for creating objects that require both durability and flexibility, such as medical devices, automotive parts, and athletic wear. TPU filaments are known for their ability to stretch and return to their original shape. TPU is the most commonly used filament, as it is one of the easiest flexible filaments to print with. It offers great layer adhesion, and as a widely used material, it is very easy to troubleshoot any printing issue. Another benefit for it being widely available is its price, as it is easy to find 1kg rolls for around 20€ and up to 70€[76]

TPA filament is a **polyamide based thermoplastic** mixed with an elastomer, it has very similar properties to TPU. TPA is known for its flexibility and strength, making it suitable for various applications. It also exhibits excellent resistance to oils and chemicals. Like TPC, TPA is considered an engineering material and may not be as readily available as TPU. Prices can vary, with a 0.5kg roll of TPA typically ranging from 30€ to 65€.

TPS also known as **SEBS(Styrene-Ethylene-Butylene-Styrene)** is a type of thermoplastic elastomer which combines the properties of rubber and plastic, this is thanks to its copolymeric build[77], making it suitable for creating soft and flexible objects, as a material it has very low moisture absorption[78] which make it the optimal material for applications like medical devices, and soft-touch grips, or any anti slip surface.

PEBA (Polyether Block Amide) is a flexible and strong material with good chemical resistance[79]. It's often used in applications where a combination of elasticity and mechanical strength is needed, as a material it offers high energy return and very high tear resistance. PEBA filaments can be used to create products such as sports equipment, seals, and medical devices. This filament is a highly technical material, the only producers of 3D printing PEBA filament are Flexfill and Kimya, which sell 0.5kg rolls at a price of 85€ and 50€[80] respectively.

2.3.5 Material selection

When considering material selection, several key factors come into play. The available materials often exhibit similar properties, including resistance to chemicals and even shore hardness. However, there are essential criteria to weigh when making a choice: availability, affordability, and the availability of information. These factors collectively contribute to the decision-making process. Nevertheless, it's important to note that for the purposes of this thesis, which focuses on generating a structure, virtually any material from the last section could be utilised

The material of choice in general is TPU (Thermoplastic Polyurethane), and this decision is influenced by several compelling factors. TPU is a well-known and widely used material within the 3D printing community. It boasts ready availability, which means it can be easily sourced from many online shops. Moreover, TPU is relatively inexpensive, making it cost-effective for a range of projects. After having selected the material, the Shore hardness which will be used must be selected.

Shore hardness, measured on the Shore durometer scale, is a standard metric used to assess the hardness or stiffness of materials, including filaments. The scale ranges from 0 to 100, with higher values indicating greater hardness, then the number is followed by a letter which indicates the scale it refers to. Conversely, lower values on the scale represent softer and more flexible materials[81]. In the case of TPU there are certain brands which offer TPU of Shore hardnesses of up to 75D (Armadillo by Ninjatek[82]) and as low as 60A (Filaflex 60A by Filaflex[83]).

In the case of TPU 95A, it indicates that it is moderately flexible and exhibits a balance between softness and rigidity. It is an ideal choice for applications that require a degree of flexibility while maintaining structural integrity. In summary, TPU 95A is a popular choice for 3D printing due to its moderate flexibility, widespread availability in online shops, affordability, and the abundance of information and resources available for troubleshooting and printing with this material. Its 95A shore hardness rating signifies a balanced level of flexibility and stiffness, making it suitable for a wide range of applications.

The chosen TPU is the **Overture TPU 95**A as it is easily found in websites like amazon at an achievable price of 23€[84]. This material has over 400 excellent reviews which reaffirmed the choice of material as it is one that can be bought by anyone .

2.4 Architected Materials

Architected materials, also known as architectured materials, modify the physical and mechanical properties of structures due to their unique topology and geometry, which were initially observed in natural foams and cellular materials like bones and corals[85]. These materials showed special properties, such as lightweightedness and even controlled mechanical properties through the topology of the structure. Imitating these natural materials led to the development of artificial lattice structures.

Artificial lattice structures have a very crucial physical property, relative density. This density is given by the ratio between the volume of the lattice and the volume of the box which bounds the entire structure. This relative density is used to characterise the architected materials as a foam or a lattice, as their mechanical properties are modified. Materials with a low relative density of less than 5% are considered foams, these show elastic nonlinear behaviours. Materials with relative densities between 10% and 50% are defined as lattice structures, these depending on the geometries of the lattice, material, and relative density may be used for energy absorption or even structural applications. Materials with densities above 60% have properties close to solid objects.

Not all architected materials are equal, the way their structure is composed, even organised, can mean different properties and ways of being produced, it is why it is necessary to classify them. This classification is based on their topological characteristics (add a figure). The initial categorization is based on the periodicity of the struc-

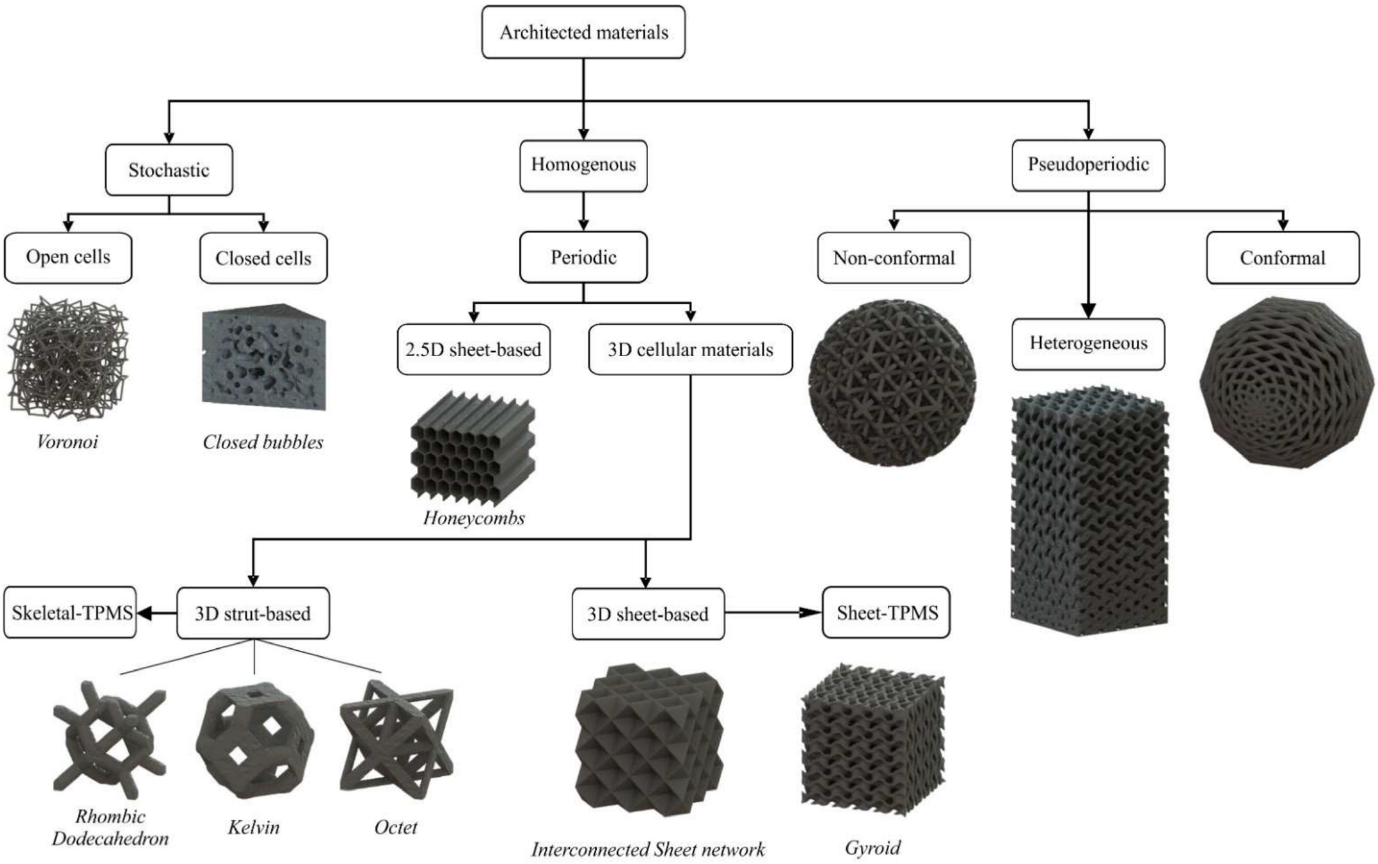


Figure 10: Classification of architected materials based on the geometry

ture, thus resulting in stochastic, homogeneous or periodic, and pseudo-periodic.

The architected materials in the stochastic family are those with a cellular structure that is non repeating, they do not have a unit cell. Any natural architected material is stochastic. There are limitations of stochastic materials, this is achieved by using randomised topological algorithms like Voronoi, and Delaunay. Stochastic materials have a distinction already explained in section 2.2, open cell and closed cell, although closed cell is the most common in stochastic materials.

Periodic, or Homogenous architected materials are the second group, and the most common one, as their periodicity means the cell unit can easily be repealed in 3 dimensions. Having the same cell unit also allows for predictability, the mechanical properties are equal everywhere. Periodic architected materials are subdivided in 2 groups, 2.5D and 3D. 2.5D structures are, in their most simplified way, an extrusion of a 2D shape. Examples of it are the honeycomb, which is widely used in the fabrication of lightweight sandwich structures. The 3D Periodic materials consist of a cell unit composed of struts or sheets interconnected, these units generate a network or in case of the sheet units they generate surfaces.

Sheet lattices are separated into shell lattices and Triply Periodic Minimal Surfaces (TPMS). Shell lattices are obtained when plates or surfaces are placed in determined positions, these often come from the modification of the strut structures. TPMS are generated through the use of trigonometric equations. These equations result in geometries which at any given point of the surface the mean curvature is equal to zero. Thus resulting in structures with higher surface area than their volume.

Pseudoperiodic architected materials consist of the same distinction between 2.5D, and 3D, the only difference is the application of variations in the cell, these being size based. Or by interacting with the boundary of the overall geometry. The first case generates a relative density variation, this kind of structure is called a functionally graded structure, they are used for distributing the loads received in a uniform way. The second case is given when the cells interact with the boundary, this being by being interrupted, or by modifying the shape to accommodate for the boundary[86].

3. Design and Testing Phase

3.1 Constraints

Constraints in design encompass three fundamental aspects. Manufacturing constraints stem from the available technologies, production speed, and technological feasibility. These dictate the practicality of realizing a design. Material constraints hinge on the inherent properties and characteristics of the materials deployed in a product's construction, impacting durability, weight, and performance. Design constraints, in turn, influence the creative and functional elements of a design, imposing requirements that affect aesthetics, ergonomics, and overall functionality. Together, these constraints shape the boundaries within which a design must operate, challenging designers to innovate and create while respecting the practical limitations set by manufacturing processes, materials, and design requirements.

Figure 11: 3D printed back protector
Own work

3.1.1 Manufacturing process

The manufacturing process will affect the resulting design, as there are constraints dependent on the process, in this case as it has been selected in section 2.3.3, Material Extrusion. This method consists of the controlled extrusion and placement of a material through a nozzle, this nozzle is aimed through controlled movements in the X, Y and Z axis. Another factor that will affect the constraints is the machinery used, there are printers which, through the use of clever solutions, solve certain issues inherent with the method. These solutions come at a price, economical as well as in the form of a reduction of available information.

Printers

In the case for this project basic hobby level printers will be used, the reasoning behind this choice is not only the availability to anyone trying to reproduce the project, but even for the production of test samples for this project. The selected machines are a **Creality Ender 5 Plus**[87] and a **Prusa i3 MK3S+**[88].

Figure 12: Creality Ender 5 Plus

Figure 13: Prusa i3 Mk3s

The Ender 5 offers a large print volume, as it has a bed size of 350x350x400mm, it uses a Cartesian frame, where the print head moves in the X and Y axis, while the bed moves on Z axis, the nozzle is fed through a bowden tube, as it does not use a direct drive.

The Prusa i3 is a smaller printer than the Ender 5, it offers a printing volume of 250x210x210mm, like the Ender 5, it also uses a Cartesian frame, although in this case, the nozzle moves in the Y and Z axis while the bed moves along the X axis. This printer uses a direct drive, which means the material is directly fed into the nozzle.

3.1.2 Material

The material limitations that will be explained in this section are not the Physical limitations of the material, nor are due to the mechanical properties of it. The limitations under focus are those that will affect the printing process.

The first common issue with TPU is the extrusion itself. It is very important to set a proper extrusion, or feed rate. TPU is an elastic material, meaning it can compress easily which in turn results in the nozzle extruding or better said, oozing filament when not required. In this case the print will have stringing issues. Similarly when the feed rate is too slow, the print might have under-extrusion issues, resulting in bad layer adhesion.

In the same line of issues, TPU is a hard material to dial to allow for retractions. Retraction is the action the printer does to reduce pressure on the molten material inside the nozzle. This action serves the purpose of stopping the nozzle from extruding material during travel between sections. TPU as it is elastic requires very long and fast retractions, meaning it will also require fast movements to bring the material back to the nozzle to start extrusion on time. TPU is usually printed, as it is recommended. Using direct drives, as the bowden tube makes it even harder to dial the retraction.

TPU is a material with very good layer adhesion, this is not a limitation, constraint or issue, it is a very good feature. It is, although, a limitation when paired with the retraction issue, and when designing “removable” parts such as supports. The use of supports with TPU is not recommended as they are harder to remove than normal due to the poor retraction and the good layer adhesion.

The final detrimental characteristic of TPU is, as any other flexible filament, is its printing speed, flexible filaments require slow printing speeds below 30mm/s. Such slow speeds mean that the material extrusion method will result in slow and long prints.

3.1.3 Design

Design limitations/objectives are the ones determined by the intended use of the design. In the case of this material the intended purpose is its use in sports protective equipment which, as much as protecting their user they must allow for comfort and mobility.

Impact protection is the main objective of this material. It must absorb an impact and rebound to its original shape ready to receive any other impact again. This impact absorption will be tested in a similar manner to the test foams for impact protection, and should result in similar enough results as any other. That the material shows similar results as other foams does not mean any protection will also do as well, any protection should pass the proper tests determined for their use.

The material must be comfortable to wear. This means the user should maintain mobility while wearing it. This can be achieved in various ways, the first one is by maintaining the dimensioning a protection already has. If the new material requires a larger thickness it will interfere with the user's mobility. Not only this interference, but, certain sports have thickness limitations on their protective equipment (ex Rugby….). The protection must also allow for movement, if the material results in higher stiffness, the athlete can see their mobility reduced, thus hindering their ability to perform.

These past constraints are those that can be observed in any other protection, making a material from scratch it is interesting to explore other constraints which could add to the features of the protection in benefit of their user. A feature which could benefit the wearer is breathability, during and while performing any sport related activity, the human body generates large amounts of heat. This heat is usually dissipated through the evaporation of sweat, if the protective equipment does not allow for the easy evaporation of sweat the wearer can see their performance hindered[89].

In this case, the material should allow for this dissipation. This should be achievable by allowing through and through access from the outside face of the protection to the inside face, or the one in contact with the user.

This breathability should not affect the comfortability of the user, if the gaps generated to allow this flow can be felt by the user. Or even dig in to the user when an impact happens, this will affect how comfortable the user is when wearing it.

Finally, the resulting structure should be programmable, by doing small changes in their structure the properties should change to the ones desired. This programmability should be as easy to do as possible, if to achieve different properties the structure has to differ from the original it will be too complex, and too many factors might enter in play. The differences should be small but meaningful.

Manufacturing Constraints

The two printers that will be used for the manufacturing of the samples are extremely basic in their features, meaning the design of the material must account for the limits of these machines. The limits, or constraints of this method, are very common in 3d printing. The first constraint to take into account is overhanging structures, these are any parts of a geometry that find themselves floating without any support. The way FDM 3D printers work is by depositing material on a surface thus drawing a 2D shape, by repeating this process the part is generated. This method works fine when the new material is supported by the material underneath it. Any face with a negative angle larger than 45 degrees can and will suffer from lower quality. Thus requiring supporting structures. Other features, like bridges, can in certain cases be self-supporting; this is dependent on how fast the nozzle is moving, and how fast is the material cooling.

When overhangs are a necessity, a solution that makes them printable is the use of support structures. These structures, which act as a scaffold are sacrificial pieces printed at the same time as the final parts. Although these parts are printed at the same time, they are designed to be easily

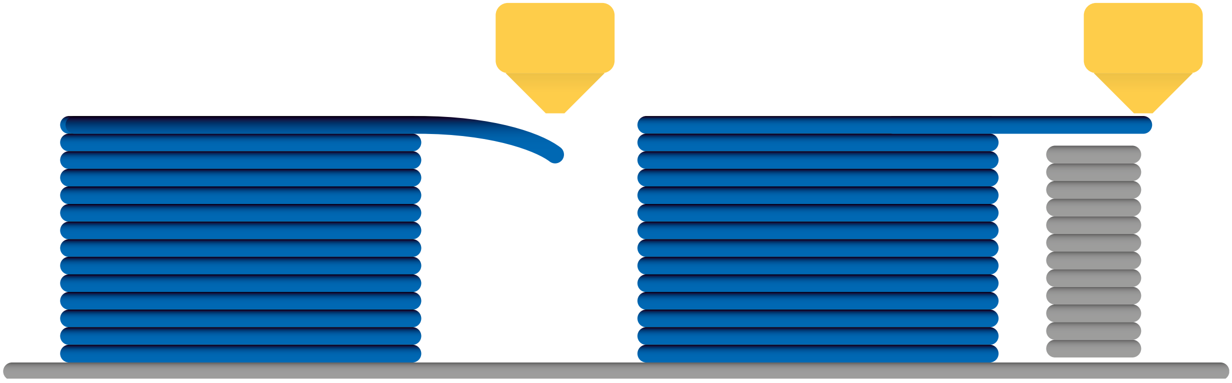
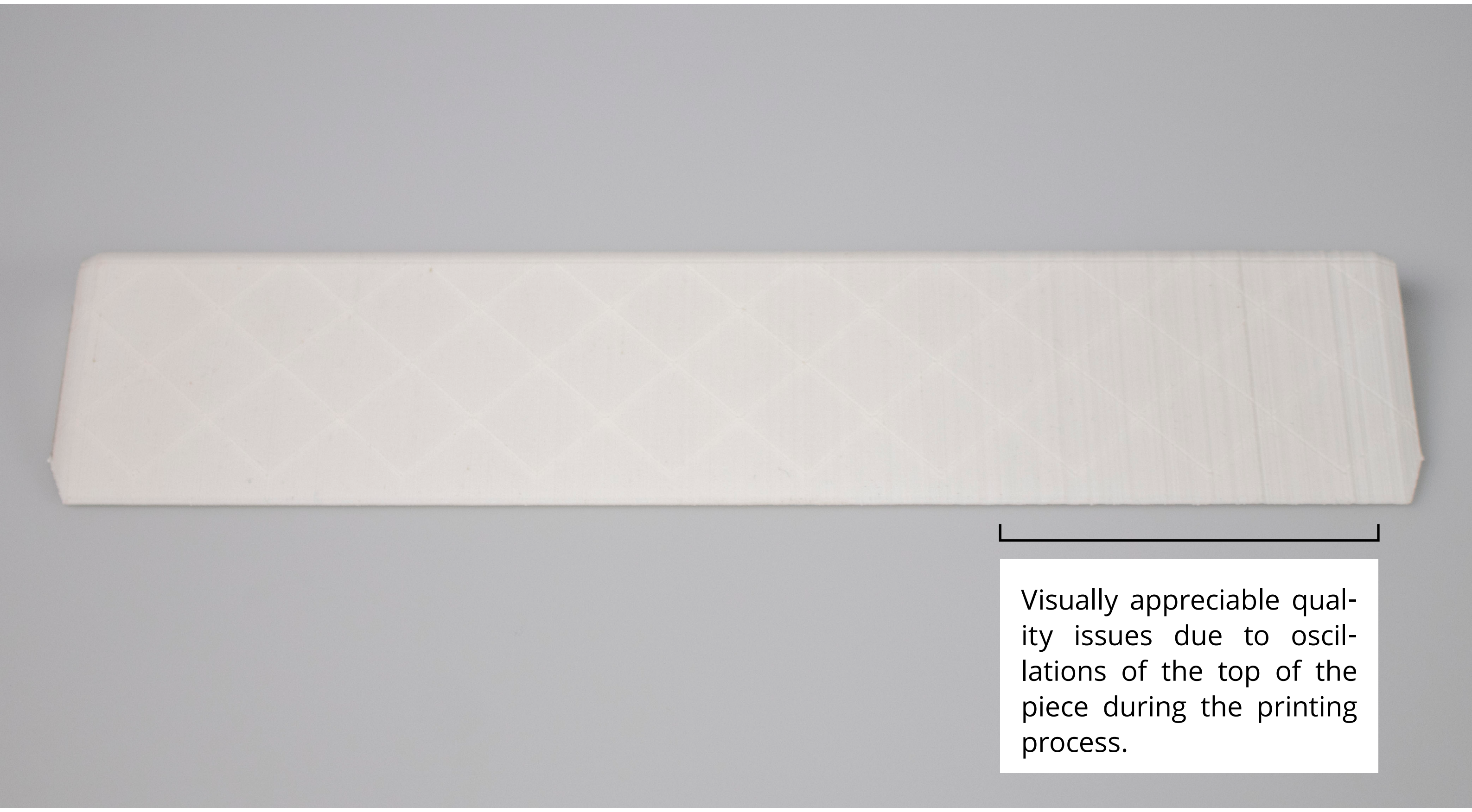


Figure 14: Unsupported overhangs vs supported overhang
Own work



Visually appreciable quality issues due to oscillations of the top of the piece during the printing process.

Figure 15: Discarded aileron, wobbling low quality related issues
Own work

removed(fig14). The removal of support parts is a post processing step which can vary in difficulty, this can be due to the ease of access to the supports, to how fragile the supported structure is. Even when the removal is easy, traces to the surface of the finished part can be easily seen, as support structures can leave rougher finishes.

One way it is possible for FDM printers to reduce the manual labour of removing the support structures and the effects of the supports on the surface finishing. This method is the use of soluble support materials, such as PVA. Using these materials the finished part can have the supports removed by placing it in a dissolvent, in case of PVA, water. This method allows for the design and production of highly complex structures or geometries, as removing the supports is not dependent on the access to them. To print using soluble supports it is required the use of multimaterial capable printers, this meaning multi nozzle capable, or the capacity of swapping materials automatically.

Another issue with FDM 3D printers is the direct contact between the nozzle and the printed part. This contact is, nearly, an unnoticeable factor except when the part is tall and thin, in that case the dragging of the nozzle while adding new material to the part can pull and move the highest part of the piece. This movement may not be consistent, thus affecting the geometry and event induce layer shifts the higher the print goes. As it can be observed in fig15 this piece is a high and thin component, with a very low infill, in this case the printing material is LightWeight PLA, which foams up to reduce its density, even in that case the entire part is rigid enough to not bend easily.

A way this is normally solved is by finding better printing orientations of the piece, when that is not possible, the control of the speed the nozzle moves can help mitigate the effects on the part. This last option can help on rigid materials, but when using soft materials, these issues are multiplied.

3.2 Benchmark

Before starting the generation of an architected material, now that the constraints are known, it is important to see what accomplishes them, and which ones do not, so that they can be used as inspiration for the design of the material. This benchmark will use the categories defined in point 2.4.

