Study of the influence of a gecko-inspired adhesive structure on the mechanical properties of specimens reinforced with glass and carbon fibres

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Resumo

Com o progresso recente na procura por materiais mais leves, duráveis e sustentáveis, a aplicação de compósitos, como as fibras de vidro e de carbono, tem-se expandido em áreas como a aeroespacial e a automóvel. Contudo, esses materiais continuam a representar desafios para o ambiente devido à sua reciclagem complicada e à sua baixa biodegradabilidade. O uso de polímeros, como o PLA, proveniente de produtos agrícolas, representa um progresso sustentável, particularmente em processos de produção aditiva que minimizam o desperdício.

Esta dissertação tem como objetivo examinar a influência de uma estrutura adesiva inspirada em lagartixas nas propriedades mecânicas de provetes reforçados com fibras de vidro ou de carbono. Com o intuito de alcançar este objetivo, foram estabelecidas as características dos materiais, criados métodos biomiméticos para a incorporação das fibras, aperfeiçoados os parâmetros de impressão e realizados ensaios de tração e flexão num equipamento universal.

Nos resultados obtidos, verifica-se uma superioridade da resistência à flexão. A aplicação do método de Taguchi permitiu identificar as combinações ideais de fatores para maximizar estas resistências. A análise ANOVA destacou que o tipo de reforço (fibra de vidro, de carbono ou sem reforço) foi determinante para a resistência à flexão e à tração, reforçando a sua importância para o desempenho mecânico.

A conclusão é que o método de Taguchi e a ANOVA são eficientes para melhorar as propriedades mecânicas do PLA reforçado, sendo o fator "tipo de reforço" o principal responsável pela melhoria do desempenho do material

Palavras-chave: Biomimetismo, Compósitos, Fibras de reforço, Fabrico aditivo

Abstract

With recent progress in the search for lighter, more durable and sustainable materials, the application of composites such as glass and carbon fibres has expanded in areas such as aerospace and automotive. However, these materials continue to pose challenges for the environment due to their complicated recycling and low biodegradability. The use of polymers such as PLA from agricultural products is a sustainable step forward, particularly in additive manufacturing processes that minimise waste.

This dissertation aims to examine the influence of a lizard-inspired adhesive structure on the mechanical properties of test specimens reinforced with glass or carbon fibres. To achieve this goal, the characteristics of the materials were established, biomimetic methods for incorporating the fibres were created, the printing parameters were improved, and tensile and flexural tests were carried out in universal equipment.

The results obtained show that flexural strength is superior. The application of the Taguchi method made it possible to identify the ideal combinations of factors to maximise these strengths. The ANOVA analysis showed that the type of reinforcement (glass fibre, carbon fibre or no fibre) was decisive for flexural and tensile strength, reinforcing its importance for mechanical performance.

The conclusion is that the Taguchi method and ANOVA are efficient for improving the mechanical properties of reinforced PLA, with the ‘type of reinforcement’ factor being the main factor responsible for improving the material's performance.

Keywords: Biomimetics, Composites, Reinforcing Fibres, Additive Manufacturing

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Chapter 1

1.1 Introduction

In recent times, the quest for materials that are lighter, stronger, and more environmentally friendly has spurred development in almost all branches of engineering and technology. Aerospace, automotive, building, and numerous other fields have witnessed the rise of materials such as glass fibre composites and carbon fibre composites, which are quite similar and provide effective cost alternatives. Evolutionary though they are, composite materials have attained widespread utility in industrial and household uses—for instance, glass fibre is lightweight and resistant to corrosion, while carbon fibre is strong yet light. However, despite their environmentally friendly promotion, access to these materials is limited due to their non-biodegradability and difficulty in recycling.

Besides the usual composite materials, the development of bio-based polymer systems, such as polylactic acid (PLA), marks a step in the right direction as far as sustainability is concerned. Agricultural products yield PLA, a biopolymer that can replace non-biodegradable petroleum-derived polymers to produce items with comparable or superior mechanical properties. This sustainable transition is commendable and supports the case of manufactured components, such as complex surface designs created with additive manufacturing, where the amount of time and material waste is greatly minimized.