3.2.1 Periodic

Periodic structures are easier to model from naught, afterall the structure is repeating all throughout the material. This simplicity and repeating of the structure results in the material having similar mechanical properties all throughout it. This group is divided into 2.5D Sheet Based materials and 3D materials.

2.5D Sheet based

Sheet based 2.5D architected materials are based on the extrusion of a 2D design, this is an oversimplification of this structure or material, not all 2.5D lattices are done by extruding a 2D design, as one of the most common structures for sandwiched panels uses a honeycomb structure made by joining sheets of a material. Paper, plastic, or even metal, in a determinate way.[90]

Such 2.5D structures, more often called honeycomb, offer what is known High out-of-plane stiffness and strength, while on the in-plane stiffness and strength are reduced by various orders of magnitude. This property allows them to be used in sandwich materials as they offer great strength at very low densities, as long as the forces are applied on the out-of-plane axis.

By modifying the 2d pattern different properties on the In-plane axis can be changed to achieve different reactions when a force is applied to the material. By modifying the shape, size, and arrangement of cells, it is possible to optimise the structure's mechanical properties, such as shear strength and yield strain. Cellular structures with negative Poisson's ratios can be designed to have high shear flexure properties. These structures exhibit a unique behaviour where they expand laterally when compressed and contract laterally when stretched. This property allows them to withstand shear forces more effectively.[91]

Due to the way these materials are made, the cells do not close on the out-of-plane axis, this means air, or any fluid can easily move through it. This means as long as this material is placed on this axis they will be breathable. Having the material form sheets on the out-of-plane axis means it is self supporting, thus resulting in an easily 3D printable material. This feature al so means it is easier to model, as one only needs to design the cross section of the material.

3D

3D based lattices can be split in two sub groups thes distribution is based on the topology that forms the cell unit. This distinction is on Strut based cells and Sheet based cells.

Strut Based

Strut based are those in which the cell is composed of what is called a strut, this is a line which connects two points, when multiple lines connect together they can generate stiff structures. A common example for strut based structures are railroad bridges(photo). In the case of architected materials this kind allows for a material that reacts to forces the same way whatsoever the direction the force is applied from. A large difference from the past 2.5D material. This strut based construction makes for a very porous material which allows for a high amount of breathability, also in all directions. Due to the way the cells work, using the struts, the density tends to be quite low, thus to generate a high enough density the scale of the cell needs to be small or the struts need to be very thick.

Strut based architected materials are hard to print depending on the scale or the method, as the method used for this project is material extrusion, this material is very hard to print. At a small enough scale the struts may be too thin to support themselves thus wobbling or not even being able to connect with the next cell, if the structure is made too big the struts may become uncomfortable for the user.

Sheet Based

Sheet based 3D architected materials are similar in concept to the strut based, the way the cells work is by being composed of planes, not struts, these planes when interconnected they form sheets. These materials can have closed or open cells, and like the strut based, the material offers the same properties in each direction. Due to being sheet based, and the possibility of having open or closed cells the breathability of the design is dependent on the unit cell.

This variability on the cell structure can also mean two other things, it is harder to model as again, cells need to interconnect, this might be very difficult to generate, as usually co plex mathematics are used to ensure the cells will interconnect properly, the second thing is that this models tend to have higher density as the sheets form entire surfaces of material.

Having entire surfaces of material means it may be, depending on the geometry of these, easier to print as the material is self supporting, as long as the angles and geometries are below those where supports are required.

3.2.2 Pseudoperiodic

Pseudo-periodic architected materials are those which have variations on their cell structure, 2.5D and 3D materials can be pseudo-periodic. Thai is due to that adding differences like, cell size, distribution or even shape, result in converting it into this family of materials.

This family of architected materials are harder to model initially as variations in the cell structure will carry large sets of variations on testing the samples. This does not remove the fact that having different properties in the material is not an interesting feature.

3.3 Design ideation

Design ideation is adding up all the information obtained to generate the idea that will shape the project from this section forward. The design must be feasible using the material and the method, thus generating a design which uses the selected concepts should, in theory, result in the best design for our needs

The easiest design to generate and manufacture is those based in 2.5D sheet based materials, although they offer the largest amount of benefits, a modification will be needed to allow for lower stiffness in the out-of-plane direction as this will allow for the fabrication of slim parts without having to fight any wobbling issues.

Designing a pattern which consists of simple lines can allow for faster printing and better results, as there should be virtually no travelling or retractions, which as stated, are common problems with flexible filaments. By making thin lines the density or cell size can be made quite small resulting in a comfortable and breathable geometry.

The base idea is to use a wave-like shape which interconnects with the previous lines and the next ones, thus generating a mesh like layer which when piled upon itself should be able to generate a geometry.

It is important to determine the correct wave shape as one that is too long can have too many contacts in the line resulting in stiffer meshes. Such shapes can also become harder to print if they are not properly supported.

3.4 CAD Software

Rhinoceros is a versatile 3D modelling software widely employed in diverse industries, including architecture, industrial design, and engineering. It facilitates the creation, analysis, and translation of intricate 3D models. Users can utilise Rhino to either build 3D models from the ground up or seamlessly import models from other software applications.

Complementing Rhino, Grasshopper stands as a visual programming language and plugin designed explicitly for Rhino. Grasshopper empowers designers and architects to develop complex parametric models and algorithms without the need for conventional coding. The core concept behind Grasshopper is data flow, where information is passed between different components or nodes, each of which performs distinct operations on the data. Users have the flexibility to craft custom components or leverage a vast library of pre-existing ones available through plugins, substantially expanding Grasshopper's functionality. This dynamic combination of Rhino and Grasshopper offers a powerful toolkit for professionals in creative and technical fields, enabling the realisation of intricate 3D designs and structures.

Why use it

Leveraging the combination of Rhino and Grasshopper provides us with a powerful platform for implementing a generative approach to sample production while enabling seamless design variations. This visual programming system offers a streamlined path from generating the initial waveforms to creating complex surfaces and ultimately arriving at the final desired shape.

Figure 16: Rhinoceros CAD software logo

Grasshopper's key strength lies in its ability to facilitate generative geometry. It empowers us to break down the design process into manageable steps. We can easily transition from crafting intricate wave lines to shaping surfaces, and finally, to achieving the desired end product. This flexibility allows us to experiment with various design iterations quickly and efficiently.

Furthermore, Grasshopper's capability to divide the final result into discrete points is instrumental. These points can then be translated into G-code, a standard machine-readable format used by 3D printers. This means that we can seamlessly transform our generative designs into tangible objects using a wide range of 3D printing devices. The integration of Rhino and Grasshopper streamlines the entire process, from conceptualization to production, making it a highly efficient and versatile tool for creating complex and customised samples.

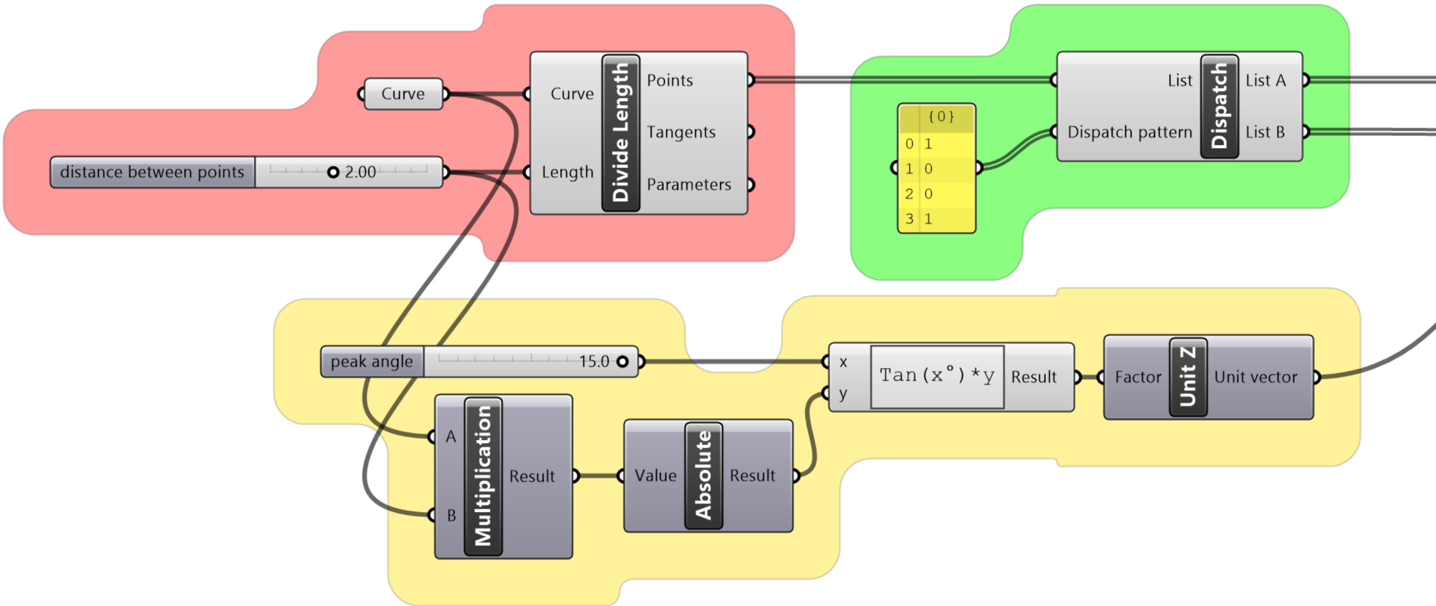
3.5 Development of Architected Material

3.5.1 Generating a wave from a line

The first step is to be able to generate a wave which can have its shape controlled. This is achieved by subdividing in a controlled manner a line into points placed equidistant from each other. The method to achieve this is as follows

A line or curve is generated, in this case a 50 mm long curve, which is then subdivided into points placed every 2 mm using the divide length function.

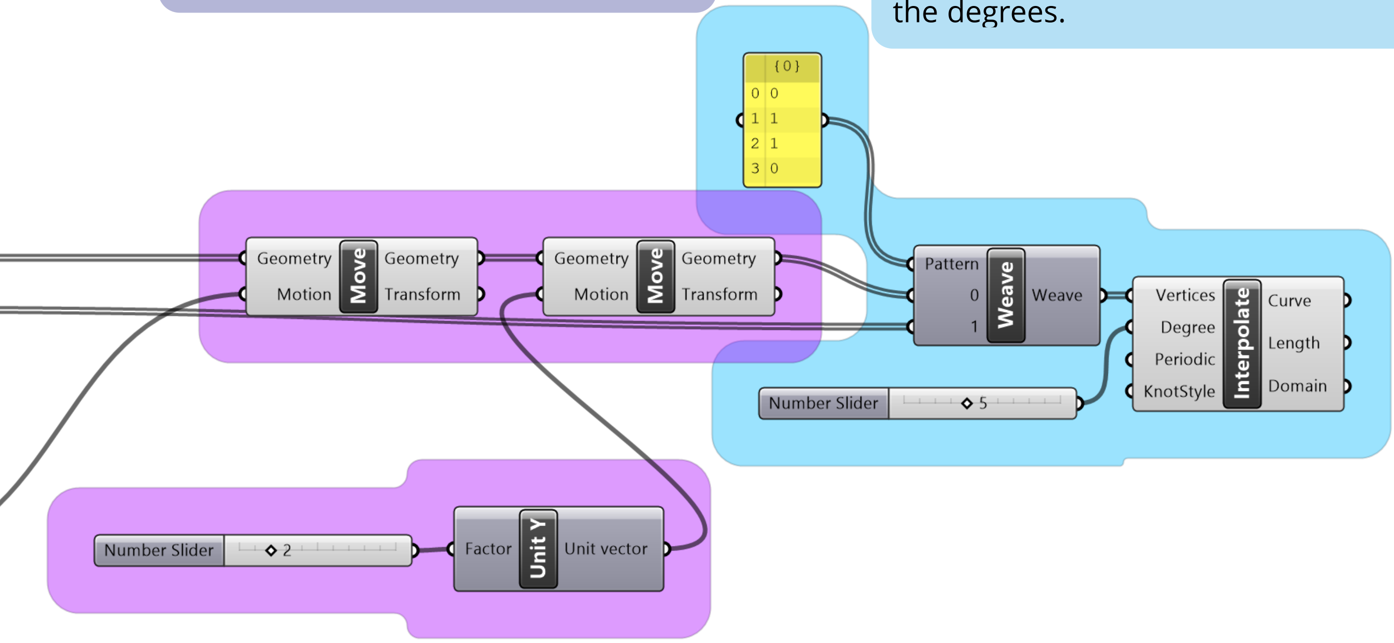
Once the curve is divided the points are isolated and subdivided using a 1001 pattern, this is achieved through the use of a dispatch function, this means the points falling in the 1 position pertain in one lits, the point in the 0 position to another list.

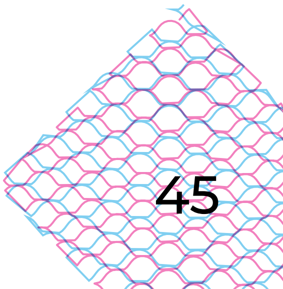


To achieve the desire output the lines are angled by calculating the Z height of the points using the Pythagorean theorem. this allows us to use a slider to select the desired angle.

The points pertaining to one of the lists are moved to a new position, this is achieved through the use of a move function, there are two move functions, as one moves the point in th Z axis and one in the Y axis, altogether they generate the angle needed for the lines.

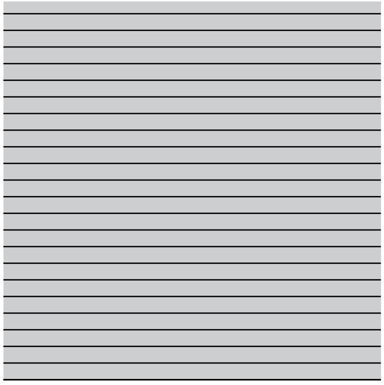
Finally the point lists are woven together using the weave function. This requires an inverted pattern thus the use of a 0110 pattern, this ensures after every point taken from list 1 two of list 2 are used, by interpolating the resulting points a curve is generated, how soft or sharp is it is controlled by the degrees.

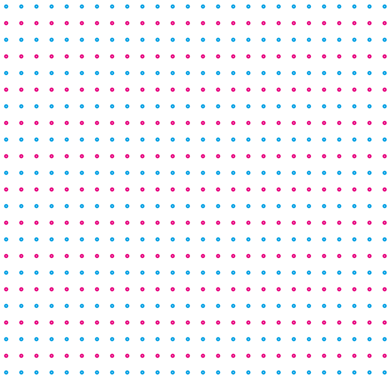




3.5.2 Generating mesh from a surface

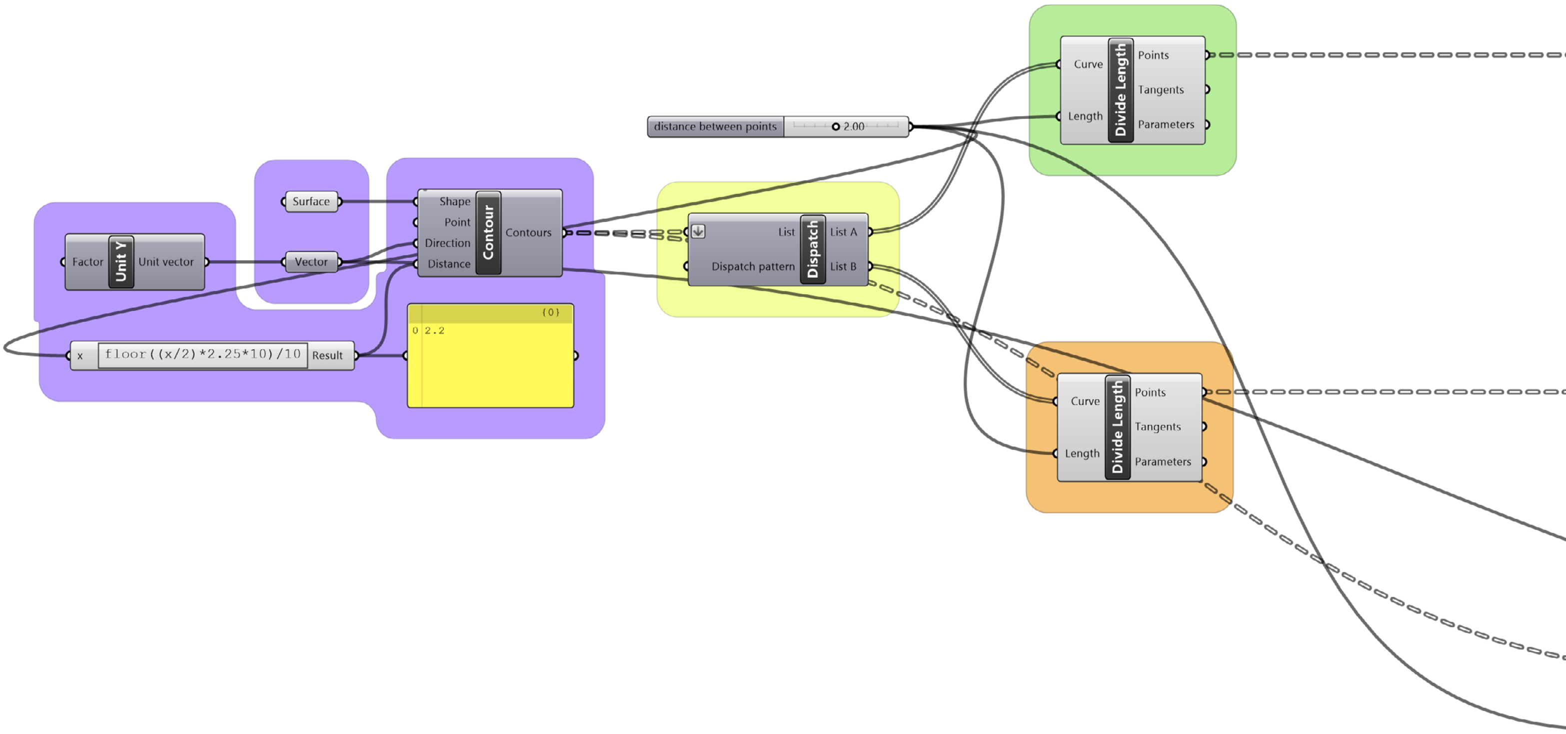
The first step is to be able to generate a wave which can have its shape controlled. This is achieved by subdividing in a controlled manner a line into points placed equidistant from each other. The method to achieve this is as follows

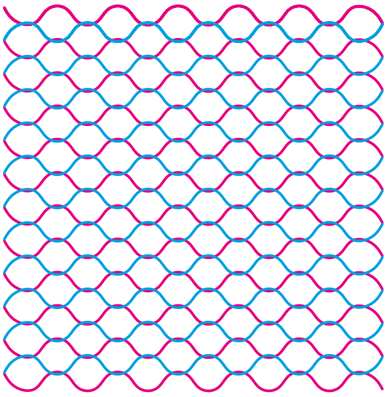


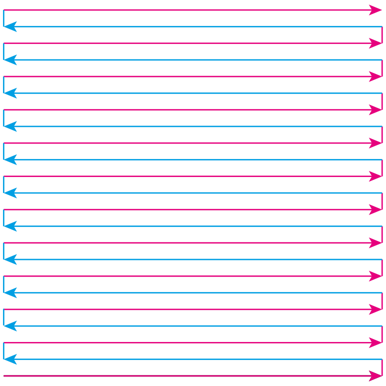


To mesh a surface the surface is subdivided into contours, the spacing is calculated through the formula observed below. This distance is key to ensure the proper connection between the waves.

Once the contours are generated, using a dispatch function these are divided into two lists using every other line, then they are subdivided using the divide lenght.

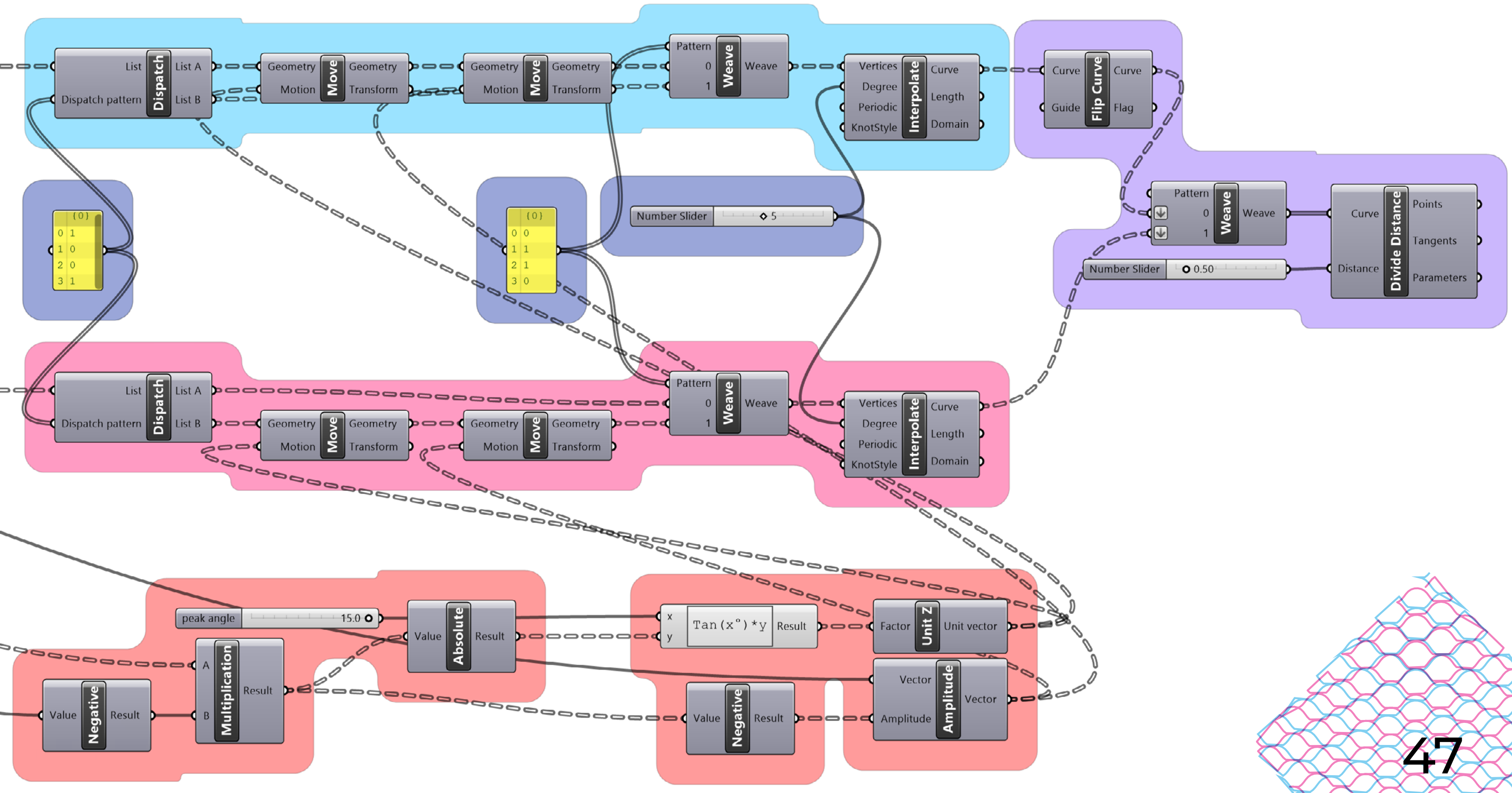






Using the same code used in the last section the lines are converted into waves, the only difference is how one of the lists is offset thus connecting the waves together.