Biomimetics, an engineering approach that leverages existing natural solutions to design new materials, is another grand design. For example, studying the adhesion mechanism of gecko feet gives rise to technologies that adhere as effectively. Here, biology and engineering come together to foster creativity.

Thus, this thesis aims to explore the evolution of composite materials, the impact of reinforcement fibres, and biomimetics on the engineering of new materials. Through a comprehensive analysis, it seeks to highlight the advantages and limitations of these materials.

1.2 Goals

The need for this study arises from the desire to improve the mechanical strength of parts printed in PLA using FDM technology.

The main aim of this study is to increase the mechanical strength of PLA specimens, with or without an adhesive structure and reinforced with glass or carbon fibre, to obtain tensile and flexural specimens that will be tested on a universal testing machine. The following steps were taken to achieve the objective:

1. Define the properties of glass, carbon fibres and PLA.

2. Develop methods, based on biomimetics, to effectively incorporate glass and carbon fibres in the PLA specimen.

3. Determine the optimum printing parameters to increase resistance.

4. Test the printed specimens in tensile and flexural tests.

5. Analysing the obtained results.

1.3 Structure

This paper is divided into six chapters, organized as follows:

The introduction chapter frames the thesis, describing its goals and dissertation structure.

The second chapter presents the theoretical information from existing studies concerning composites, reinforcing fibres, matrices, addictive manufacturing, biomimetics, tensile and bending tests, as well as Taguchi and ANOVA techniques.

The third chapter presents the beginning of the application of the Taguchi method, along with the materials and methods used to make the specimens.

The fourth chapter outlines the efforts made to achieve the final adhesive structure, along with the results from both tests.

The fifth chapter employs the Taguchi analysis method and analysis of variance (ANOVA) to evaluate the results.

The sixth chapter presents the work's main conclusions.

Chapter 2

State-of-the-art

2.1 Composites

Since the dawn of civilisation, composites have played a crucial role in human life. It allowed the first civilisations to build their homes out of mud and straw. However, during the Second World War, the greatest discoveries were made in fibre-reinforced polymers, which led to the first successfully tested boat hull being presented in 1946 and society continuing to make advances in this area. They are used in various areas of everyday life such as construction and engineering projects, medical applications, energy and transport, sports, among others (ATIRA, 2021).

By definition, a composite material is made up of two or more materials that are different in properties and do not dissolve with each other, i.e. they are made by joining a reinforcing fibre with compactable matrix materials of metallic, polymeric or ceramic origin (Pereira L. , 2020).

Glass fibre-reinforced composites (GFRC) are characterised by a thermosetting plastic resin that is subsequently reinforced with glass fibre. Their use has advantages such as reduced part weight, high mechanical strength, corrosion resistance, low moisture absorption, low tooling costs and design versatility (Sathishkumar, 2014).

The proper selection of glass fibre and resin is essential to produce quality GFRC. With the need to produce the best possible product, composites with different compositions, shapes and orientations have been created, leading to a constant increase in research (Jay Prakash Srivastava, 2022).

2.2 Reinforcing Fibres

Reinforcing fibres comprise individual filaments with small diameters dissipated by a polymeric material. Although the filamentary nature of the fibres prevents them from being applied directly, they must have mechanical properties superior to the matrix they reinforce (Castro, 2013).

To achieve the best results, the fibres must (Romão, 2003):

- Have a higher modulus of elasticity than the polymer to be reinforced.
- Higher tensile strength than the polymer to be reinforced.
- Geometry that allows good adhesion to the matrix.
- Resistance to deterioration in contact with the matrix.

Factors such as the nature of the reinforcement, the number of fibres, their orientation and length also influence the characteristics of composites. They can therefore be categorised according to Figure 1 (M.Daniel & Ishai, 2006):

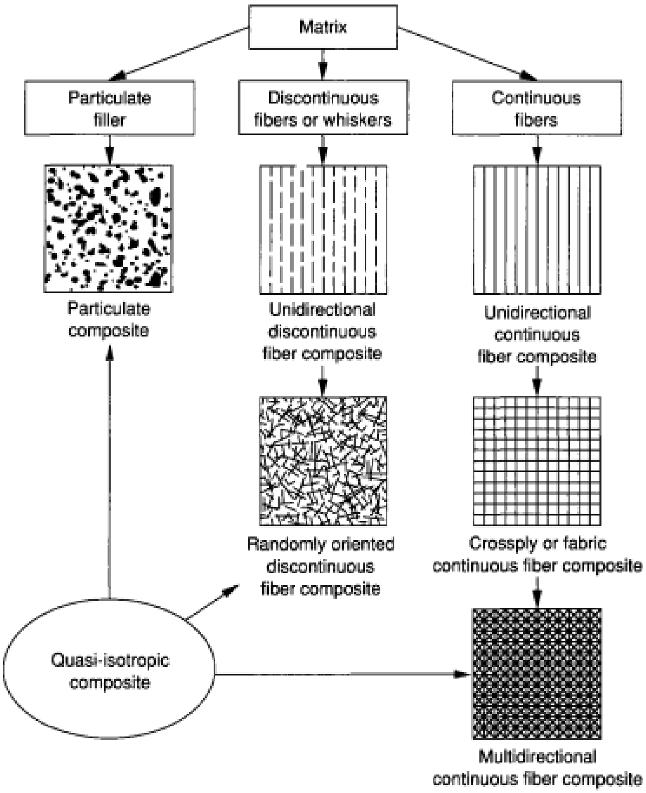


Figure 1: Classification of composite materials (M.Daniel & Ishai, 2006)

Particle-reinforced composites are characterised by the random distribution of particles of different sizes. This characteristic allows the materials to be considered almost homogeneous, considering any scale larger than the size of the reinforcing particles (M.Daniel & Ishai, 2006).

Composites with short or discontinuous fibres, on the other hand, have a length of between 10 and 50 mm. If the fibres are oriented in a certain direction, the material becomes orthotropic and if they are arranged randomly, the material is almost isotropic (M.Daniel & Ishai, 2006).

Continuous fibre composites are distinguished from others firstly because they have long fibres, which results in composites with improved mechanical properties. This type of material also allows the fibres to be oriented in a single direction, in two directions (woven) and in multiple directions, which leads to a material with almost isotropic characteristics. Finally, this type of composite has a fibre volume of between 20 and 60% (M.Daniel & Ishai, 2006).

One of the factors influencing the characteristics of composite materials is the amount of fibre. Up to a certain value, increasing the volume of fibres leads to an improvement in their mechanical properties. If they exceed a certain amount of reinforcement, the matrix loses its ability to infiltrate all the fibres, which results in a decrease in the composite's mechanical properties (Florez, 2019).

The type of fibre also influences the final properties of the composite material. Fibre types are divided into man-made fibres, industrially produced fibres and natural fibres created by nature (Paulo, 2022).

2.2.1 Natural Fibres

The category of natural fibres includes fibres from animal, mineral and vegetable sources. In the composites industry, natural fibres of plant origin are the most widely accepted, which has contributed to an increase in studies into them to replace synthetic fibres (Oksman et al., 2003).

Natural fibres have advantages such as low weight, high strength and stiffness and low cost (Paulo, 2022). In addition, ecological advantages are predominant in natural fibres. Some of these are the low energy required to produce them, their availability, and the fact that they are non-toxic, ecologically viable, organic and carbon dioxide neutral (Castro, 2013).

The disadvantages of this type of fibre as reinforcement are low resistance to water absorption, low thermal stability, variety in quality and poor adhesion at the fibre-matrix interface (Giacomini, 2003) (Castro, 2013).

The continued use of natural fibres as reinforcements in polymeric materials is directly linked to their properties, highlighting their sustainable and economic advantages and the resistance and adhesion challenges they face.

2.2.2 Synthetic Fibres

Synthetic fibres are widely used to reinforce composite materials as they have superior mechanical properties.

The use of this category of fibres allows them to be applied in demanding industries such as aeronautics and space. Some of the most widely used fibres are carbon, glass and aramid fibres (Castro, 2013). The use of this type of fibre for reinforcement provides a final composite with good mechanical properties, such as high tensile strength, rigidity and resistance to corrosion. However, the high cost of production, the environmental impact associated with the manufacture and decomposition of these fibres and the loss of mechanical characteristics at high temperatures represent disadvantages to be taken into account when using them as reinforcement (Navaratnam, Selvaranjan, Jayasooriya, Rajeev, & Sanjayan, 2023).