A difference can be observed in the finishing points where, as it can be seen one group of lines is inverted, this allows the mesh to be printed in a travel-less form, once this is done, both lists are grouped. Finally this can be divided into points to start the Gcode generation.

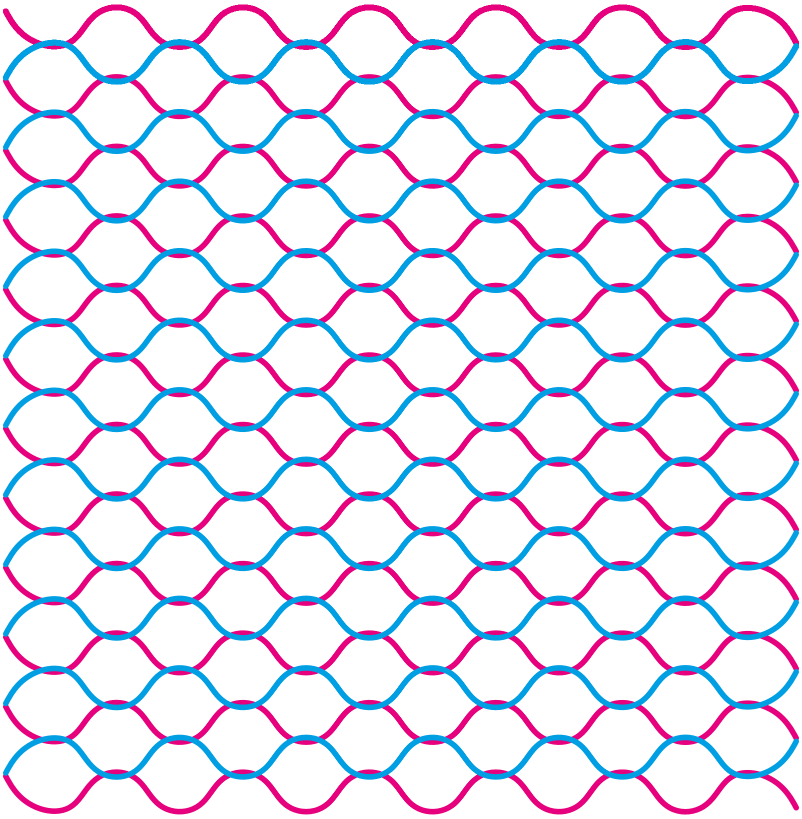


3.5.3 Choosing the shape

After establishing the methodology for creating and implementing various shapes and using these shapes to construct a mesh, the pivotal task is to determine the most suitable shape for the intended purpose. The selection process entails a multifaceted approach, commencing with the generation of a diverse array of shapes, followed by the practical application of 3D printing to assess their viability. During this evaluation, shapes that manifest inherent printing challenges leading to immediate failures are naturally eliminated.

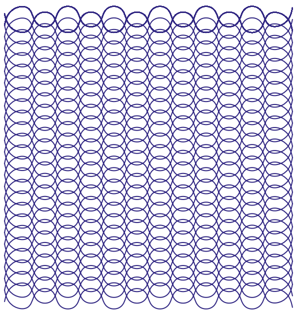
As previously elucidated, the primary objective is to craft a waveform that seamlessly interconnects with itself. Striking the right balance is paramount – an excessive number of connections may inadvertently render the material overly rigid, while excessively large wave lines may obscure the intended wave shape, resulting in straight lines with disparate structural characteristics interspersed throughout.

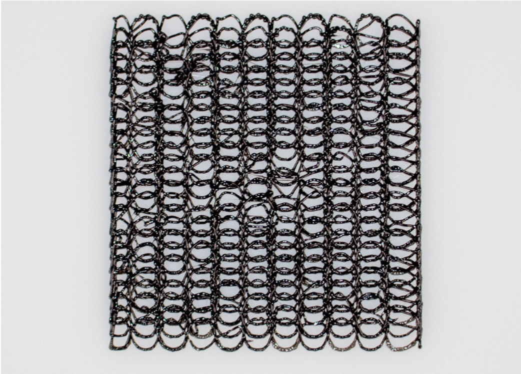
The selection process hinges on identifying a mesh configuration that achieves the delicate equilibrium of minimal contact points while ensuring successful 3D printing. Furthermore, the chosen mesh design incorporates smaller wave lines and capitalizes on connecting waves from their tips, thereby reducing the overall number of lines required for printing. This dual advantage not only enhances the print quality but also optimizes printing time and efficiency.

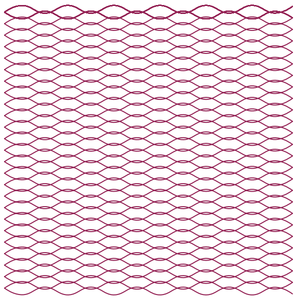


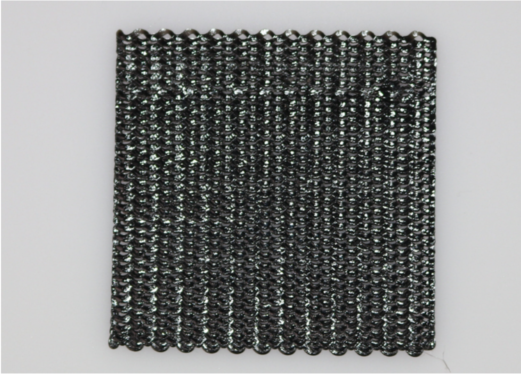
Simulated/
Generated
mesh

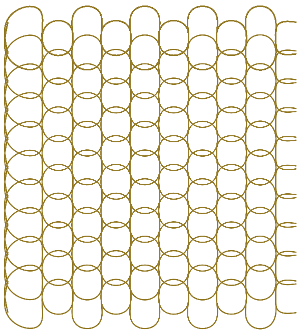
Printed Sample
of the Mesh

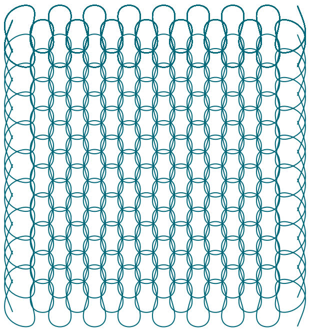


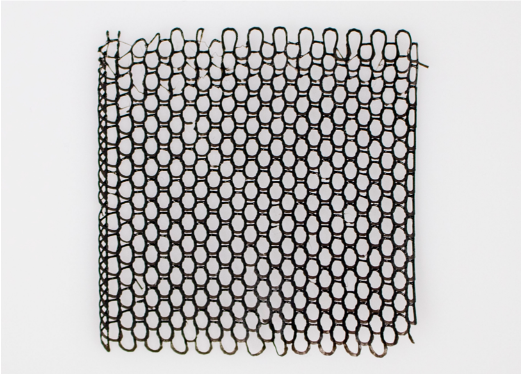






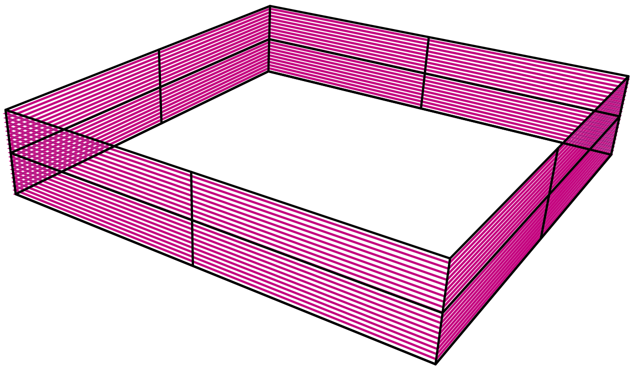


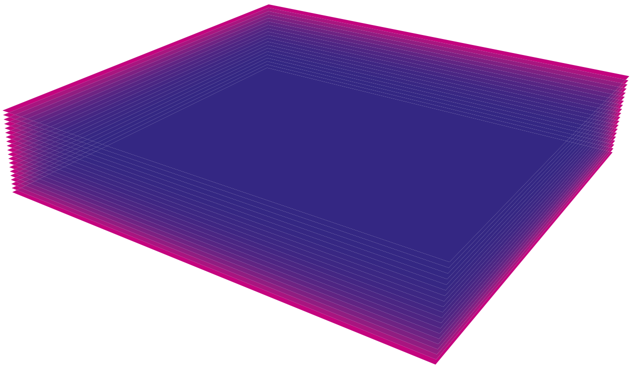




3.5.4 Slicing a volume

Converting a volume into a 3D mesh is as easy as overlapping surfaces that have been sliced, or meshed using the method explained at **point 3.5.2**. Applying the surface method to a volume proved to be easier than expected, if the volume can be split in surfaces these can be treated using the previous code.

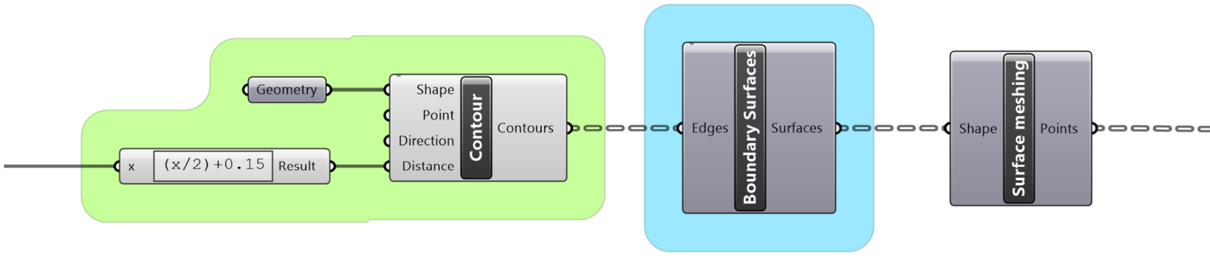




In this case a square block is a very straightforward procedure, the way this is done is by slicing the volume's outer surfaces in horizontal lines.

It's important to note the formula which dictates the separation of the layers uses the data obtained from the formula which calculates the height of the points to achieve the proper angle, this formula results in a lower space thus ensuring the layers have enough support.

Once the division has been made the lines are converted into surfaces which can be then processed by the surface processing tool created in point 3.5.2.



3.5.5 Writing the Gcode

G-code, which stands for "Geometric Code" or "Gestured Code," is a widely used programming language in the field of computer-aided manufacturing (CAM), 3D printing, and CNC (Computer Numerical Control) machines. It is a set of instructions used to control the movements and actions of these machines. G-code is a series of alphanumeric commands that tell a machine how to move, where to move, and what actions to perform, such as cutting, drilling, or 3D printing

In G-code, each command typically begins with a letter (e.g., G, M) followed by a number, and additional parameters can be added to provide more specific instructions. For example, a simple G-code command might look like this:

G01 X10 Y20 Z5 F100

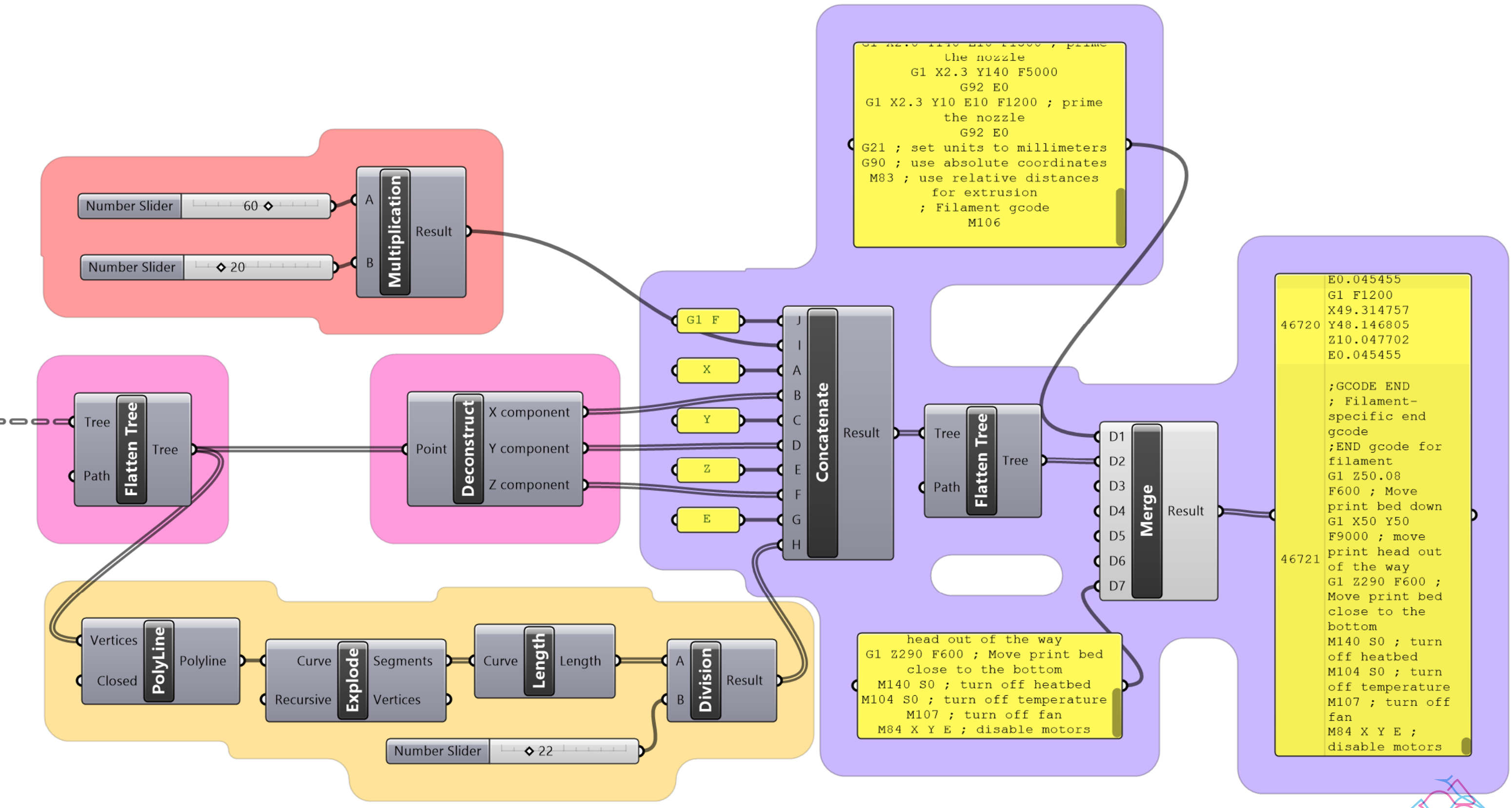
In this example, the G01 command indicates a linear move, with X, Y, and Z coordinates specified, and a feed rate of 100 units per minute (F100).[92]

This section sets the Feed rate at 20mm per minute.

This sections reads the points from the wave lines curves and separates them in their coordinate X.Y and Z.

This section sets the extrusion rate, in this casae a very low setting.

This section joints all the information while labeling it correctly, it inserts the begining and ending of a Gcode from Cura Slicer. once finished the result can be extracted and stored as .Gcode



```
the nozzle
G1 X2.3 Y140 F5000
G92 E0
G1 X2.3 Y10 E10 F1200 ; prime
the nozzle
G92 E0
G21 ; set units to millimeters
G90 ; use absolute coordinates
M83 ; use relative distances
for extrusion
; Filament gcode
M106
```

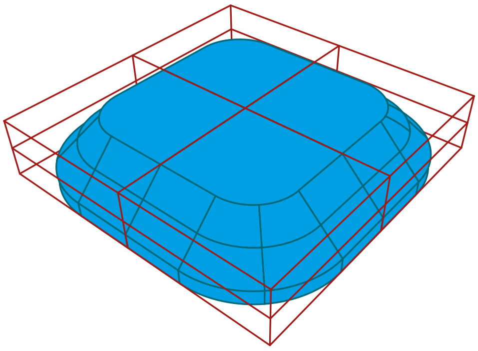
```
head out of the way
G1 Z290 F600 ; Move print bed
close to the bottom
M140 S0 ; turn off heatbed
M104 S0 ; turn off temperature
M107 ; turn off fan
M84 X Y E ; disable motors
```

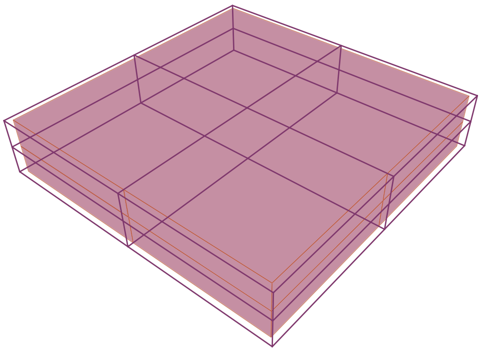
```
      E0.045455
      G1 F1200
      X49.314757
46720 Y48.146805
      Z10.047702
      E0.045455

      ;GCODE END
      ; Filament-
      specific end
      gcode
      ;END gcode for
      filament
      G1 Z50.08
      F600 ; Move
      print bed down
      G1 X50 Y50
      F9000 ; move
46721 print head out
      of the way
      G1 Z290 F600 ;
      Move print bed
      close to the
      bottom
      M140 S0 ; turn
      off heatbed
      M104 S0 ; turn
      off temperature
      M107 ; turn off
      fan
      M84 X Y E ;
      disable motors
```

3.5.6 Slicing a Geometry

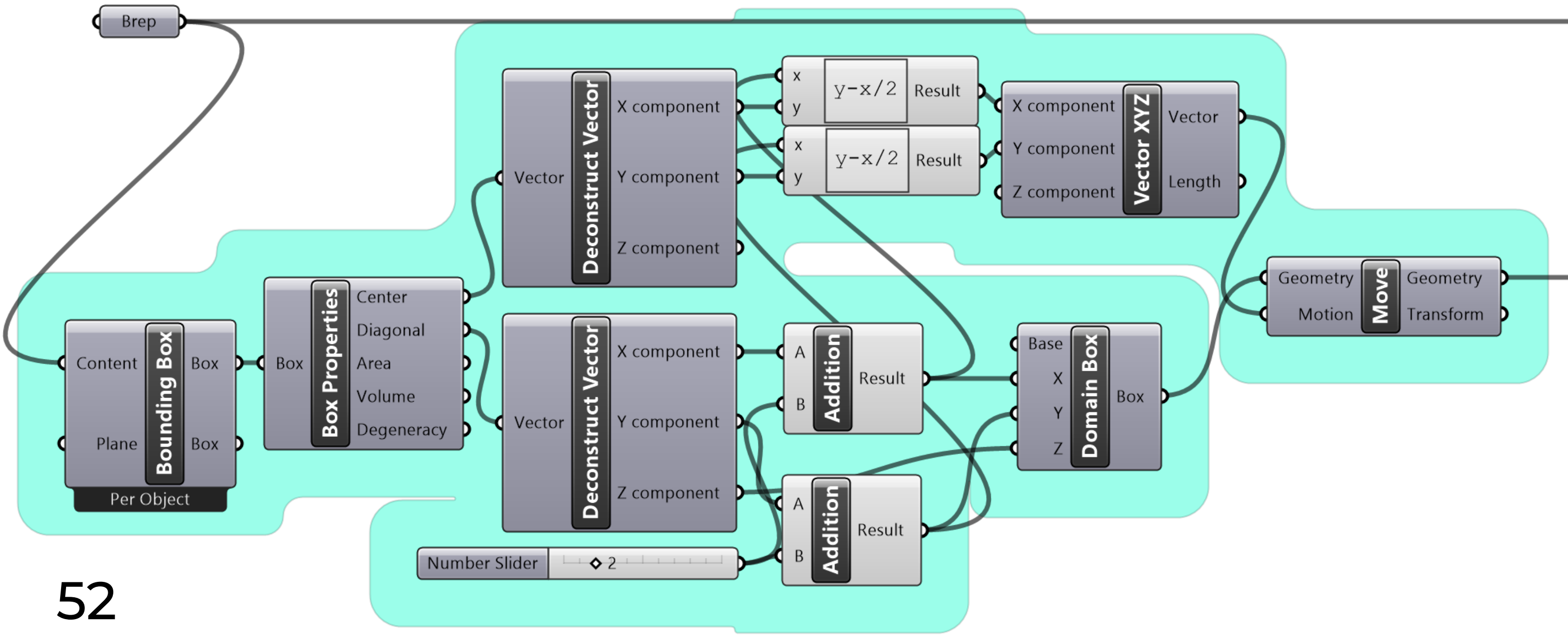
Once able to slice volumes one of the first things tried was to slice an object that had curves, due to these curves the mesh changed properties as the waves did not intersect the way they were designed to(fig17). This is the main reason a method which analyses the geometry was developed, this method allows slicing parts with complex shapes without affecting the structure of the material(fig18).



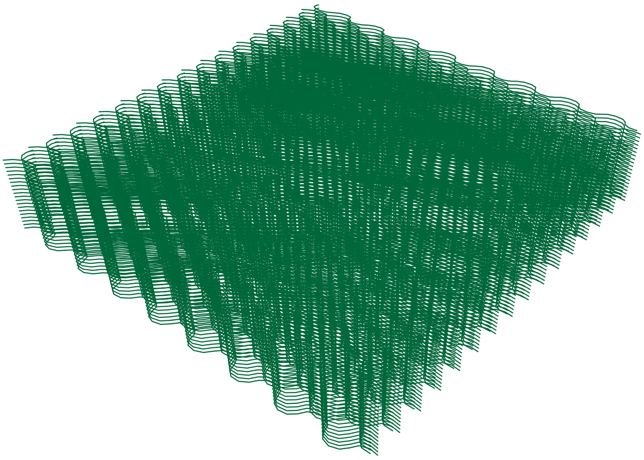


This part of the code works by inserting a geometry or a Brep, this is then converted into a bounding box, this box has the maximum width, length, and height of the object it encompasses.

For the generation of the mesh the bounding box is enlarged in width and length, in this case just by 2mm extra. Having a larger box allows for the waves to properly generate without being affected by the boundary, without generating too many useless points. Part of the code recenters this enlarged box, as when enlarged, this is done from the corner closest to the 0 point in the CAD environment.



Once the basic bounding box is sliced using the volume slicer used in point 3.5.4 the resulting waves are then passed through a culling program, this takes the list, selects the points that fall in the interior of the geometry an erases the rest thus resulting in a mesh unaffected by the geometry of the part.



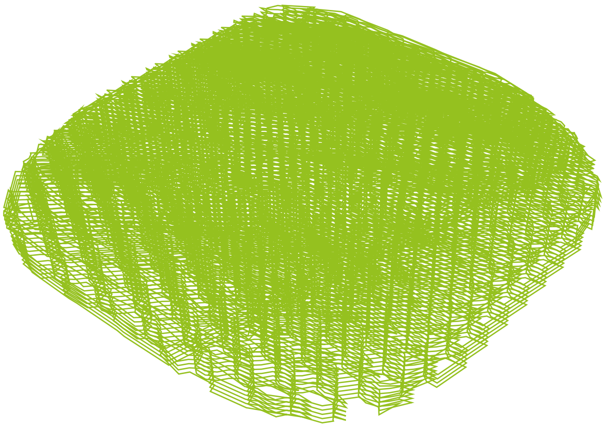


Figure 17: Circular chamfered Puck mesh
Own work

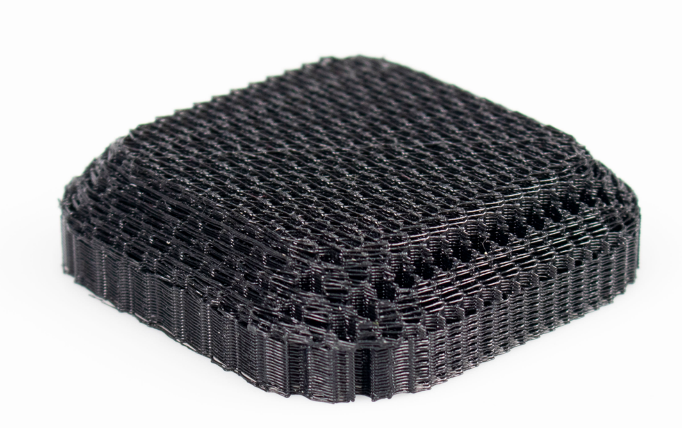
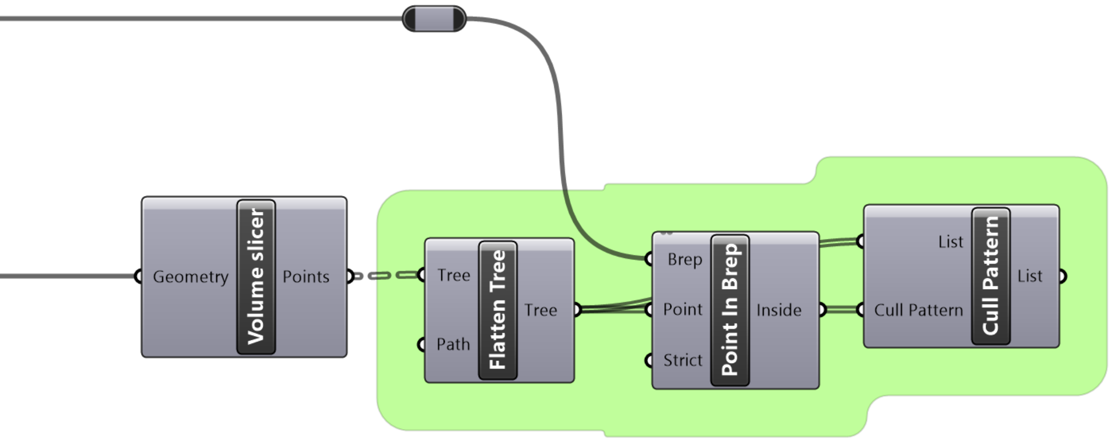


Figure 18: Volume test sample with Pattern culling
Own work



3.6 Testing Method/Technique

When evaluating architected materials for use in sports protective equipment, it is crucial to establish a robust benchmark for performance assessment. In this context, ISO 4651 offers precisely that, allowing researchers to systematically gauge the dynamic cushioning capabilities of their architected materials. By conducting tests according to this standardised procedure, researchers can ascertain the material's suitability for specific applications and guarantee its safety during use. ISO standards, like ISO 4651, provide a universally understood framework, ensuring that results can be trusted not only within the research community but also by industry stakeholders.

To further validate the performance of architected materials, a comparison with materials that have passed rigorous safety checks and are established as safe for use becomes necessary. For instance, conducting tests on a piece of foam derived from sports protective equipment offers a reliable point of reference. Sports protective gear is subject to stringent quality and safety standards. Therefore, a foam piece from such equipment, known to be safe, can serve as a trusted benchmark against which the architected material's performance can be measured

3.6.1 ISO 4651

The International Standard ISO 4651:1988 outlines a rigorous procedure for assessing the dynamic cushioning performance of cellular rubber materials and flexible cellular plastics, specifically those utilised in packaging applications. The primary objective of this standardised test is to ensure quality assurance, although it also offers valuable data for design considerations. The method entails measuring the peak deceleration when a mass is dropped onto a standardised test specimen. The rationale for employing this standard is rooted in the fact that sports protective equipment standards primarily evaluate the final product rather than isolating and evaluating the material properties. Consequently, sports protection standards typically require higher impact energies and rely on specific impactors tailored to each type of protection and its intended use conditions.

The standard prescribes a specific set of testing apparatus, including a drop hammer equipped with an impactor larger than the surface of the sample, an anvil with a mass 100 times greater than the hammer, and recording equipment. Each component of the apparatus is designed to meet stringent requirements to ensure accuracy and reliability. ISO 4651 outlines two types of dynamic testing equipment: guided vertical drop testers and pendulum testers, providing flexibility to accommodate various testing needs. While the standard does not specify the exact recording equipment, it mandates that the equipment must be capable of accurately capturing deceleration-time pulses within the specified duration. Transducers, amplification means, and recorders are among the essential components of the recording equipment. The transducers can be of the piezoelectric or strain gauge type, with a requirement that their natural vibration frequencies align with the characteristics of the impact pulse. The frequency response of the recorder is also crucial for effectively measuring peak deceleration.

To ensure consistent and reproducible results, the test specimens must adhere to precise dimensional and uniformity criteria as specified by the standard. The standard stipulates that the test pieces should have dimensions of 150mm by 150mm with a thickness of 50mm, all within a tolerance of plus or minus 5mm. Furthermore, the orientation of the test pieces during testing should closely mimic real-world conditions. ISO

4651 recommends using at least ten test pieces for each set of tests to enhance statistical validity.

Prior to testing, the samples undergo pre-conditioning under specific environmental conditions. Conditioning includes maintaining stable temperature and humidity levels for a predetermined duration. The exact test conditions should be agreed upon between the supplier and purchaser to ensure consistency in testing conditions.

The testing procedure involves subjecting the test piece to multiple impacts, typically three drops per sample, at fixed velocities corresponding to heights of 250mm, 750mm, and 1250mm, and under static stresses generated by five different weights. Measurements are taken for both the peak deceleration and the recovery of the test piece over time. The corrected value of peak deceleration is calculated using the original thickness of the test piece and the impact velocity.

In presenting the results, the test report should encompass critical information, including a reference to the International Standard, a detailed description of the material being tested, specific test conditions, and details on the number of drops and drop heights used in the testing process. This comprehensive standard for dynamic cushioning performance evaluation plays a vital role in ensuring the safe transportation and storage of products, particularly by maintaining the integrity of packaging materials.

3.6.2 Control sample

Figure 19: Decathlon Fouganza back protector
Decathlon

A control sample will be used to compare the results from the architected material. Such comparison allows for a baseline to understand how well or how poorly the material fares in a test. Using a control sample from an off the shelf product ensures the material has had to pass through similar testing, and accomplishes the standards required for such protection to be sold in europe.

The sacrificial protection must fit a certain criteria, its main protective material must be foam based, it should not be composed of a mix of different densities. The material must be easy to remove from the protection, if the material is damaged through its removal this could affect the end result. Finally there must be enough material for the control samples.

The selected protection is the **Decathlon Fouganza "kids and adult flexible horse riding back protector"**[93](fig19), this protector is as stated by the seller, "Light and comfortable to wear, our flexible back protector adapts to the shape of your body for maximum comfort and great freedom of movement, completely discreet!"

This product has been certified for horse riding by an expert, based on standard EN1621-2 (level 1) Back protectors against mechanical shocks for motorcyclists".Back protectors are not permitted during competitions requiring you to wear a body protector: for the cross-country test in eventing and the marathon test in combined driving competitions.

The protector bought is a size M with a price of 63,48€, this was chosen as it offers a large area made out of Polyurethane foam, assembled in **four 5mm** thick layers which were glued together in 3 different spots(fig 20).

The uppermost layer was extracted and cut to generate three samples, one unglued, one glued with a single drop of glue at the centre and one glued with a drop at each corner. This was done to ensure the results could not be affected by the glue, or lack of.

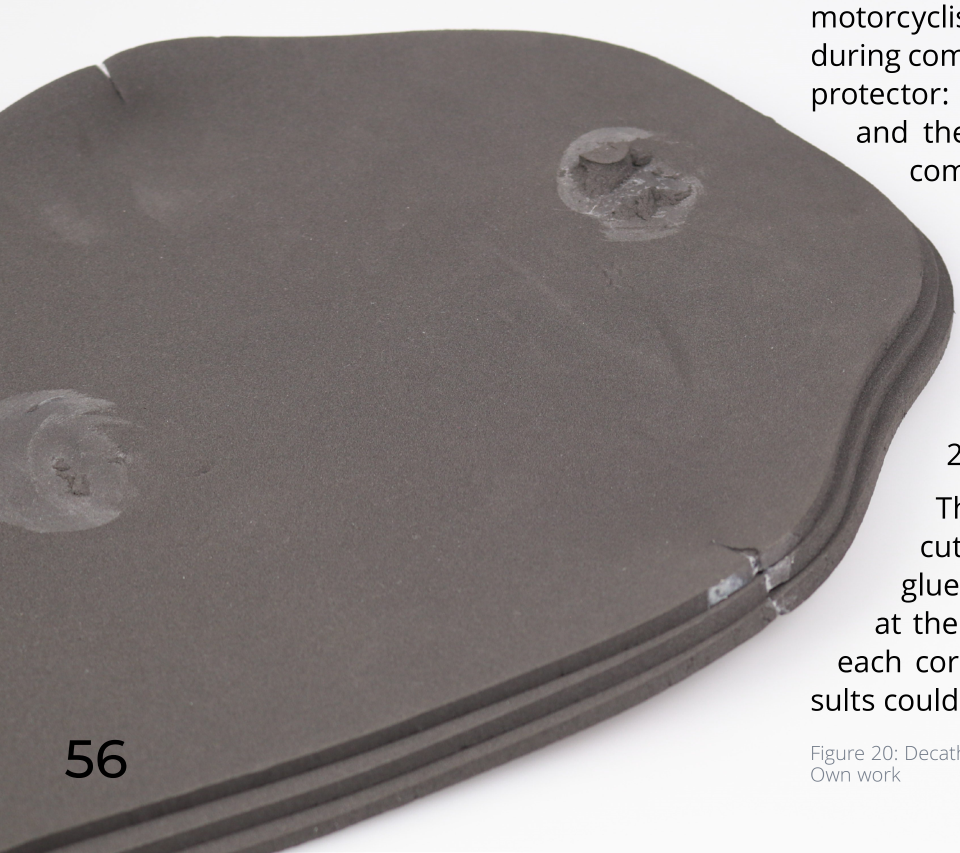


Figure 20: Decathlon Fouganza back protector Polyurethane Foam insert
Own work

3.6.3 Testing equipment
Dynatup 8250

The Dynatup 8250 (fig21) is a drop-weight impact test tower designed to assess the impact properties of a wide range of materials and components across various impact velocities. The resulting data is invaluable for evaluating the performance of these materials and components. Additionally, it offers the capability to perform impact tests in non-ambient conditions using an integrated environmental chamber. It's important to note that this machine is equipped with a 5 kg weight and a 7.5 kN impact cell as the sole available options for conducting the tests.

This will help determine the height for a scale of impact joules. Using the energy at impact in joules instead of the static stress will allow the testing to continue even though there are clear differences with the ISO standard. This is also the reason why the control sample needed is taken from an off-the-shelf product, as this will have had to pass controls to ensure the users safety.

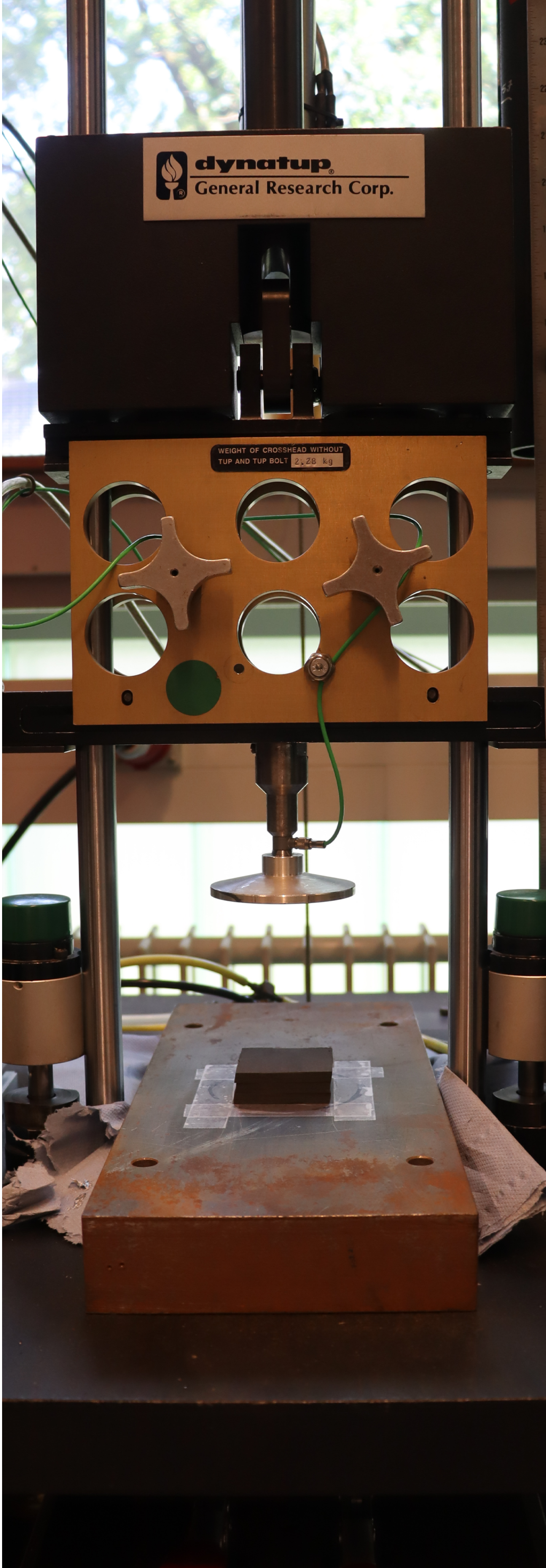


Figure 21: Dynatup 8250 at University of Twente
Own work

3.6.4 Test variations

This section delves deeply into the intricacies of conducting dynamic cushioning performance tests, emphasising the necessity to adapt and, in certain scenarios, deviate from the ISO 4651 standard. These **adaptations** arise from a multitude of factors, including the unavailability of specialised testing equipment, constraints within the production process, and the distinctive characteristics of the material being examined. It is crucial to note that these deviations are not made lightly; rather, they are driven by the imperative need to achieve accurate, dependable, and contextually relevant results.

Throughout the ensuing sections, each departure from the ISO 4651 standard will be meticulously examined, accompanied by comprehensive explanations. These insights will provide a clear understanding of how these adaptations have been strategically employed to address the unique challenges presented by the testing environment. This ensures that the research findings remain robust, meaningful, and directly applicable to real-world scenarios where the engineered materials are intended for use. In essence, this section serves as a critical prelude to the subsequent discussions, illustrating the careful considerations that underpin the research methodology.

The first significant deviation pertains to the size and quantity of samples. The deviation from the prescribed ISO 4651 shape of **150 x 150 x 50mm** arises from two primary issues. Firstly, the **unavailability** of an impactor larger than 60mm in diameter presents a challenge in meeting the requirement of using an impactor larger than the surface of the sample. Secondly, considerations regarding printing time and material usage come into play. A sample of the specified ISO dimensions would demand extensive printing time and excessive material consumption. To address this, the selection of sample size was influenced by the **5mm** thickness of the **foam insert** from the Fouganza back protector, which cannot be altered. Therefore, it was decided to scale the thickness to one-third of the original while slightly reducing the dimensions to ensure fitting within the impactor's area. Consequently, the utilised samples have dimensions of **45 x 45 x 15mm.**

Furthermore, there is a deviation in the number of samples employed. The ISO standard calls for the use of ten samples per variation, which is logical when characterising foam materials. However, in our case, producing ten samples per variation becomes impractical, considering the substantial time required for each sample's 3D printing, ranging from **45 minutes to 1 hou**r. With a total of twelve variations to be tested, adhering strictly to the ISO standard would necessitate between **7 hours and 30 minutes** to **10 hours** for each variation.

Another substantial variation relates to the drop conditions. ISO 4651 specifies the use of five different weights (static stresses) and testing at three different heights. As previously outlined in the testing equipment section, we have access to only one weight option. Consequently, instead of conducting tests at the prescribed three different heights **(250mm, 750mm, and 1250mm)**, our testing focuses on impact joules (utilising the provided formula). This approach determines the height based on impact joules, allowing us to continue the testing despite clear differences from the ISO standard. Additionally, this deviation underscores the necessity of using a control sample sourced from an off-the-shelf product, as it would have passed safety controls, ensuring user safety throughout the evaluation process.

4. Results and Discussion

4.1 Testing results

The tests were done at the mechanical testing lab at The University of Twente, where all the machines and testing equipment allowed the characterization of the samples. The tests were conducted on a set of 12 samples with a second set made to be used as substitute in case of a failure, there were also 4 extra samples to be used to calibrate the testing apparatus. Finally 2 sets of 3 polyurethane foam samples which come from the Fouganza back protector.

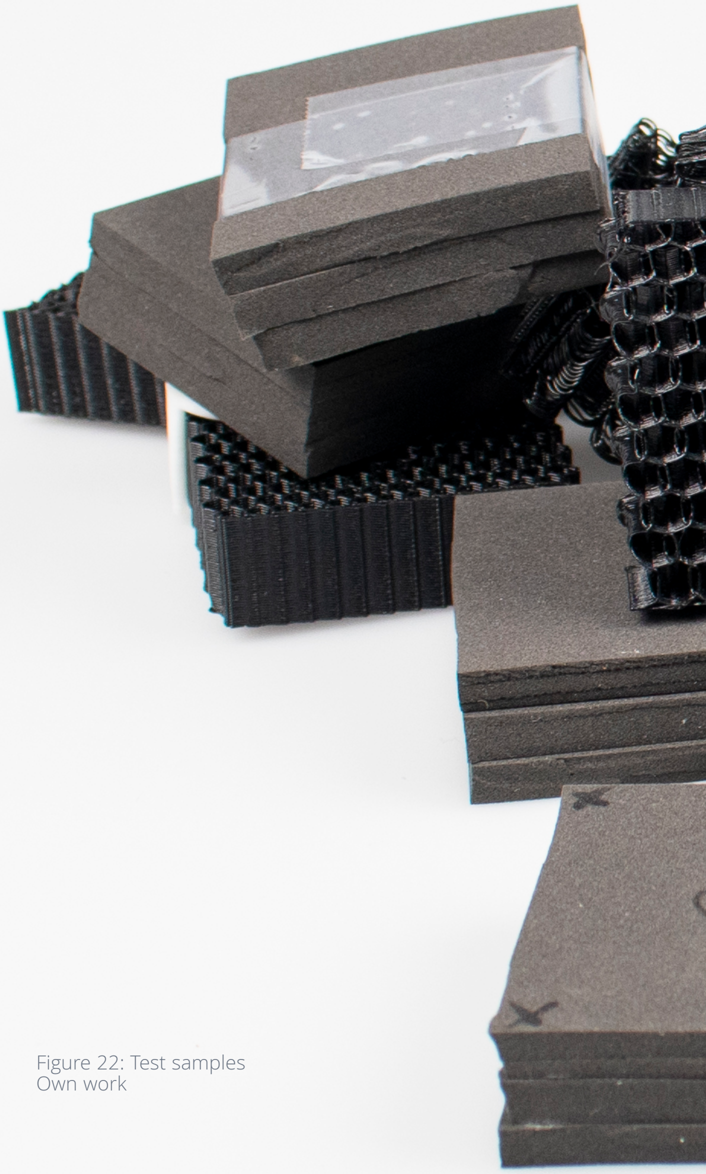
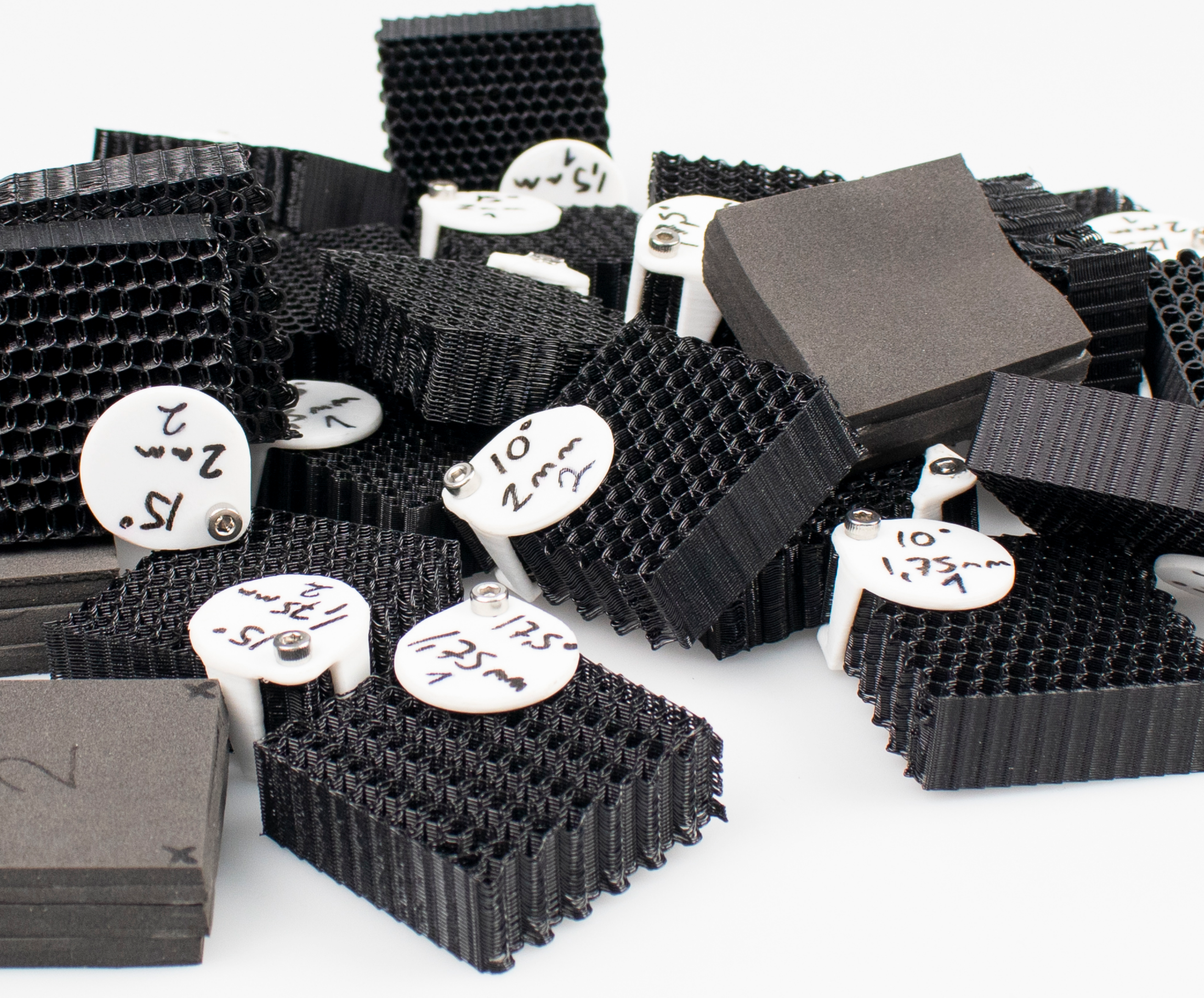


Figure 22: Test samples
Own work


15° 2mm 2
10° 2mm 2
10° 1.75mm 1
15° 1.75mm 1.2
17.5° 1.75mm 1
15° mm 1

4.1.1 Test procedure

The modifications made to the testing procedure, as mentioned in point 3.6, were implemented to closely align with a modified version of ISO 4651. These adjustments were essential to ensure that the testing could be conducted as accurately as possible, yielding reliable results. The primary divergence resulting from these changes pertains to the creation of the cushioning diagram.