Despite the mechanical advantages of glass and carbon fibres, it is important to consider the associated environmental impacts, highlighting the balance between mechanical performance and environmental sustainability when selecting reinforcements for composites.

2.2.2.1 Glass Fibres

Although its history goes back to the 18th century, with the invention by Rene Ferchault de Reaumur, the use of fibreglass gained prominence after it was transformed into yarn in 1935. Its initial application in the aeronautical industry opened the door to various lucrative sectors such as the automobile, naval and chemical industries. (Jay Prakash Srivastava, 2022)

Glass fibre as a reinforcement for GFRC is a thermosetting composite material in which the use of glass fibres gives properties such as lightness, heat resistance and dimensional stability. The complex chemical interaction in the manufacture of glass fibre reinforced composites (GFRP) requires careful handling, and factors such as the shape, quantity and composition of the resins, as well as the orientation of the reinforcements, influence the final properties (Jay Prakash Srivastava, 2022).

This type of material has many significant advantages in a variety of industrial and domestic applications. Glass fibre has excellent corrosion resistance, is lightweight (a quarter of the weight of steel) and has good mechanical strength, making it the preferred choice for a variety of environments, from the manufacture of automotive parts to the construction of structures such as bridges. In addition, its excellent electrical properties, coupled with its high specific strength and freedom of processing and shape, make it a versatile option that is widely used in circuit boards, ships and other industrial products and applications (Almeida, 2012).

However, there are some disadvantages that need to be considered. The disadvantages of this material include its non-biodegradability, the requirement for a protective layer to prevent humidity absorption, its fragility in high-impact applications, and its higher initial manufacturing costs compared to traditional materials (Almeida, 2012) (Jay Prakash Srivastava, 2022).

The processing of this type of fibre begins with melting the glass to a liquid state. It is then extruded through small holes in a platinum-rhodium spinneret where it is stretched and finally wound on a mandrel or reel to facilitate handling and transport. This method is adopted because of its ability to produce fibres with precise and uniform diameters (Castro, 2013).

With the continued use of this type of fibre, the need arose for fibres for a more specific industry. The first category to be created was ‘E-Glass’, which stands for electrical grade. Thus, a category was created that associates a specific letter with the type of fibre. The following image (Figure 2) shows the various categories and their dominant properties (Jay Prakash Srivastava, 2022).

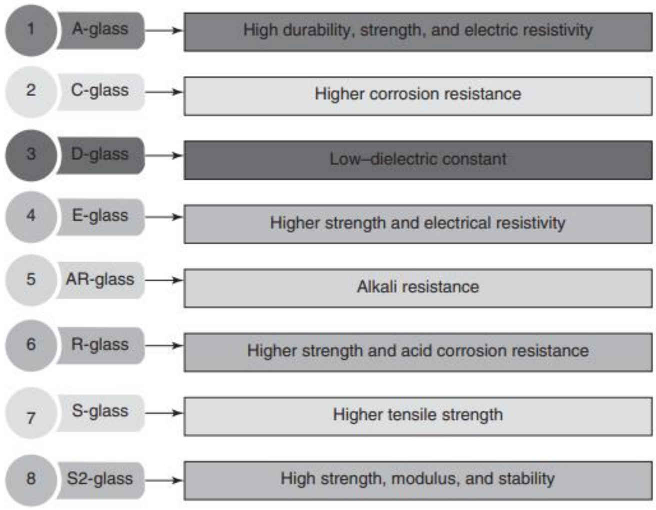


Figure 2: *Glass fibre categories and properties (Jay Prakash Srivastava, 2022)*

Finally, fibreglass has undergone a significant evolution since its invention in the 18th century and has become a widely used material in various industries. Its properties such as lightness and strength make it valuable in a variety of industrial and domestic applications. Although it has advantages such as resistance to corrosion, it is important to consider its limitations, such as non-biodegradability and the need for coatings to protect against humidity. The production process is fundamental to guaranteeing the quality of the fibre, which continues to evolve with specific categories such as 'E-Glass'.

2.2.2.2 Carbon fibres

Carbon fibre was discovered in 1879 when Thomas Edison carbonised cotton and bamboo threads to create pure carbon filaments. These contained 20 per cent carbon and low strength and stiffness. A British research center didn't discover the potential of this type of fiber until 1963 (Associates, 2019).