In this adapted procedure, each sample underwent a drop test three times, with one-minute intervals between each test. The drop height was carefully selected to cover a range of impact energies, spanning from 2J to 8J. All samples were tested at the same height in sequence, and this process was repeated for each specified drop energy.

The focal point of the entire project lies in the cushioning diagram. However, due to certain limitations associated with the equipment at our disposal, we were compelled to modify the testing method. The primary change in the modified cushioning diagram relates to the exclusion of static stress components. This is justified by the fact that, in our specific context, these components remain constant. The area of impact remains the same, the weight of the objects involved is consistent, and the gravitational constant does not vary.

These modifications were made out of necessity, as the original testing procedure would have been heavily hindered. Without an appropriate cushioning diagram, we are left with no alternative but to rely on guesswork and approximation to interpret the data. Additionally, issues arose in accurately measuring the movement of the hammer, further complicating the situation. Consequently, it is essential to acknowledge that the deformation measurements may not be entirely reliable.

In summary, while the changes to the testing procedure were made to align with ISO 4651 and to ensure accurate results, certain equipment limitations and issues with measurement have hindered our ability to create a comprehensive cushioning diagram. Consequently, we are compelled to rely on approximations and estimates in interpreting the data, recognizing that the results may not be entirely definitive.

It is important to note that even though having a control sample generates a base line, any change such as thickness , or impact conditions might result in a different output which the samples of the architected material do not mimic. It si important also, to realise many other protections use different foams and thickness for various reasons, this testing is to prove the viability, not to characterise it.

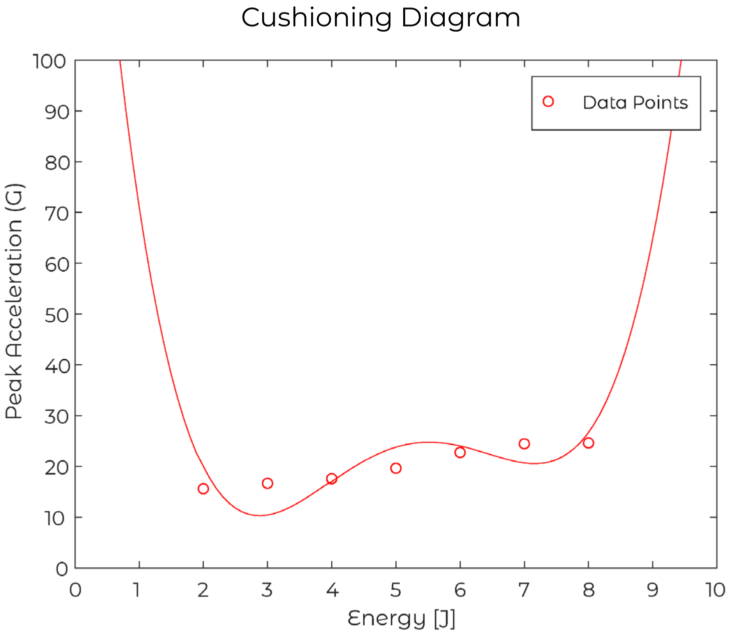
Figure 23: Test day at University of twente using Dynatup 8250
Own work

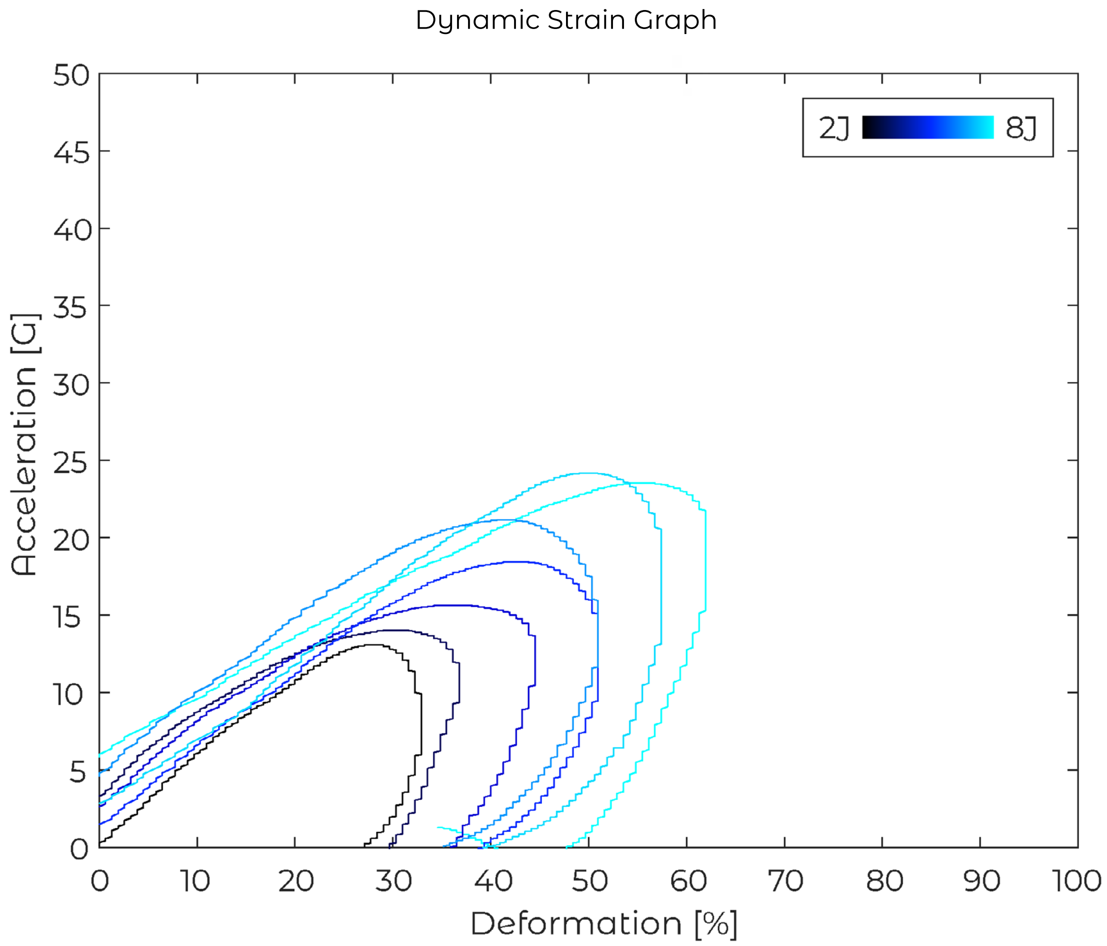
4.1.2 Control sample

Figure 24: Polyurethane Foam Samples
Own work

The control sample comes out of the extraction of the Foam insert inside the Fouganza back protector, these 3 samples are composed of three 5 mm thick layers of Polyurethane Foam. Each of the three samples have a difference in how they were glued, although the results did not show any comparable differences.

A clear observation done during and after the testing phase is that this foam tends to show memory-like characteristics. The foam took longer to bounce back into shape, even sticking to the impactor after each impact, in some occasions, when not stored properly the other samples left imprints and even deformed the foam. This was solved by letting the foam rest.





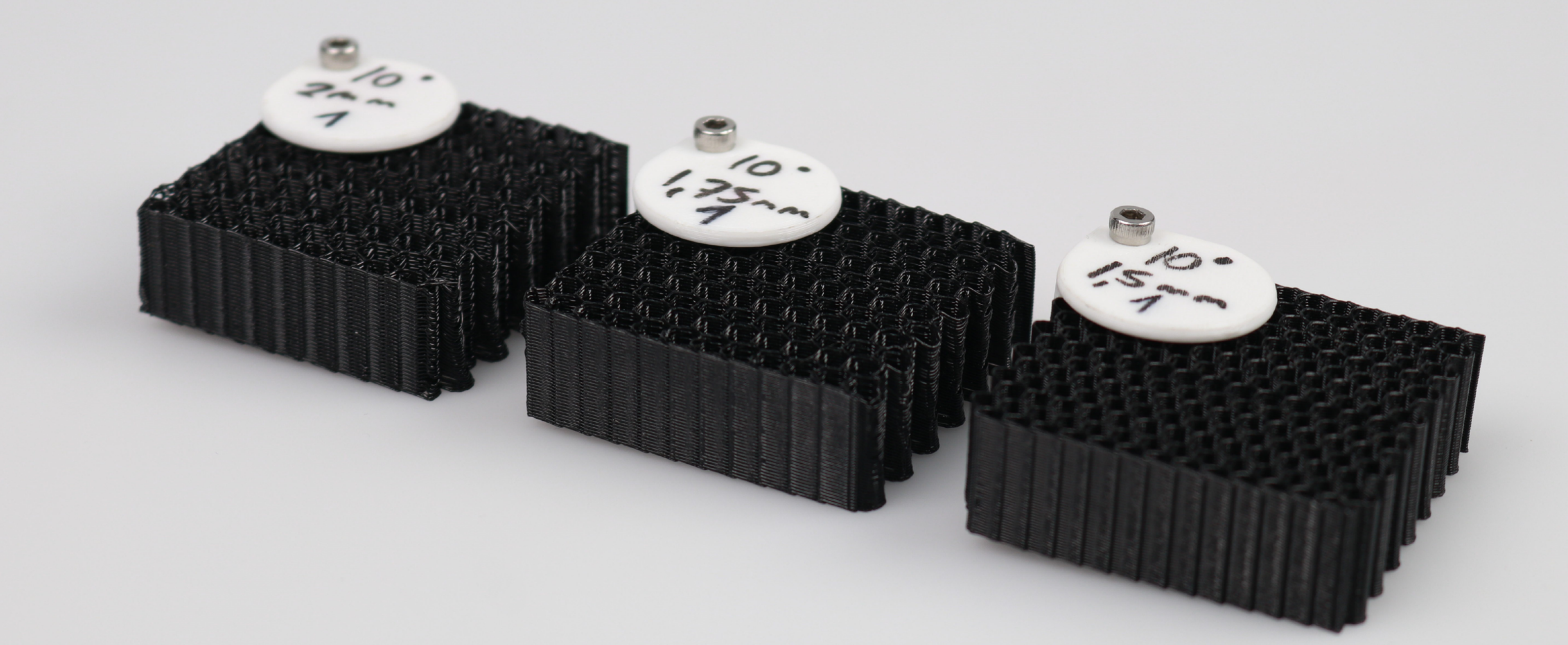
The results obtained from testing the control sample, which in this case is the Polyurethane foam extracted from the Fouganza back protector, across a range of impact energies from 2 Joules to 8 Joules, have yielded an approximation of a cushioning diagram. In this diagram, it is noted that the peak acceleration or maximum deceleration on impact consistently falls within the 20G range. This finding is also supported by observations from the Dynamic Strain graph.

Moreover, when examining the Peak deceleration observed in the previous graph, it becomes apparent that the maximum deformation of the foam material increased from 30% at 2J to 60% at 8J. This demonstrates how the Polyurethane foam behaves under different impact energy levels.

This sets a baseline to understand the tests of the architected materials. As the sample pool is quite large the samples under focus are those that exhibit a similar curve in the cushioning diagram. Once these promising materials are identified, their dynamic strain diagrams can be compared to that of the Polyurethane foam. This comparative analysis will allow a better understanding of the performance and suitability of the architected materials in various impact scenarios.

4.1.3 Material samples

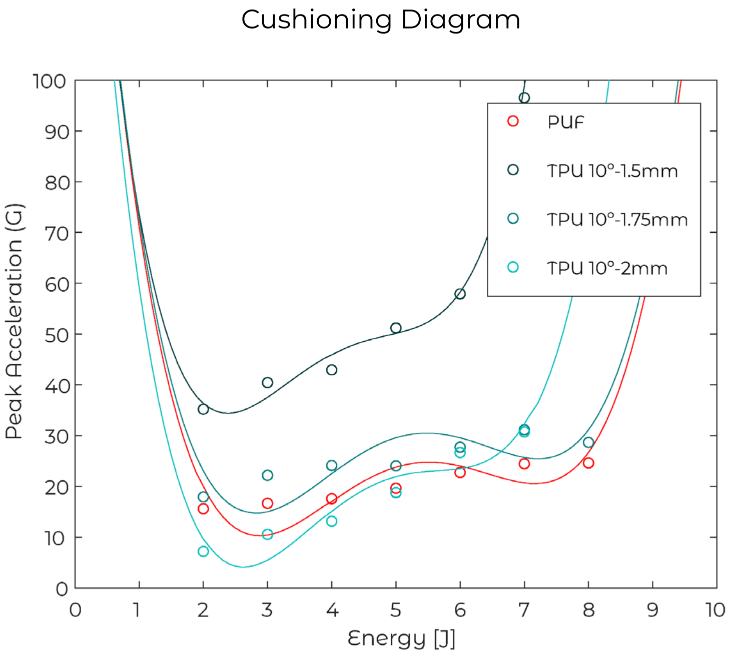
Figure 25: TPU 10° Samples
Own work



TPU 10º

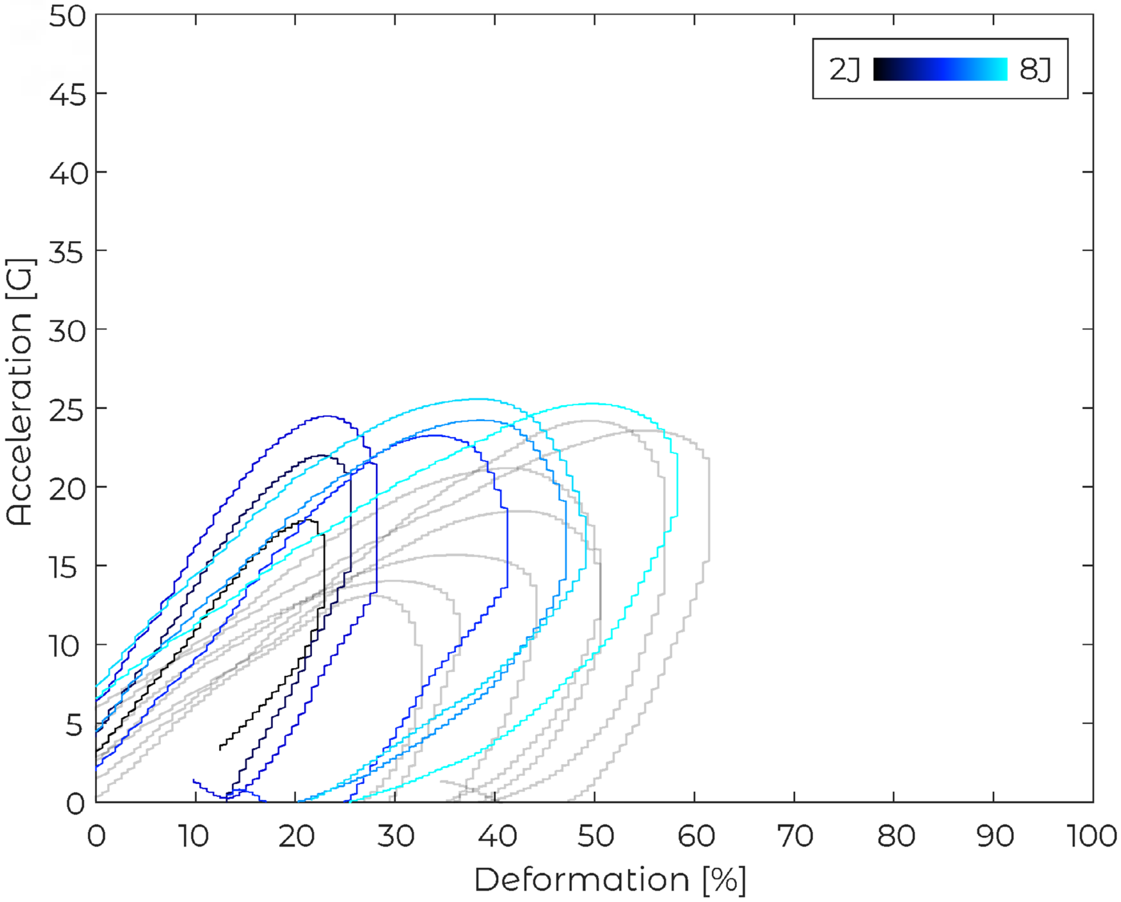
These 3 samples are formed by generating a wave line tilted at the shallow angle of 10 degrees, these were expected to result in stiffer geometries as there is more material piled upon itself. Such a shallow angle results in less gaps generated between lines thus not allowing the same level of compression as the samples with higher angles.

As depicted in the provided graph, the results of TPU 10° are compared to the red line which represents the Polyurethane Foam sample. The graph shows that the TPU samples exhibit behaviour quite similar to the control Polyurethane foam sample. However, there are some notable differences among the TPU samples.



- **Samples with a structure of 10° angle at 2mm:** These samples, which deviate slightly from the control sample, appear to fail at higher impact energies.
- **Sample composed of 10° angle at 1.75mm:** This sample closely approximates the original Polyurethane foam line. This suggests that this specific TPU sample retains properties similar to the control sample and is worth further investigation.
- **Sample generated through a structure of 10° at 1.5mm:** This particular sample stands out as it generated the stiffest structure among all the TPU samples. The peak deceleration for this sample ranges from under 40G to nearly 100G. This indicates a more robust and rigid response to impact.

Dynamic Strain Graph



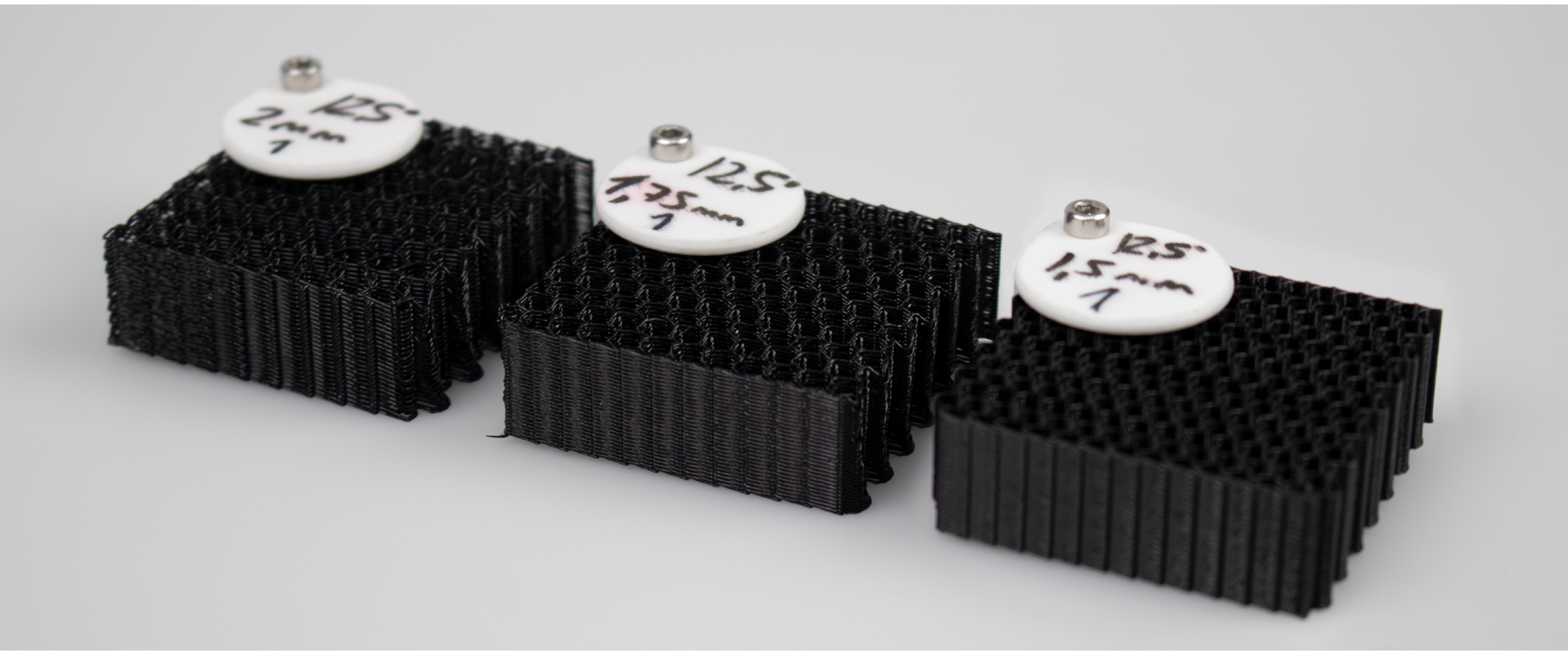
The observations made from Dynamic Strain Graph prove a different image, at lower impact energies, the TPU architected structure exhibits higher stiffness compared to the Polyurethane Foam (PUF), which leads to a slightly higher peak deceleration. This outcome is expected, as the stiffness of the material influences its response to lower-energy impacts.

However, what's particularly promising is that as the impact energy increases, the deformation of the TPU architected structure closely matches that of the Polyurethane Foam, and the peak decelerations generated by the TPU approach those of the control material. This suggests that the TPU foam is capable of effectively mimicking the behaviour of Polyurethane foam, meeting the objectives set for it.

These findings indicate that the TPU 10° architected structure can serve as a viable alternative to the Polyurethane foam, offering a versatile material that can match the desired cushioning properties across a range of impact energies. This material could be well-suited for various applications, especially if consistent cushioning performance is required under different impact conditions.

In summary, while the TPU samples generally demonstrate behaviour similar to the Polyurethane foam control sample, the choice of structural parameters, such as angle and point separation, has a significant impact on their performance. The sample with a 10° angle at 1.5mm seems to offer a stiffer structure, while the sample with a 10° angle at 1.75mm closely matches the control sample's behaviour.