The constant search for lighter, stronger and more durable materials has meant that carbon fibre has become a widely used material. Some of the industries in which it is used are the aerospace industry, in structural components; in the automotive industry, in high-performance cars and electric vehicles to reduce weight and increase efficiency; for the manufacture of sports equipment, such as tennis rackets and golf clubs; in the construction industry, as structural reinforcement and, finally, in the energy industry in components such as wind turbines (Palanikumar, 2012).

Carbon fibres fall into several categories: high and low modulus, PAN (polyacrylonitrile) and pitch. High modulus fibres are weaker during the shear modulus and low modulus fibres are weaker during the buckling modulus (Rahul D. Sandhanshiv1, 2020). PAN fibres, on the other hand, have a high capacity to absorb mechanical energy and are more cost-effective. Finally, Pitch fibres stand out for having a higher modulus of elasticity (stiffness) and for being more expensive (A, 2023). Figures 3 and 4 show some properties of PAN-type and Pitch-type carbon fibres, respectively.

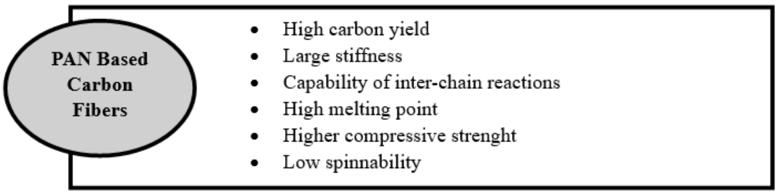


Figure 3: Properties of PAN carbon fibres (Rahul D. Sandhanshiv1, 2020)

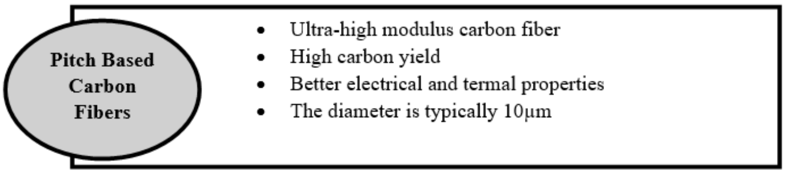


Figure 4: Properties of Pitch carbon fibres (Rahul D. Sandhanshiv1, 2020)

Carbon fibre stands out for its many advantages. Its lightness and strength allow for applications where saving weight while maintaining high tensile strength and rigidity is essential. It also has good corrosion resistance, which together with its ability to withstand harsh environments gives the material high durability. In addition, carbon fibre improves the energy efficiency of vehicles and structures, since its low weight reduces fuel consumption and subsequently the associated carbon emissions. Finally, this material can take many forms, which allows it to be used in a wide variety of products, allowing for greater design freedom (Maqsood & Rimašauskas, 2021) (Hernandez, 2022) (CCUK, 2021).

On the other hand, it has disadvantages that can limit its application. These include the higher cost due to the high cost of materials and the complexity of production. In addition, carbon fibre's ability to conduct heat and electricity is a limitation in some applications. The difficulty of processing it can also be an obstacle since its abrasiveness and heat generation require the use of specific equipment and techniques. The difficulty and cost of recycling this material is also a significant obstacle. Finally, the manufacturing process's variability in carbon fibre properties reduces the material's predictability (Hernandez, 2022) (CCUK, 2021).

Since its discovery in the 19th century, it has been increasingly used in a wide range of industries. This is due to its many advantages such as lightness, strength, durability and versatility. However, some of the possible obstacles to its use must be considered, such as its high cost, its ability to conduct heat and electricity, the difficulty of processing it, the difficulty of recycling it and, finally, the variability of its properties.

2.3 Matrices

In the manufacture of composite materials, one of the most important stages is the choice of matrix. The matrix is the continuous phase of a composite and in addition to maintaining the cohesion of the fibres, it protects the fibres from their environment and during handling and distributes and redistributes the load on the fibres, which contributes to the structural integrity of the composite. (Almeida, 2012)

The matrix can be metal, ceramic, cement or polymer. The choice must take into account the type of components to be produced. Some of the requirements that must be considered are cost, mechanical and thermal performance and the ability to perform their main functions: protecting the fibres, transmitting stress and providing adhesion between fibres (Silva, 2005).

Polymers are widely used because they have a low density and are easy to process. Polymers as matrices are defined as thermoplastic or thermosetting, as shown in the following Figure 5 (Castro, 2013).

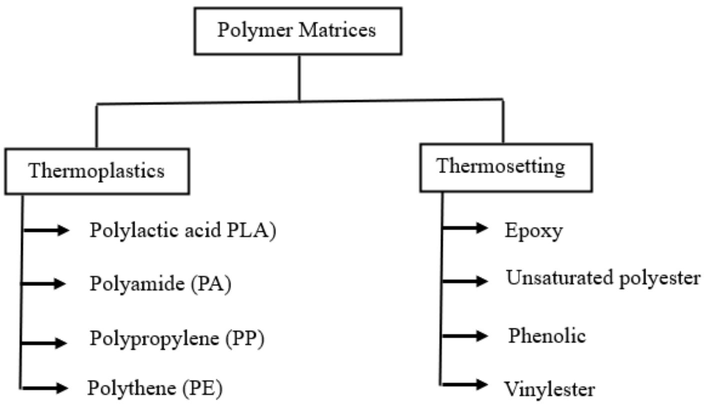


Figure 5: Examples of thermoplastic and thermosetting polymeric matrices (Castro, 2013)

Thermoplastic matrices can be repeatedly melted and solidified while maintaining their mechanical properties, which means they are easier to process, easier to recycle and have greater toughness compared to thermosetting matrices (Romão, 2003).

Thermosetting matrices, on the other hand, have characteristics such as taking on a permanent shape when heated, superior rigidity and resistance. They also have a low cost, high-temperature resistance and slow degradation when subjected to loads. These characteristics make this type of matrix a good choice for structural components (Romão, 2003).

Thus, the choice of matrix not only influences the properties of the composite but also defines the configuration and performance of the manufactured product.

2.3.1 Polylactic Acid (PLA)

Polylactic acid (PLA) stands out as one of the most important biodegradable synthetic polymers, belonging to the category of thermoplastic polyesters (DRPIĆ, 2023). This material is obtained from renewable sources such as sugar beet, corn and sugar cane, so it is a viable option for replacing synthetic polymers derived from petroleum (Santhiya Peremel, 2023). Figure 6 shows the chemical structure of polylactic acid.

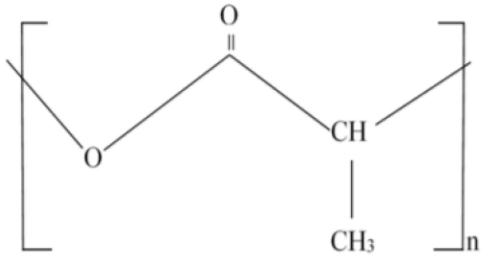


Figure 6: Chemical structure of polylactide acid (Salem Al Zahmi, 2022)

PLA has some characteristics that make it particularly attractive. The similarity of its mechanical properties to traditional polyesters and the fact that its life cycle uses a tenth of the fossil energy of synthetic polymers means that the use of this polymer has a wide range of applications. Alongside these, physical, chemical and thermal properties influence the processing of the material. For example, the glass transition, melting and thermal degradation temperatures are 60ºC, 180ºC and 200ºC, respectively. Table 1 shows some physical properties of PLA (Castro, 2013).

Table 1: Physical characteristics of PLA (Usha Sanivada, 2020)

Polymer	Density (g/cm3)	Tensile Strength (MPa)	Young Modulus (GPa)	Glass Transition Temperature (°C)	Melting Temperature (°C)
PLA	1.21–1.25	21-60	0,35-3,5	45-60	150-162

Molecular weight is one of the parameters that most influence the characteristics of PLA. The higher the molecular weight, the greater its mechanical resistance, the lower its ductility, the lower its transparency and the more difficult it is to process. Mechanical resistance increases because the polymer chains are longer, making it easier to intertwine them; ductility decreases because polymers with a higher molecular weight are more rigid and fragile; it is less transparent because it has a denser molecular structure and therefore more points of light obstruction and, finally, it makes processing more difficult because the increase in molecular weight translates into an increase in viscosity (Lobo, 2018).