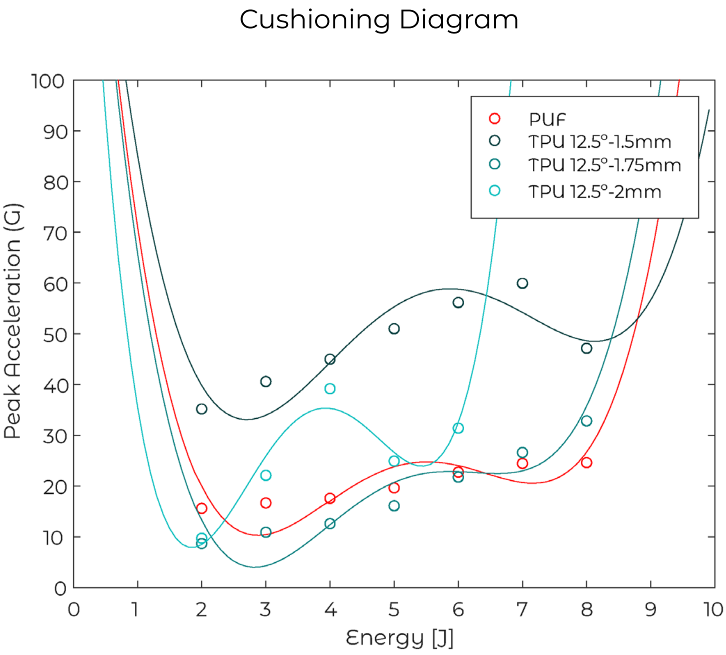
Figure 26: TPU 12.5° Samples
Own work



TPU 12.5º

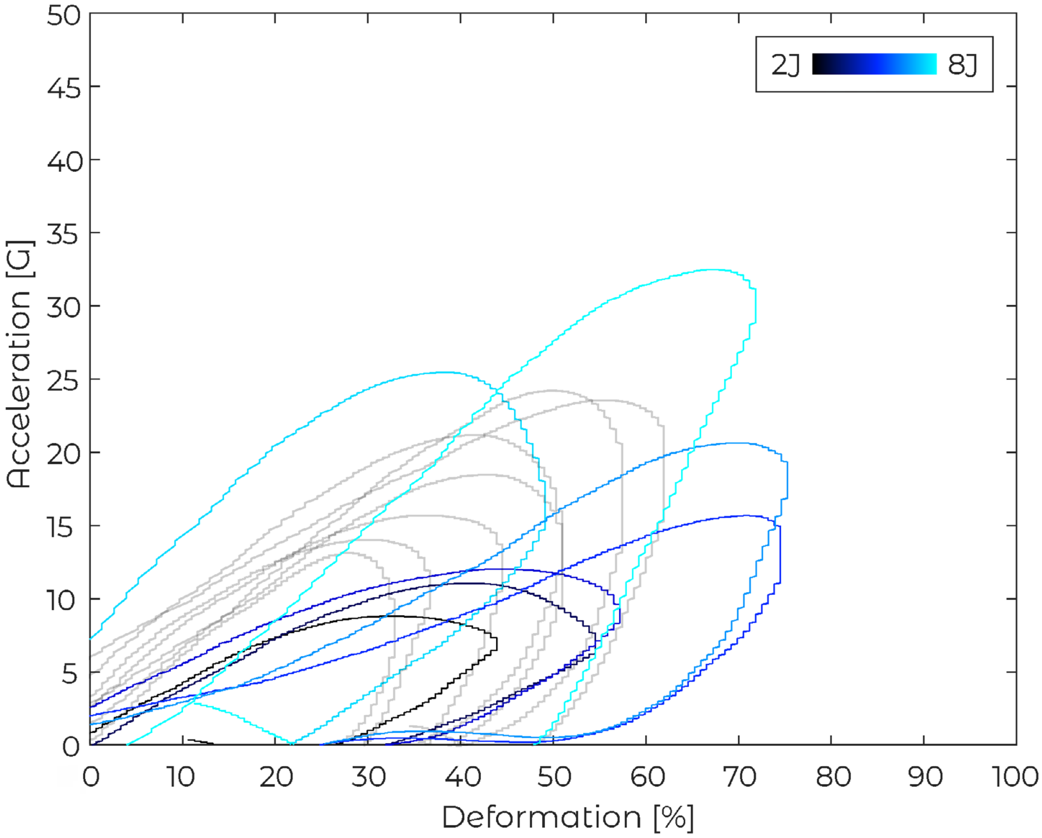
These 3 samples are sliced by generating a wave line tilted at an angle of 12.5 degrees, these were expected to result in less material piled up as the 10° samples, the results show how this small variation of density does affect the stiffness of the samples. Such a small change of angle meant less layers are printed and although the gaps generated between lines are still small they allow better compression than the sample at a lower angle while still offering better stiffness than the higher angles.

As depicted in the provided graph, the results of TPU 12.5° are compared to the red line which represents the Polyurethane Foam sample. The graph shows that one of the TPU samples exhibits behaviour quite similar to the control Polyurethane foam sample. However, there rests show notable differences against the PUF sample.



- **Structure at 12.5° angle at 2mm:** These samples rapidly failed the test showing very different results at different energies
- **Sample of 12.5° angle at 1.75mm:** this sample closely approximates the original Polyurethane foam line. This will be the sample under focus.
- **Structure of 12.5° at 1.5mm:** This sample generated a stiffer structure. Although after steadily increasing the peak deceleration as the energy increased, at the highest impact the peak deceleration dropped.

Dynamic Strain Graph



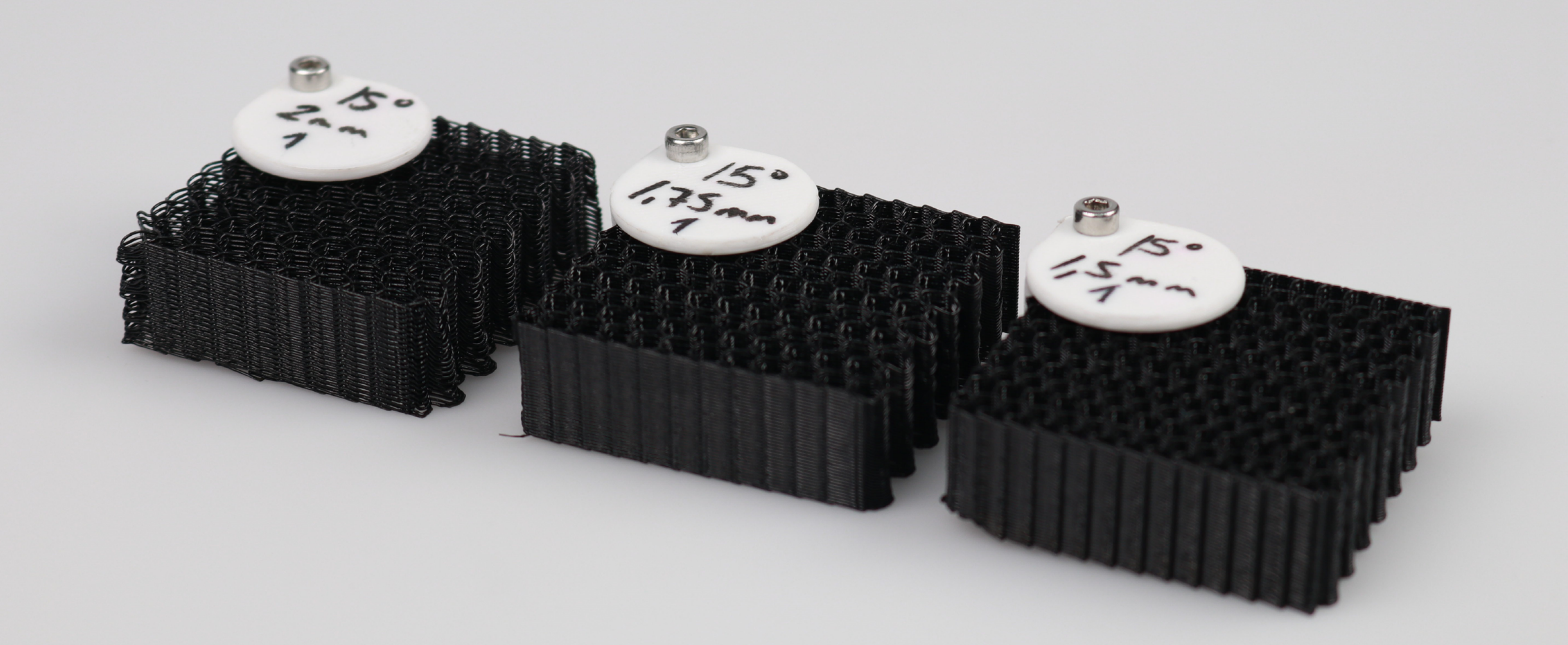
The observations made from Dynamic Strain Graph prove a different image, at lower impact energies, the TPU architected structure exhibits very low stiffness compared to the Polyurethane Foam (PUF), which leads to a lower peak deceleration. This outcome is expected, as the stiffness of the material influences its response to lower-energy impacts.

However, what's surprising with this graph is that as the impact energy increases, the deformation of the TPU architected structure starts to change, not matching or resembling the graph of the Polyurethane Foam, and the peak decelerations generated by the TPU seem to go as an exaggerated version of the control material.

These findings indicate that the TPU 12.5º architected structure can serve as a viable alternative to the Polyurethane foam, although more testing would be required to make sure it is a fully viable structure, or to determine if the results were skewed. This sample did not offer consistent cushioning performance under different impact conditions.

In summary, while the TPU samples are generally to be very different from the Polyurethane foam control sample, the choice of structural parameters, such as angle and point separation, has a significant impact on their performance. The sample with a 12.5º angle at 1.75mm closely matches the control sample's behaviour in the cushioning curve diagram but did not match at all in the Dynamic Strain Graph.

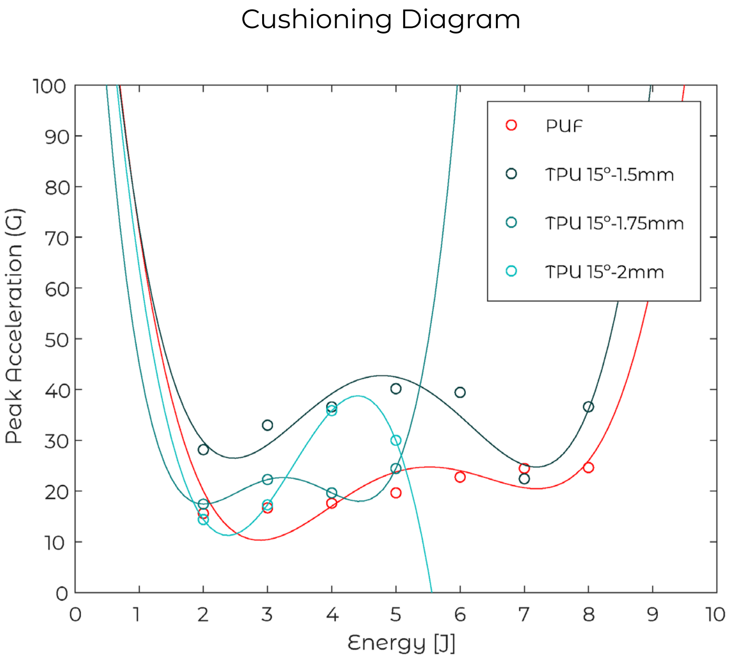
Figure 27: TPU 15° Samples
Own work



TPU 15º

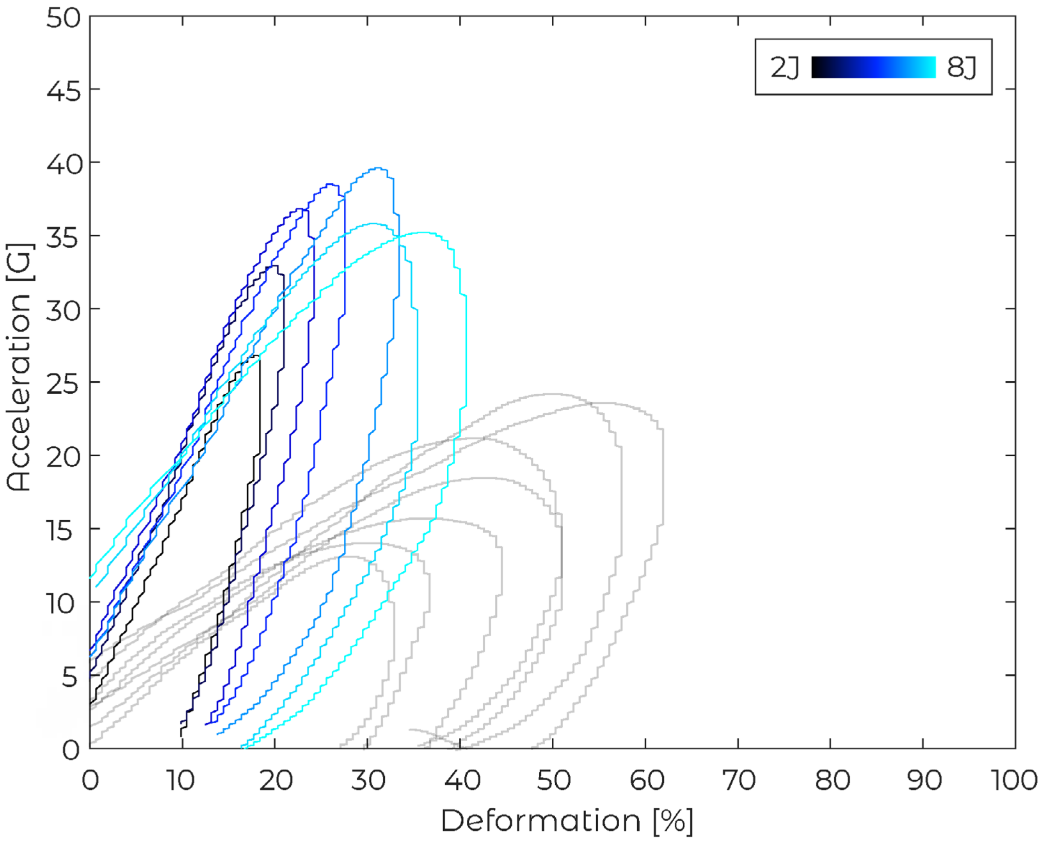
These 3 samples come from slicing the volume with a 15 degree angle, these were expected to generate the best results, less material piled up as the 12.5° degree samples but still enough while not reaching the levels of the 17.5° , the results show how this variation of the angle does affect the stiffness of the samples. This structure should bring the overall stiffness to a lower point, meaning the samples that have fared well in the last two cases should not work.

As depicted in the provided graph, the results of TPU 15° are compared to the red line which represents the Polyurethane Foam sample. The graph shows that none of the TPU samples exhibits behaviour quite similar to the control Polyurethane foam sample. However, the sample with the points spaced 1.5 mm draws a curve which resembles the PUF one, just at a higher peak deceleration.



- **Sample at 15° angle at 2mm:** These samples rapidly failed by rapidly reaching peak compression.
- **Sample of 15° angle at 1.75mm:** This sample fared a similar result as the previous one.
- **Sample of 15° at 1.5mm:** This sample generated a stiff structure. Which replicates the curve of the PUF although the 7J energy point should be considered as an outlier.

Dynamic Strain Graph



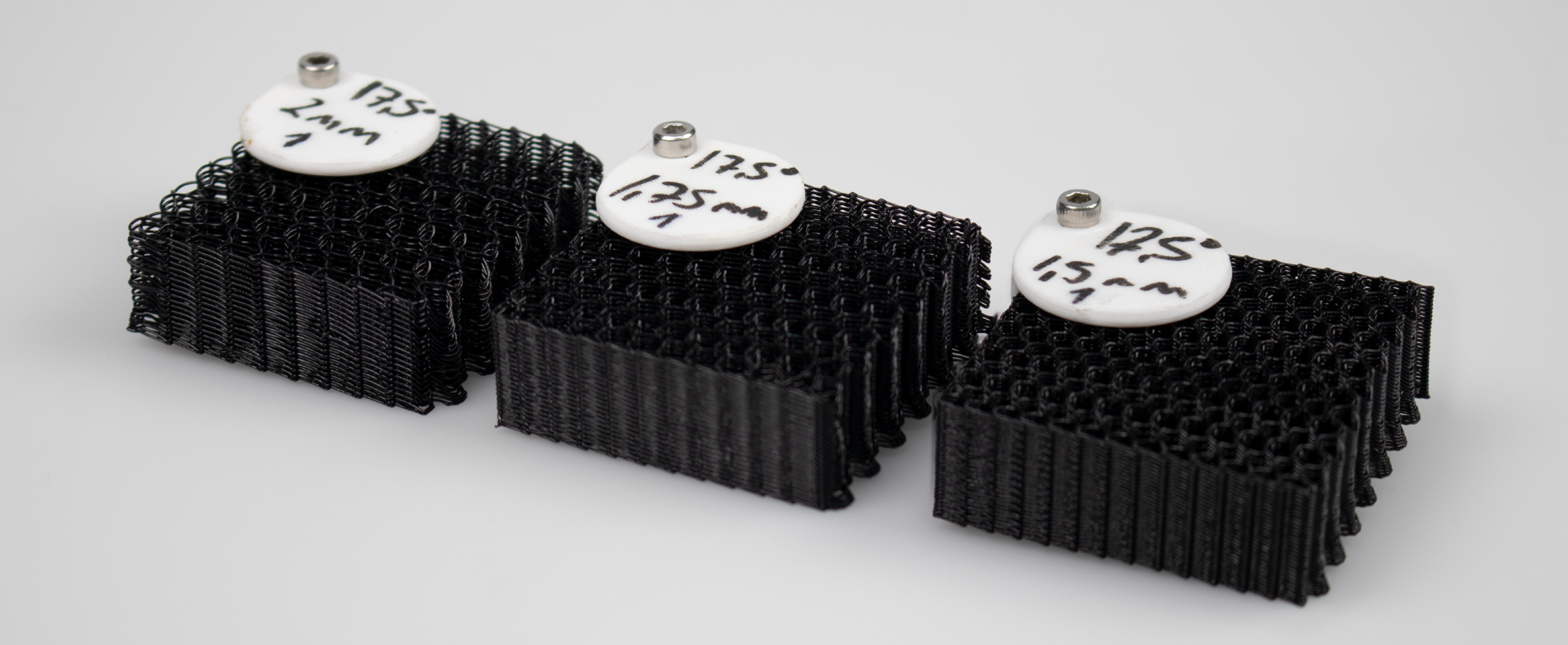
The observations made from Dynamic Strain Graph prove a very optimistic image, the TPU architected structure exhibits higher stiffness compared to the Polyurethane Foam (PUF), which leads to a higher peak deceleration. This outcome is expected, as the stiffness of the material influences its response to lower-energy impacts, a notable feature is although the deformation and peak deceleration do not match the PUF one, the shape and progression through the energies resembles the PUF one.

These findings indicate that the TPU 15º architected structure can serve as a viable alternative to the Polyurethane foam, although as a higher stiffness sample, this piece would be useful for overshell like pieces, as its stiffness can help spread the forces while maintaining mobility This samples did offered consistent cushioning performance under different impact conditions.

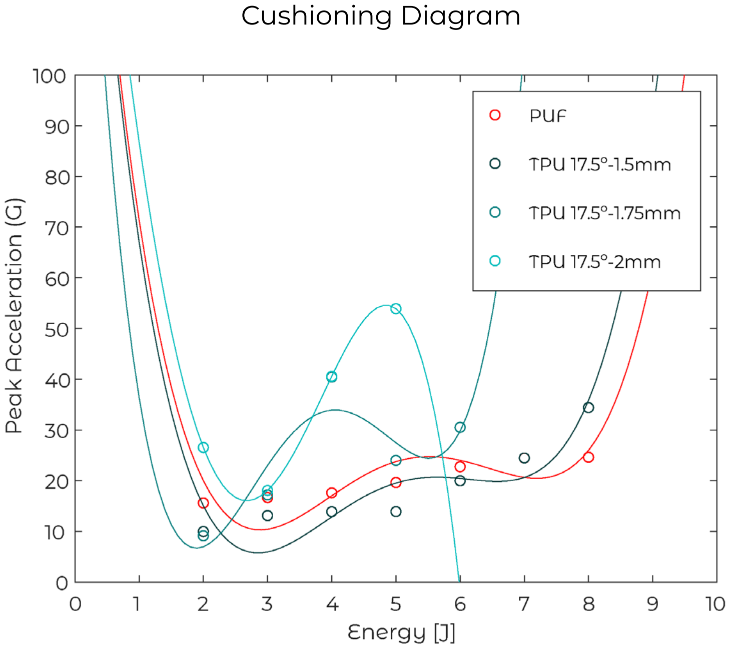
In summary, while the TPU samples are generally different from the Polyurethane foam control sample, the choice of structural parameters, such as angle and point separation, has a significant impact on their performance rapidly eliminating the lower density ones. The sample with a 15º angle at 1.5 mm matched the control sample's behaviour in the cushioning curve diagram and in the Dynamic Strain Graph.

(It's worth noting how on this graph the peak deceleration at 7 Joules does not drop below 35 G while in the Cushioning curve this goes lower than 25 G. This is the reason why this point is an outlier and another look at the data and calculations should be done to ensure better accuracy)

Figure 28: TPU 17.5º Samples
Own work



TPU 17.5º



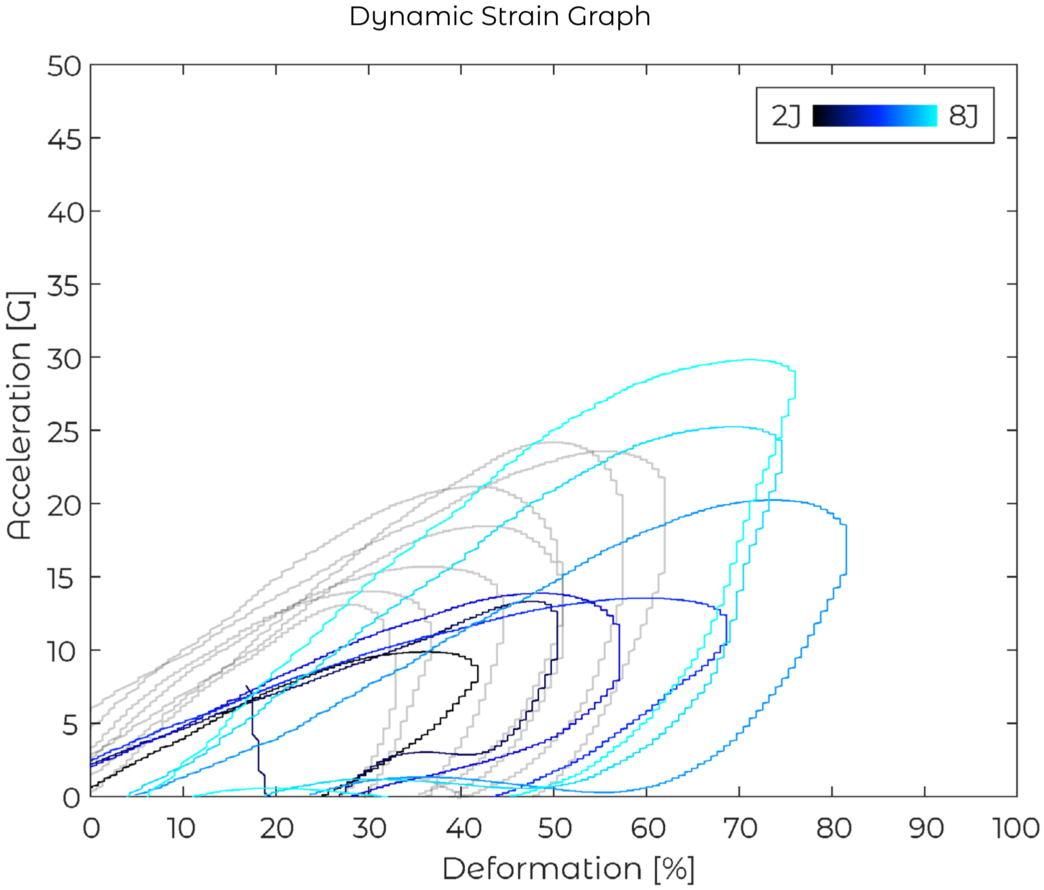
The 3 samples from slicing at 17.5 degrees, were expected to generate the softest results, these are the samples with less material piled up as the 17.5º degree is near the limit where the nozzle could print without issues, the results show how this variation of the angle does lower the stiffness a lot, as the spaces between lines are easily observable with the naked eye.

As depicted in the provided graph, the results of TPU 17.5º are compared to the red line which represents the Polyurethane Foam sample. The graph shows that the TPU samples failed before providing any good data except the 1.5 mm one. Which closely matched the line even getting below it.

Sample at 17.5º angle at 2mm: These samples rapidly failed by rapidly reaching peak compression.

Sample of 17.5º angle at 1.75mm: This sample fared a similar result as the previous one.

Sample of 17.5º at 1.5mm: This sample generated a stiff structure. Which replicates the curve of the PUF in a much cleaner way.