The versatility of this material's processing possibilities makes it possible to produce a wide range of end products with different geometries and sizes. Compatibility with various equipment used in common thermoplastic processing techniques, such as 3D printers and injection moulding machines, means that the initial production cost is not significant (Paulo, 2022).

PLA degenerates into non-toxic materials under certain conditions of temperature and humidity, with degradation initially occurring through a non-enzymatic hydrolytic process. This composite dissolves in water only if the molecular weight is very low, although this can reduce rapidly after water infiltration, the mass and shape can be preserved until the degradation is very pronounced. During processing, to avoid degeneration of the polymer, temperatures above 200ºC should be avoided. It is therefore considered that the degradation of this polymer depends not only on molecular behaviour but also on surface properties, porosity and the presence of additives in the process (Almeida, 2012).

In short, PLA has become an alternative to traditional synthetic polymers, as it is biodegradable and has similar properties. Along with these characteristics, its versatility and life cycle efficiency increase the range of applications in industry, the main disadvantage of PLA being the need for precautions throughout processing.

2.4 Additive Manufacturing

Additive manufacturing, or 3D printing, is a technique used to manufacture components based on CAD models, which can take a wide range of shapes. This method achieves the desired shape by layering the material (Armin Jarimi, 2024).

This process goes through several stages, from CAD design and subsequent conversion to an SL file, through machine set-up and processing to post-processing. The following diagram (Figure 7) shows this processing chain (Sinha, 2021).

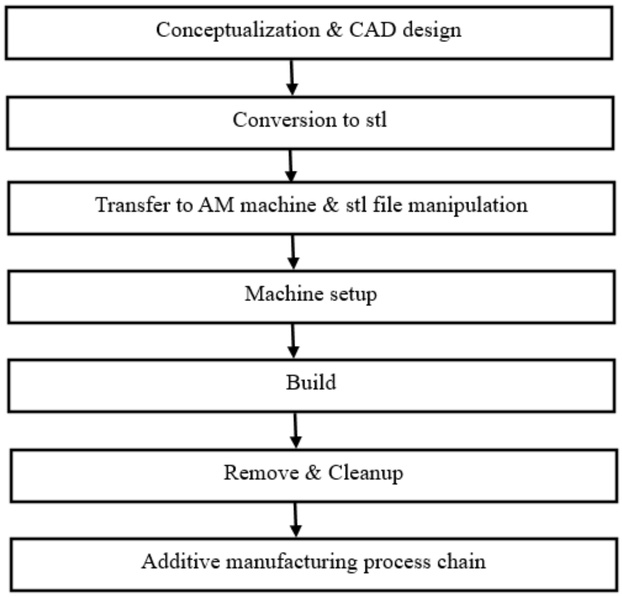


Figure 7: Addictive Manufacturing Process Chain (Sinha, 2021)

This technique has been gaining popularity in industries such as aerospace, military, medical and architectural, automotive and construction. Compared to traditional manufacturing methods, additive manufacturing allows for versatility in the materials chosen for production, which can be metal, ceramic or plastic. In addition, the technique is less costly as it does not require complex equipment, its design and production cycle is shorter and the need for stock is eliminated. Additive manufacturing also allows each product to be adapted to your needs. However, characteristics such as the possibility of poor adhesion between layers, a long production time for large parts, high initial investment in high-quality printers and limited resolution compared to methods such as CNC machining are disadvantages to be taken into account when producing by additive manufacturing (Noshin Tasnim Tuli, 2024) (Maqsood & Rimašauskas, 2021).

Additive manufacturing of fibre-reinforced composite materials (FRAM) combines the advantages of composite materials with those of additive manufacturing. It eliminates the human factor, making it possible to manufacture single components simultaneously. This method enables the placement of fibres in various orientations and patterns, resulting in composite materials with improved mechanical properties (Noshin Tasnim Tuli, 2024).

There are different types of 3D printing processes such as: stereolithography (SLA), selective laser sintering (SLS), selective laser melting (SLM), direct metal deposition (DMD) and finally fused deposition modelling (FDM) (Armin Jarimi, 2024). We will delve deeper into the fused deposition modelling process in the following subchapter.