The observations that can be extracted from the Dynamic Strain Graph prove a very optimistic image, it resembles the one shown in the case of TPU 12.5° 1.75mm, although in a much more organised manner. The TPU architected structure exhibits a low stiffness compared to the Polyurethane Foam (PUF) at lower impact energies, which leads to lower peak decelerations, while as it goes higher the stiffness increases, with the peak deceleration increasing as well. The shape and progression through the energies initially resembles the one of the PUF, albeit with lower peak decelerations, it is once the impact energy surpasses 6 J the shape changes and the peak deceleration sky rockets while the deformation scales back by nearly 10%.

This indicates that the 17.5° architected structure can serve as a viable alternative to the Polyurethane foam. In summary, while the first two TPU samples are generally different from the Polyurethane foam control sample, thus failing immediately. The sample with a 17.5° angle at 1.5mm did not match the control sample's behaviour in the Dynamic Strain Graph, but it's close resemblance to the Cushioning Curve diagram means its properties are useful and while not optimal, might serve a useful purpose due to the small wave shape.

4.1.4 Best results

In this cushioning graph the four selected samples are compared to each other, it is interesting to see the variability at lower energy impacts while they do find an intersection at the higher impact.

As each of the samples was analysed, their Dynamic graphs showed in some occasions similar behaviours to the control sample, in others there were unexpected ones. The way some of the structures act was close to what one could have expected.More testing, with variations on the geometry of the samples, could prove if some of the selected samples should have been eliminated while some of the eliminated samples would actually work better.

Another issue with the samples is the way these were sliced, these samples were generated through the method explained in section 3.5.4. This method results in two side walls (fig29) which if they had been modelled using the method explained in point 3.5.6 this side wall would not exist(fig30). It is unknown if this difference brings a large difference to the functionality of the parts. But it is safe to assume the results should be a bit lower than their results with said wall.

An interesting feature which could not be proven, was the use, and feasibility of lower density samples, this is due to the low thickness of the samples, as the lower density sample would rapidly reach their peak deformation. In some cases when the sample would not be fully crushed the safety features of the testing equipment, implemented to ensure the longevity of the impactor cell, would stop the impactor before even reaching a full stop on the sample.

Thicker samples would not run into this problem, which means this could have helped reach higher energy impacts. This may mean the results, once more, could be different from those shown here. On the other hand, adding more impacts at different energies would result in an overwhelming amount of data. The data used for the analysing of the samples is already a large amount, added to the lack of experience in data processing having more could have been deteriorating to the final result.

Even though these issues with the testing are existent, and a certain amount of scepticism is required, the sample made out using the structure at 17.5° 1.5mm gave results which, as explained in its section, although different in strain, these were very positive as they showed not to be a large issue, but in some cases maybe a feature.

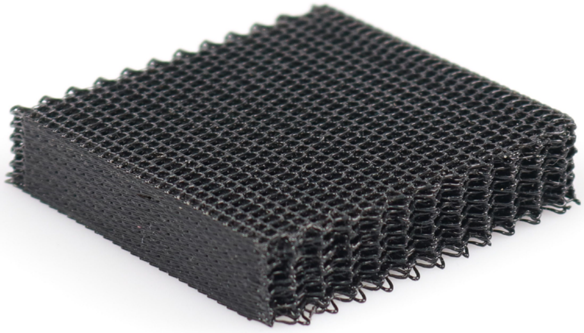


Figure 29: TPU Sample with solid side wall
Own work

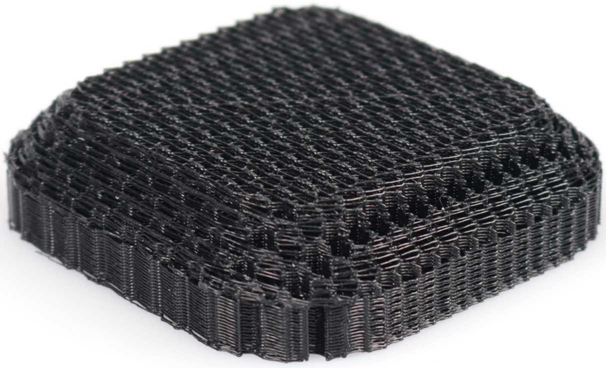
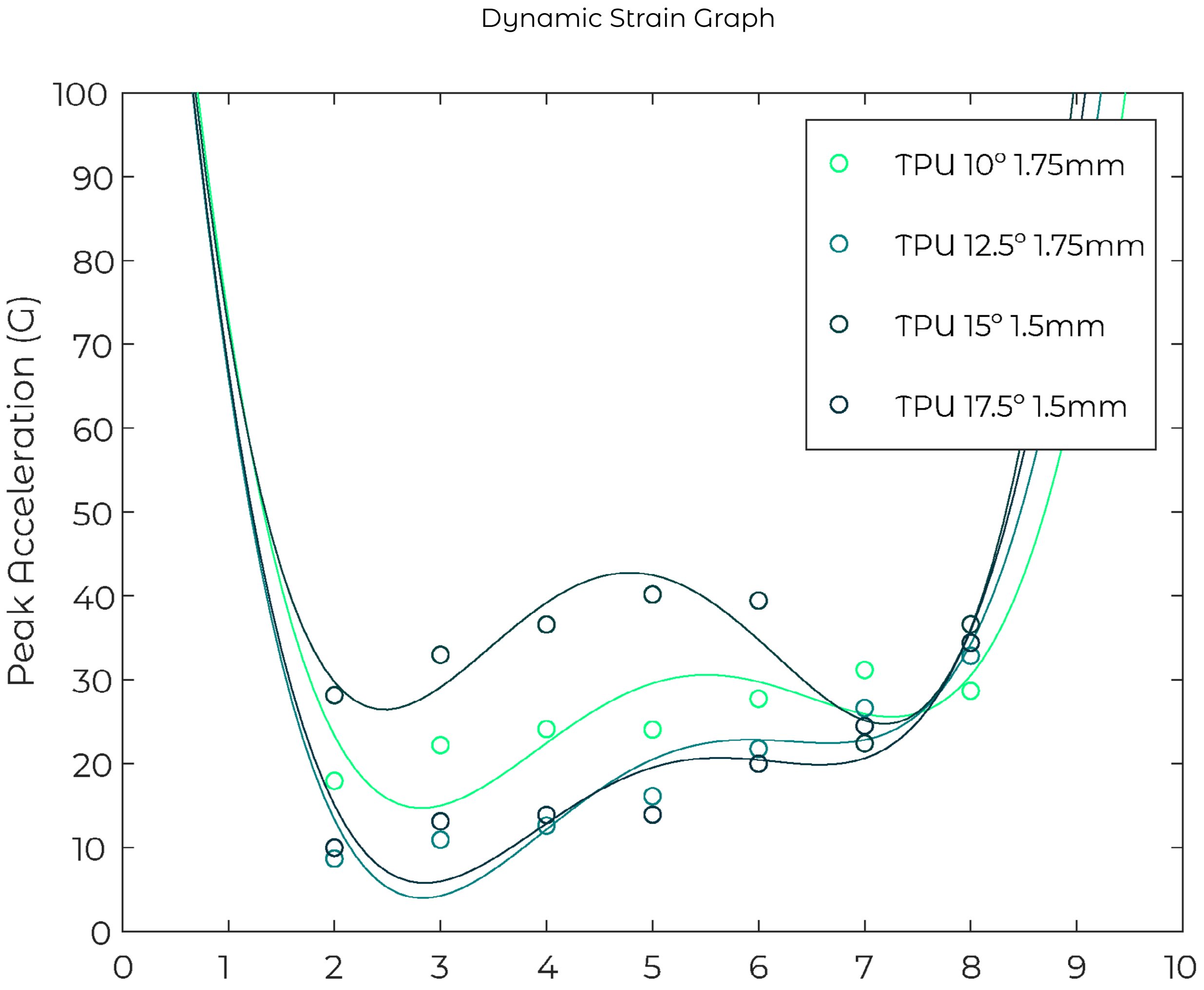


Figure 30: TPU Sample without solid side wall
Own work


Dynamic Strain Graph
Peak Acceleration (G)
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
6
7
8
9
10
TPU 10° 1.75mm
TPU 12.5° 1.75mm
TPU 15° 1.5mm
TPU 17.5° 1.5mm

4.2 Application

The next phase in the research involves the replication of a back protector's core material using 3D printing technology. After meticulously selecting structures that closely resemble the material properties of the Fouganza back protector, the task of 3D printing the insert of the protector using the architected material at three different densities. These density choices are informed by our experimental findings, and they serve two primary purposes.

The first purpose of designing this with different densities is testing and proving the feasibility of printing various apparent densities and wave sizes simultaneously. Up to this point,each density or shape has been printed separately. Secondly, to create a denser upper layer that can better distribute point loads over a larger area, thereby reducing the impact felt by the user.

Figure 31: Polyurethane Foam insert from Fouganza back protector
Own work

Figure 32: Failed print of the TPU architected back protector insert
Own work

The slicing process was accomplished using a modified version of the Grasshopper programming, which allowed us to apply multiple densities at different heights seamlessly. This program's flexibility facilitated our efforts without encountering any significant challenges.

During the preliminary stages, issues were encountered with smaller prototypes that shared similar geometries with the final product(fig32). These prototypes exhibited poor printing quality, particularly at the intersection between variations in wave size. Without adequate support, layer transitions led to immediate print failures. However, this problem was efficiently resolved by overlapping the first layer of the new density with the preceding one, creating a more stable foundation for subsequent layers.

Once this challenge was overcome, the model of the final geometry for the back protector was generated. Given that the geometry exceeded the available print surface, it was divided into two parts to be joined in a post-processing step. The joining process needed to ensure user safety and avoid any potential hazards, thus the use of any hard joint was not feasible, or any surface which when glued could generate a harder or stiffer part. To address this, the back protector is designed split in two parts, with a deliberate 10° angled division. This division allows for careful alignment of the first part during printing, enabling the second part to be seamlessly added on top. This results in the fusion of the TPU material to itself, forming a robust bond without compromising the back protector's properties(fig33).

The joining was a stressful operation although the parts seemed to be haphazardly hanging (fig34) and while it may seem the nozzle assembly can collide with the part already printed there were no issues. Careful placing and fixing the already printed part may seem a cumbersome step. Even more than joining the parts using any other method, the reality is, it is not, by coding in the Gcode, an indicator, a pause, and having the nozzle move out of the way to allow for the operation. This became an easy and rapid process to do.

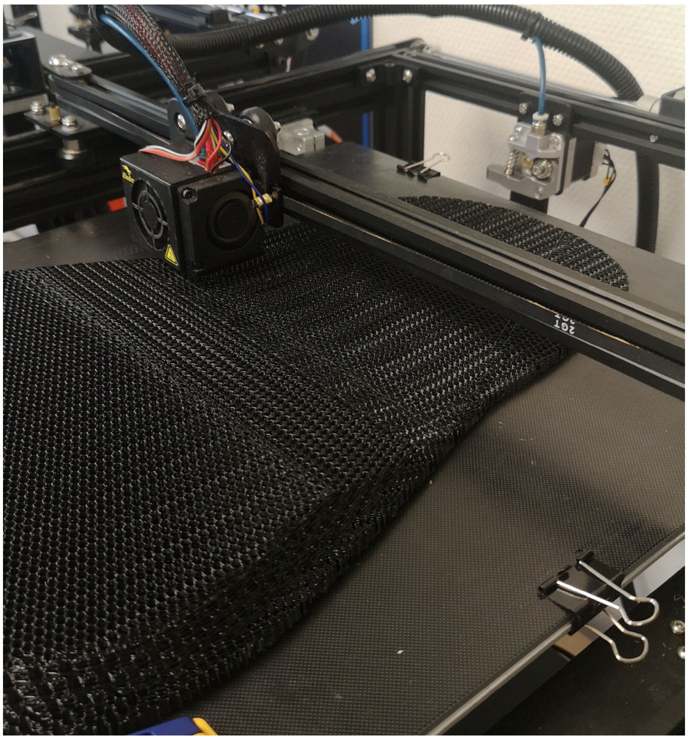


Figure 33: printing of the 2nd half and joining of theTPU architected back protector insert
Own work

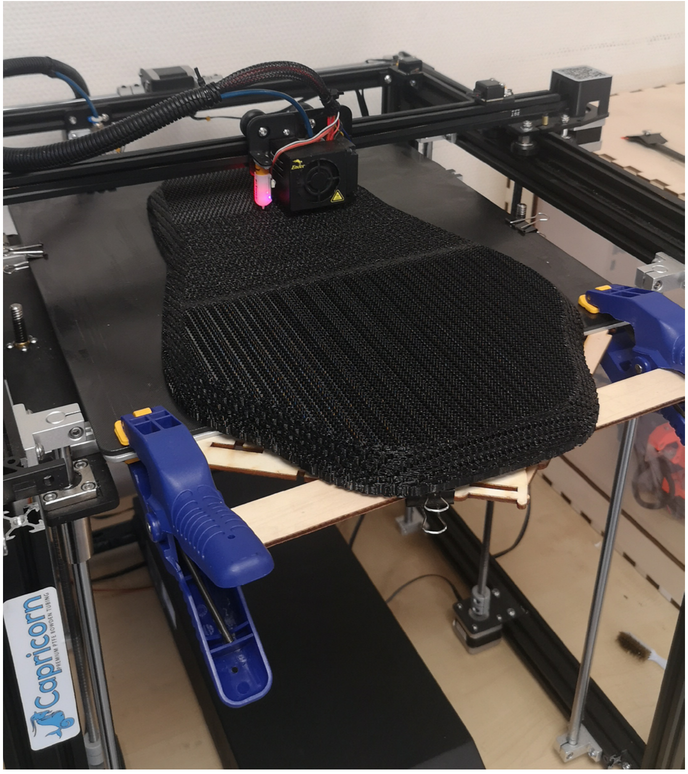


Figure 34: temporal support for the 1rst half of the TPU architeted back protector
Own work

Subsequently, the 3D printed back protector was subjected to unconventional testing, involving repeated impacts. While the standard testing methods outlined in EN1621-2 were not applicable due to tool constraints, the unconventional testing approach undertaken provided valuable insights. Despite the unconventional nature of our testing and the absence of precise scientific measurements, the 3D printed back protector demonstrated a remarkably similar performance to the original product.

The 3D printed protector was placed in its carrier vest, this is the garment that was obtained from extracting the Polyurethane Foam insert. Once this was done, multiple colleagues wore it and gave their opinions, many concluding in it not feeling much difference from other back protectors. A common occurrence was it being a bit stiffer than the original one. A theory that could not be tested properly is its breathability, this would only be able to be proven using long extensive wearing times, while doing some extraneous sport.

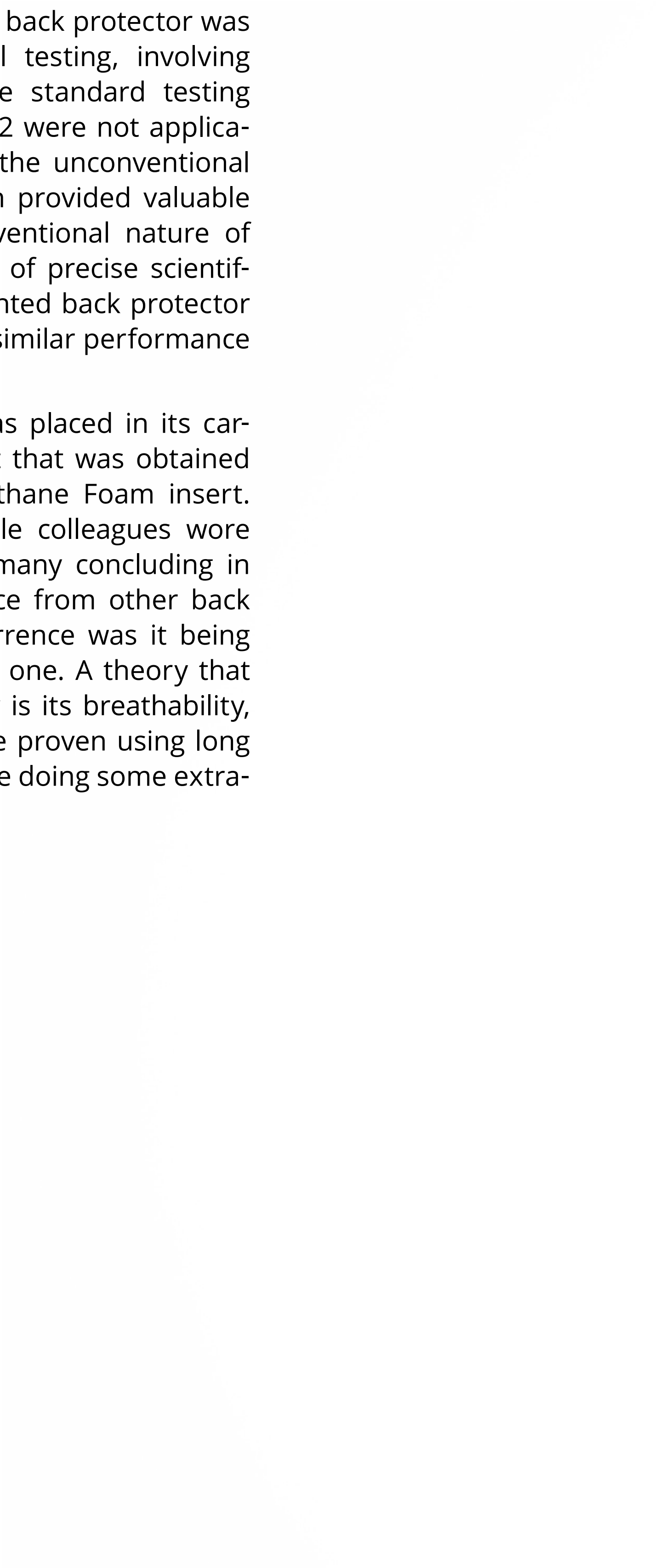


Figure 35: Back protector with TPU architected strcuture insert placed inside
Own work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fouganza
fouganza

4.3 Discussion

The explained specific samples of the results are those that matched the curve of the foam extracted from the fouganza back protector. These samples proved the viability of the material, although this proof is deeply focused on the use in a back protector. There are many sports protective equipment, each with different testing standards, which mimic the forces and conditions in which they work. Not only are there specific tests for the protection and even the sport they are used in, but the normatives in such sports also affect the way they work.

While a chest plate is an easy part to imagine, when applied to differents ports, American Football, Rugby, Motocross, Field Hockey goalie, each have certain specific constraints, the rugby one cannot be over 5mm thick and it has very specific compressibility laws (laws are the rugby rules), while in hockey the chest plate is a thick foam pad, and in motocross or american football, these are hard shells.

This means a sample that might not have been selected during the testing, as it was too soft could work in rugby because it can mimic the rulings set on it. While one that is too stiff could be used to expand the hard shell to a wider area without risking loss of mobility (although in this case,foreign object penetration could become once more, a problem).

Having used the data provided by the testing helped generate a protection which did help show much more the viability of this architected structure, it is not a definitive test, although concepts such as large format printing, multiple apparent densities layered upon each other, and merging parts during the printing were proven.

As this material's functionality has been proven, new doors open, one of the reasons this project was started is due to the lack of a material which could have allowed the design of an ultra-customized protection. Now methods could be designed to create the personalised shape, and layered density for a user's specific body shape.

5. Conclusions

The culmination of this research project has brought significant insights and accomplishments in the development of an architected material for sports protective equipment. In line with our stated objectives, the journey, although unconventional, chaotic, and full of turns, allowed us to understand the foam materials used in sports-based personal protectors, to delve into the intricacies of 3D printing, with a particular focus on off-the-shelf FDM 3D printers, and comprehend the properties of Thermoplastic Polyurethane (TPU) as the selected material. The aim was to enhance the design and manufacturing processes of personal protective equipment, with the ultimate goal of improving user comfort, safety, and performance in sports activities.

The research of additive manufacturing methods was in a certain way, a bit over the top, as the available methods were known beforehand. Unlike this case, the research on the materials, from the already existing foams to the materials used for 3d printing, allowed and brought some knowledge which helped better research and set for the testing methods.

Through the research process, the set objectives were successfully achieved and, in many aspects, exceeded initial expectations. The testing results demonstrated that the architected material developed possesses characteristics that make it a viable option for sports protective equipment. Particularly noteworthy is the fact that some of the samples yielded results remarkably similar to those of the control sample, providing strong evidence of the material's promise.

Moreover, the practicality and functionality of the material was able to be showcased by successfully 3D printing a full-sized back protector, fulfilling the objectives of breathability and ease of printing, which although difficult due to the large size, accomplished the objectives established .

However, it is crucial to acknowledge certain areas that require further attention and improvement. The use of TPU as a printing material, while offering several advantages, did present a limitation in terms of printing speed, as it tends to be slower compared to other materials. Additionally, the testing phase faced constraints due to the unavailability of specialised testing tools, necessitating some adaptations in our approach. Although the obtained data is valuable, there is potential for more comprehensive testing and analysis.

Furthermore, the Grasshopper code employed in the project, while functional, would greatly benefit from optimization. Specifically, optimising the code to generate waveforms mathematically could enhance efficiency, reducing CPU and RAM usage due to not using large amounts of points . Lastly, the data processing aspect of our research could have been further refined with the expertise of a skilled data analyst. The testing resulted in large amounts of data which was hard to understand and process, the resulting processed data was more manageable but the graphing and comprehension of it was still a hard job. With more experience a better matlab programming could have been made to better prepare the data, drawing the graphs and eliminating outliers.

In conclusion, our journey in developing this architected material for sports protective equipment has yielded promising results. We have accomplished our set goals and demonstrated the material's potential. Nevertheless, there remains room for refinement and optimization in various aspects of the research. This serves as an invitation for future research endeavours to build upon our achievements and further enhance the development, testing, and application of innovative materials in the realm of sports protective equipment.

6. Future work

This project as stated in the conclusions is nowhere perfect, from its conception, the design of an ultra-customizable sports protective equipment, which found feasibility issues in the possibility of testing to the availability of a material which could be used for it. To the end result, which still found issues on the testing phase. There are many points which could not only be improved they could become a project in themselves.

Further testing of the material, using many more samples having many more variations, from thickness surface area, apparent densities. Generating larger amounts of data, would require someone better prepared and experienced to process all the data and generate a better way to communicate the properties generated by each different variation of the architected structure. Categorising this data would also allow better ease of use selecting the right variations for the desired properties.

The first is Optimization, while in the conclusions a simile of this point is stated, in this case it's not meant to be an optimization on grasshopper, but a proper program. The geometry is clear, if it can be developed any other easy variable density could be achieved in a better way than layer by layer, thus achieving the possibility of actively designing stiffer regions and softer ones, one next to each other. Having it programmed in a different way could also allow for better slicing of more complicated geometries. Another interesting possibility is it being used as any other 3D printing slicer where one could easily select the properties desired for a model, and easily obtain an output.

Finally not one only project but hopefully a lot more, it would be interesting to see the application off this architected material in a customised piece of protection, not such as the back protector designed and printed for this project, but one where through the use of parametric design a piece is made custom for a user. It would be interesting to show results of testing not the foam but the protection, as stated the standards for testing protective equipment require very specific impactors at higher impact energies.

All in all it would be interesting and fulfilling to see this project's results be used or further improved by anyone, if this project results in people being able to further the field of ultra-customizable gear as they do not become blocked by the lack of architected structures and materials easily printable without specific printers.

7. References

[1] ‘Armour | History, Types, Definition, & Facts | Britannica’. Accessed: Jun. 10, 2023. [Online]. Available: https://www.britannica.com/topic/armour-protective-clothing

[2] ‘Personal Protective Equipment in Sports: History and Future - ThermoPro’. Accessed: Jun. 07, 2023. [Online]. Available: https://thermopro.com/personal-protective-equipment-in-sports-history-and-future/

[3] G. Salvaterra, ‘Evolution of Sports-related Headgear’, Sports Med. Arthrosc. Rev., vol. 24, no. 3, p. e34, Sep. 2016, doi: 10.1097/JSA.0000000000000122.

[4] ‘American football - Football Safety, Big Three, NCAA, and Forward Pass | Britannica’. Accessed: Jun. 07, 2023. [Online]. Available: https://www.britannica.com/sports/American-football/Managing-the-violence-of-the-game

[5] ‘10 Taping and Strapping techniques for Rugby’. Accessed: Jun. 14, 2023. [Online]. Available: https://www.physique.co.uk/Buyers-Guides/Rugby-Taping-Techniques

[6] ‘Padding, taping and bracing sports injuries - Sports Injury Prevention’. Accessed: Jun. 14, 2023. [Online]. Available: https://www.medic8.com/healthguide/sports-medicine/prevention/padding.html

[7] S. Dlugosch, H. Hu, and A. C. Chan, ‘Impact Protective Clothing in Sport: Areas of Application and Level of Utilization’, Res. J. Text. Appar., vol. 16, no. 3, pp. 18–28, Aug. 2012, doi: 10.1108/RJTA-16-03-2012-B002.

[8] D. G. Patrick, R. Van Noort, and M. S. Found, ‘Scale of protection and the various types of sports mouthguard’, Br. J. Sports Med., vol. 39, no. 5, pp. 278–281, May 2005, doi: 10.1136/bjsm.2004.012658.

[9] D. Turner, ‘Apparel incorporating a protective element and method of use’, US8713719B2, May 06, 2014 Accessed: Oct. 13, 2023. [Online]. Available: https://patents.google.com/patent/US8713719B2/en?q=(Protective+Apparel)&oq=Protective+Apparel

[10] ‘Foam | chemical compound | Britannica’. Accessed: May 05, 2023. [Online]. Available: https://www.britannica.com/science/foam

[11] J. P. Andrés, ‘Selección de Materiales en el Proceso de Diseño’.

[12] ‘Foamed plastic | Britannica’. Accessed: May 05, 2023. [Online]. Available: https://www.britannica.com/technology/foamed-plastic

[13] Foamrite, ‘What Is The Difference Between Open Cell Foam and Closed Cell Foam?’, Foamrite. Accessed: May 11, 2023. [Online]. Available: https://foamrite.co.uk/what-is-the-difference-between-open-cell-foam-and-closed-cell-foam/

[14] ‘Closed-Cell Foams | Foam Factory, Inc.’ Accessed: May 11, 2023. [Online]. Available: https://www.foambymail.com/closed-cell-foams.html

[15] ‘Is Foam Recyclable? (And How Do You Dispose Of Foam?) - Thinking Sustainably’. Accessed: May 12, 2023. [Online]. Available: https://www.thinkingsustainably.com/is-foam-recyclable/

[16] ‘Why is Polystyrene/Styrofoam Not Recyclable?’ Accessed: May 12, 2023. [Online]. Available: https://www.wastewiseproductsinc.com/blog/the-problem-with-recycling-styrofoam/

[17] ‘Polyolefins - Whiteley - Major Reference Works - Wiley Online Library’. Accessed: Jun. 26, 2023. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/14356007.a21_487

[18] H. Maddah, ‘Polypropylene as a Promising Plastic: A Review’, 2163-1352, vol. 2016, pp. 1–11, Jan. 2016, doi: 10.5923/j.ajps.20160601.01.

[19] S. Kitagawa, T. Nakayama, and M. Isono, ‘Process for producing polypropylene foam’, US4766159A, Aug. 23, 1988 Accessed: Aug. 14, 2023. [Online]. Available: https://patents.google.com/patent/US4766159A/en

[20] B. P. Federation, ‘Expanded Polypropylene (EPP)’, British Plastics Federation. Accessed: Aug. 14, 2023. [Online]. Available: https://www.bpf.co.uk/plastipedia/polymers/Expanded_Polypropylene_EPP.aspx

[21] A. Alsabri, F. Tahir, and S. G. Al-Ghamdi, ‘Environmental impacts of polypropylene (PP) production and prospects of its recycling in the GCC region’, Mater. Today Proc., vol. 56, pp. 2245–2251, Jan. 2022, doi: 10.1016/j.matpr.2021.11.574.

[22] V. P. Ranjan and S. Goel, ‘Recyclability of polypropylene after exposure to four different environmental conditions’, Resour. Conserv. Recycl., vol. 169, p. 105494, Jun. 2021, doi: 10.1016/j.resconrec.2021.105494.

[23] J. Scheirs and D. Priddy, Modern Styrenic Polymers: Polystyrenes and Styrenic Copolymers. John Wiley & Sons, 2003.

[24] ‘History of Polymers & Plastics for Teachers’. Accessed: Jun. 29, 2023. [Online]. Available: https://web.archive.org/web/20121114004304/http://plastics.americanchemistry.com/Education-Resources/Hands-on-Plastics/Introduction-to-Plastics-Science-Teaching-Resources/History-of-Polymers-Plastics-for-Teachers.html

[25] K. A. Howard, ‘Method for manufacturing expanded polystyrene foam components from used polystyrene materials’, US5217660A, Jun. 08, 1993 Accessed: Jun. 29, 2023. [Online]. Available: https://patents.google.com/patent/US5217660A/en?inventor=Kevin+A.+Howard%2c

[26] ‘L_2019155EN.01000101.xml’. Accessed: Jun. 30, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX-%3A32019L0904

[27] N. V. Gama, A. Ferreira, and A. Barros-Timmons, ‘Polyurethane Foams: Past, Present, and Future’, Materials, vol. 11, no. 10, p. 1841, Sep. 2018, doi: 10.3390/ma11101841.

[28] ‘Polyurethane global market volume 2029’, Statista. Accessed: Jul. 09, 2023. [Online]. Available: https://www.statista.com/statistics/720341/global-polyurethane-market-size-forecast/

[29] ‘Polyurethane’, Wikipedia. Jul. 04, 2023. Accessed: Jul. 09, 2023. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Polyurethane&ol-

did=1163453834#cite_note-4

[30] M. Shoaib Suleman, S. Khan, N. Gull, W. Aleem, M. Shafiq, and T. Jamil, ‘A Comprehensive Short Review on Polyurethane Foam’, Int. J. Innov. Sci. Res., vol. 12, pp. 165–169, Dec. 2014.

[31] S. Marx, W. Odendaal, A. Williams, U. Vermeulen, A. Grobler, and L. C. Muller, Production of bio-degradable polyurethane foam from sugarcane bagasse and biodiesel-derived crude glycerine. ETA-Florence Renewable Energies, 2015. doi: 10.5071/23rdEUBCE2015-3AV.3.21.

[32] M. J. Kwon, D. H. Lim, I. C. Choi, H.-W. Kwon, and C.-S. Ha, ‘Preparation and properties of ethylene-vinyl acetate copolymer-based blend foams’, J. Elastomers Plast., vol. 53, no. 1, pp. 68–82, Feb. 2021, doi: 10.1177/0095244319900375.

[33] C. Z. Paiva Junior, R. S. Peruchi, F. de C. Fim, W. de O. S. Soares, and L. B. da Silva, ‘Performance of ethylene vinyl acetate waste (EVA-w) when incorporated into expanded EVA foam for footwear’, J. Clean. Prod., vol. 317, p. 128352, Oct. 2021, doi: 10.1016/j.jclepro.2021.128352.

[34] S. M. Khan, N. Gull, R. U. Khan, and M. T. Z. Butt, ‘Polyvinylchloride (PVC): Structure and Properties Relationship’, in Polyvinylchloride-based Blends: Preparation, Characterization and Applications, V. P. M. and R. N. Darie-Nita, Eds., in Springer Series on Polymer and Composite Materials. , Cham: Springer International Publishing, 2022, pp. 19–47. doi: 10.1007/978-3-030-78455-3_2.

[35] J. Thornton, ‘Environmental Impacts of Polyvinyl Chloride (PVC) Building Materials’.

[36] I. Gibson, D. Rosen, and B. Stucker, ‘Introduction and Basic Principles’, in Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, I. Gibson, D. Rosen, and B. Stucker, Eds., New York, NY: Springer, 2015, pp. 1–18. doi: 10.1007/978-1-4939-2113-3_1.

[37] T. Wohlers and T. Gornet, ‘History of additive manufacturing’, 2015.

[38] K. V. Wong and A. Hernandez, ‘A Review of Additive Manufacturing’, ISRN Mech. Eng., vol. 2012, pp. 1–10, Aug. 2012, doi: 10.5402/2012/208760.

[39] A. Jandyal, I. Chaturvedi, I. Wazir, A. Raina, and M. I. Ul Haq, ‘3D printing – A review of processes, materials and applications in industry 4.0’, Sustain. Oper. Comput., vol. 3, pp. 33–42, Jan. 2022, doi: 10.1016/j.susoc.2021.09.004.

[40] R. Bogue, ‘3D printing: the dawn of a new era in manufacturing?’, Assem. Autom., vol. 33, no. 4, pp. 307–311, Jan. 2013, doi: 10.1108/AA-06-2013-055.

[41] ‘The 7 categories of Additive Manufacturing | Additive Manufacturing Research Group | Loughborough University’. Accessed: Jul. 10, 2023. [Online]. Available: https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/

[42] P. J. Bártolo, Stereolithography: Materials, Processes and Applications.

Springer Science & Business Media, 2011.

[43] ‘The recent development of vat photopolymerization: A review’, Addit. Manuf., vol. 48, p. 102423, Dec. 2021, doi: 10.1016/j.addma.2021.102423.

[44] ‘Ultralight, ultrastiff mechanical metamaterials | Science’. Accessed: Jul. 11, 2023. [Online]. Available: https://www.science.org/doi/10.1126/science.1252291

[45] ‘SLA vs. DLP: Differences and Comparison’. Accessed: Jul. 11, 2023. [Online]. Available: https://www.xometry.com/resources/3d-printing/sla-vs-dlp-3d-printing/

[46] ‘One-step volumetric additive manufacturing of complex polymer structures | Science Advances’. Accessed: Jul. 11, 2023. [Online]. Available: https://www.science.org/doi/full/10.1126/sciadv.aao5496

[47] S. Sun, M. Brandt, and M. Easton, ‘2 - Powder bed fusion processes: An overview’, in Laser Additive Manufacturing, M. Brandt, Ed., in Woodhead Publishing Series in Electronic and Optical Materials. , Woodhead Publishing, 2017, pp. 55–77. doi: 10.1016/B978-0-08-100433-3.00002-6.

[48] R. Singh et al., ‘Powder bed fusion process in additive manufacturing: An overview’, Mater. Today Proc., vol. 26, pp. 3058–3070, Jan. 2020, doi: 10.1016/j.matpr.2020.02.635.

[49] K. C. Datsiou, E. Saleh, F. Spirrett, R. Goodridge, I. Ashcroft, and D. Eustice, ‘Additive manufacturing of glass with laser powder bed fusion’, J. Am. Ceram. Soc., vol. 102, no. 8, pp. 4410–4414, 2019, doi: 10.1111/jace.16440.

[50] ‘A review of the process physics and material screening methods for polymer powder bed fusion additive manufacturing - ScienceDirect’. Accessed: Jul. 12, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0079670018303071

[51] P. Mercelis and J. Kruth, ‘Residual stresses in selective laser sintering and selective laser melting’, Rapid Prototyp. J., vol. 12, no. 5, pp. 254–265, Jan. 2006, doi: 10.1108/13552540610707013.

[52] B. Ferrar, L. Mullen, E. Jones, R. Stamp, and C. J. Sutcliffe, ‘Gas flow effects on selective laser melting (SLM) manufacturing performance’, J. Mater. Process. Technol., vol. 212, no. 2, pp. 355–364, Feb. 2012, doi: 10.1016/j.jmatprotec.2011.09.020.

[53] T. Duda and L. V. Raghavan, ‘3D Metal Printing Technology’, IFAC-Pap., vol. 49, no. 29, pp. 103–110, 2016, doi: 10.1016/j.ifacol.2016.11.111.

[54] I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, ‘Binder Jetting’, in Additive Manufacturing Technologies, I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, Eds., Cham: Springer International Publishing, 2021, pp. 237–252. doi: 10.1007/978-3-030-56127-7_8.

[55] A. Mostafaei et al., ‘Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges’, Prog. Mater. Sci., vol. 119, p. 100707, Jun. 2021, doi: 10.1016/j.pmatsci.2020.100707.

[56] M. Ziaee and N. B. Crane, ‘Binder jetting: A review of process, ma-

terials, and methods’, Addit. Manuf., vol. 28, pp. 781–801, Aug. 2019, doi: 10.1016/j.addma.2019.05.031.

[57] O. Gülcan, K. Günaydın, and A. Tamer, ‘The State of the Art of Material Jetting—A Critical Review’, Polymers, vol. 13, no. 16, Art. no. 16, Jan. 2021, doi: 10.3390/polym13162829.

[58] C. B. Williams and L. B. Bezek, ‘Material Jetting of Polymers’, Jun. 2020, doi: 10.31399/asm.hb.v24.a0006551.

[59] B. P. Connor, ‘Material Jetting of Ceramics’, Jun. 2020, doi: 10.31399/asm.hb.v24.a0006550.

[60] H. Yang et al., ‘Performance evaluation of ProJet multi-material jetting 3D printer’, Virtual Phys. Prototyp., vol. 12, no. 1, pp. 95–103, Jan. 2017, doi: 10.1080/17452759.2016.1242915.

[61] I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, ‘Material Extrusion’, in Additive Manufacturing Technologies, I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, Eds., Cham: Springer International Publishing, 2021, pp. 171–201. doi: 10.1007/978-3-030-56127-7_6.

[62] V. Kishore and A. A. Hassen, ‘Chapter 6 - Polymer and composites additive manufacturing: material extrusion processes’, in Additive Manufacturing, J. Pou, A. Riveiro, and J. P. Davim, Eds., in Handbooks in Advanced Manufacturing. , Elsevier, 2021, pp. 183–216. doi: 10.1016/B978-0-12-818411-0.00021-5.

[63] A. K. Gupta, Krishnanand, and M. Taufik, ‘The effect of process parameters in material extrusion processes on the part surface quality: A review’, Mater. Today Proc., vol. 50, pp. 1234–1242, Jan. 2022, doi: 10.1016/j.matpr.2021.08.110.

[64] I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, ‘Directed Energy Deposition’, in Additive Manufacturing Technologies, I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, Eds., Cham: Springer International Publishing, 2021, pp. 285–318. doi: 10.1007/978-3-030-56127-7_10.

[65] H. Yi, Q. Wang, and H. Cao, ‘Wire-arc directed energy deposition of magnesium alloys: microstructure, properties and quality optimization strategies’, J. Mater. Res. Technol., vol. 20, pp. 627–649, Sep. 2022, doi: 10.1016/j.jmrt.2022.07.083.

[66] Y. Bai, A. Chaudhari, and H. Wang, ‘Investigation on the microstructure and machinability of ASTM A131 steel manufactured by directed energy deposition’, J. Mater. Process. Technol., vol. 276, p. 116410, Feb. 2020, doi: 10.1016/j.jmatprotec.2019.116410.

[67] I. Gibson, D. W. Rosen, and B. Stucker, ‘Sheet Lamination Processes’, in Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing, I. Gibson, D. W. Rosen, and B. Stucker, Eds., Boston, MA: Springer US, 2010, pp. 223–252. doi: 10.1007/978-1-4419-1120-9_8.

[68] A. Hehr and M. Norfolk, ‘A comprehensive review of ultrasonic additive manufacturing’, Rapid Prototyp. J., vol. 26, no. 3, pp. 445–458, Nov. 2019, doi:

10.1108/RPJ-03-2019-0056.

[69] B. G. Mekonnen, G. Bright, and A. Walker, ‘A Study on State of the Art Technology of Laminated Object Manufacturing (LOM)’, in CAD/CAM, Robotics and Factories of the Future, D. K. Mandal and C. S. Syan, Eds., in Lecture Notes in Mechanical Engineering. New Delhi: Springer India, 2016, pp. 207–216. doi: 10.1007/978-81-322-2740-3_21.

[70] ‘Copolyester elastomer | Thermoplastic, Synthetic, Polymer | Britannica’. Accessed: Sep. 04, 2023. [Online]. Available: https://www.britannica.com/science/copolyester-elastomer

[71] ‘Sharing insights elevates their impact’, S&P Global. Accessed: Sep. 04, 2023. [Online]. Available: https://www.spglobal.com/commodityinsights/en/ci/products/copolyester-ether-chemical-economics-handbook.html

[72] ‘TPC’, Formfutura. Accessed: Sep. 05, 2023. [Online]. Available: https://formfutura.com/c/filaments/tpc-filaments/

[73] ‘123-3D.nl - 3D-printers | kits | parts | filament’, 123-3D.nl. Accessed: Sep. 05, 2023. [Online]. Available: https://www.123-3d.nl

[74] ‘Addigy F2060 HT’, Formfutura. Accessed: Sep. 05, 2023. [Online]. Available: https://formfutura.com/product/addigy-f2060-ht/

[75] ‘TPU filament - learn everything about the TPU material for 3D printing’. Accessed: Sep. 05, 2023. [Online]. Available: https://tractus3d.com/materials/tpu/

[76] ‘123-3D.nl - 3D-printers | kits | parts | filament’, 123-3D.nl. Accessed: Sep. 05, 2023. [Online]. Available: https://www.123-3d.nl

[77] ‘What is TPS | Styrenic Block Copolymers | HEXPOL TPE’. Accessed: Sep. 06, 2023. [Online]. Available: https://www.hexpol.com/tpe/resources/tpe-academy/what-is-tpe/what-is-tps/

[78] ‘TPE-SEBS-95A | IC3D Printers’. Accessed: Sep. 06, 2023. [Online]. Available: https://www.ic3dprinters.com/shop/tpe-sebs-95a/

[79] ‘Flexfill PEBA 90A “Black Transparent”’, Fillamentum.com. Accessed: Sep. 07, 2023. [Online]. Available: https://shop.fillamentum.com/products/flexfill-peba-90a-black-transparent

[80] ‘Kimya PEBA-S 3D Filament (PEBAX®)’, Kimya.fr. Accessed: Sep. 07, 2023. [Online]. Available: https://www.kimya.fr/en/product/3d-peba-s-filament-kimya/

[81] ‘Hardness’. Accessed: Sep. 07, 2023. [Online]. Available: https://web.archive.org/web/20070707141201/http://www.calce.umd.edu/general/Facilities/Hardness_ad_.htm#3.5

[82] ‘Armadillo 3D Printer Filament (75D)’, NinjaTek. Accessed: Sep. 07, 2023. [Online]. Available: https://ninjatek.com/shop/armadillo/

[83] ‘TPU Filament Filaflex 60A, flexible filament for 3d printing’, Recreus. Accessed: Sep. 07, 2023. [Online]. Available: https://recreus.com/gb/filaments/1-filaflex-60a.html

[84] ‘OVERTURE TPU filament 1.75mm 1kg (2.2lbs) spool, size accuracy +/- 0.05mm (Black) : Amazon.nl: Business, Industry & Science’. Accessed: Sep. 05, 2023. [Online]. Available: https://www.amazon.nl/-/en/OVERTURE-filament-1-75mm-dimensional-accuracy/dp/B08X6P6YNC/ref=sr_1_5?keywords=tpu&qid=1693923624&sr=8-5

[85] L. J. Gibson, ‘Modelling the mechanical behavior of cellular materials’, Mater. Sci. Eng. A, vol. 110, pp. 1–36, Mar. 1989, doi: 10.1016/0921-5093(89)90154-8.

[86] N. Kladovasilakis, K. Tsongas, D. Karalekas, and D. Tzetzis, ‘Architected Materials for Additive Manufacturing: A Comprehensive Review’, Materials, vol. 15, no. 17, Art. no. 17, Jan. 2022, doi: 10.3390/ma15175919.

[87] ‘Creality 3D Printer Ender 5 Plus 350X350X400mm Large Ender Series’. Accessed: Sep. 11, 2023. [Online]. Available: https://www.creality3dofficial.eu/products/creality-ender-5-plus-3d-printer

[88] ‘Original Prusa i3 MK3S+ 3D Printer kit | Original Prusa 3D printers directly from Josef Prusa’, Prusa3D by Josef Prusa. Accessed: Sep. 11, 2023. [Online]. Available: https://www.prusa3d.com/product/original-prusa-i3-mk3s-3d-printer-3/

[89] H. MacLeod, S. Cooper, S. Bandelow, R. Malcolm, and C. Sunderland, ‘Effects of heat stress and dehydration on cognitive function in elite female field hockey players’, BMC Sports Sci. Med. Rehabil., vol. 10, no. 1, p. 12, Jun. 2018, doi: 10.1186/s13102-018-0101-9.

[90] Z. Wang, ‘Recent advances in novel metallic honeycomb structure’, Compos. Part B Eng., vol. 166, pp. 731–741, Jun. 2019, doi: 10.1016/j.compositesb.2019.02.011.

[91] J. Ju and J. D. Summers, ‘Compliant hexagonal periodic lattice structures having both high shear strength and high shear strain’, Mater. Des., vol. 32, no. 2, pp. 512–524, Feb. 2011, doi: 10.1016/j.matdes.2010.08.029.

[92] D. G. Cuevas and G. Pugliese, Advanced 3D Printing with Grasshopper, Clay and FDM. Independently published., 2020.

[93] ‘Fouganza Kids’ and Adult Flexible Horse Riding Back Protector - Black - Decathlon’. Accessed: Oct. 05, 2023. [Online]. Available: https://www.decathlon.co.uk/p/kids-and-adult-flexible-horse-riding-back-protector-black/_/R-p-8957

[94] J. V. Cerney, Complete Book of Athletic Taping Techniques: The Defensive Offensive Weapon in the Care and Prevention of Athletic Injuries. Parker Publishing Company, 1972.

[95] ‘The Latest in 3D Printing News’, Carbon. Accessed: Oct. 19, 2023. [Online]. Available: https://www.carbon3d.com/news

[96] ‘Medios de comunicación | Impresoras 3D Original Prusa vendidas directamente por Josef Prusa’, Prusa3D by Josef Prusa. Accessed: Oct. 19, 2023. [Online]. Available: https://www.prusa3d.com/es/pagina/medios-de-comunicacion_987/?_gl=1*kzsji8*_ga*MTUyODcwNzIzNS4xNjk3MzgwODU4*_

ga_3HK7B7RT5V*MTY5NzczMTQ1MS4yLjEuMTY5NzczMTUyMS42MC4wLjA.

[97] ‘Protolabs Media Kit: Photos’. Accessed: Oct. 19, 2023. [Online]. Available: https://www.protolabs.com/en-gb/media-kit/photos/

[98] ‘Ultrasonic consolidation’, Wikipedia. Sep. 27, 2022. Accessed: Oct. 20, 2023. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Ultrasonic_consolidation&oldid=1112643706

[99] ‘DED’, AddUp. Accessed: Oct. 19, 2023. [Online]. Available: https://addupsolutions.com/machines/ded/

[100] R. M. & Associates, ‘Rhinoceros 3D’, www.rhino3d.com. Accessed: Oct. 20, 2023. [Online]. Available: https://www.rhino3d.com/