2.4.1 Fused Deposition Modelling

In 1989, Scott Crump patented the process of fused deposition modelling. The idea was born nine years earlier when the author tried to create a toy frog for his daughter using a hot glue gun. This process is then based on the construction of solid objects using thermoplastics melted in layers. The first 3D printer was launched in 1991 and quickly gained a foothold in the automotive, aerospace and medical industries. Since then, advances in materials, precision and speed have made it one of the most accessible and popular additive manufacturing technologies (Siemiński, 2021).

This process begins by heating the chosen polymer filament to a molten state and then extruding it through the 3D printer's nozzle. The nozzle has three degrees of freedom, allowing the material to be deposited according to the g-code instructions on the build platform. This material is deposited in layers until the final object is obtained. After printing, the part is removed and has the option of being cleaned, sanded, painted or milled to improve its functionality. This process is shown in the following image (Figure 8) (Fredrick Madaraka Mwema, 2020).

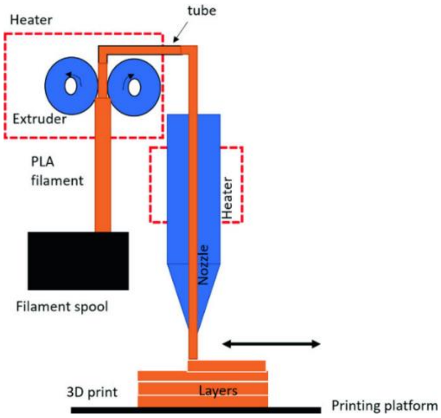


Figure 8: Principle of fused deposition modelling (Fredrick Madaraka Mwema, 2020).

Various parameters, which fall into two distinct categories: machine parameters and material parameters, influence the FDM process. The former refer to the parameters that are specified in the slicing software where the g-code file will be generated. The material parameters are the characteristics of the material used. These factors will influence the quality and performance of the printed parts. Figure 9 shows the parameters that influence the fused deposition modelling process (Fredrick Madaraka Mwema, 2020).

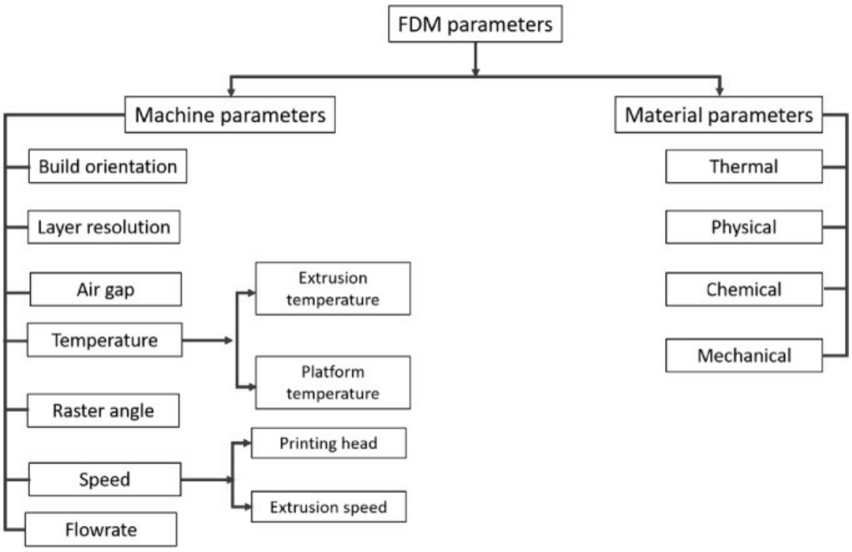


Figure 9: Parameters influencing fused deposition modelling (Fredrick Madaraka Mwema, 2020)

This process has several advantages and disadvantages. The advantages include the low cost of the equipment and material used, as well as less waste of the latter; the small size of the equipment, which allows it to be installed in non-industrial environments and, finally, the good mechanical resistance. However, the random shrinkage of the material, the longer manufacturing time and the poor surface finish are some of the disadvantages of this additive manufacturing process (Abreu, 2015).

The main areas of application for this additive manufacturing process are the automotive and aerospace industries, in molds and prototypes; in medicine, in the manufacture of prostheses; as an academic tool; and in architecture, in the manufacture of models (Ferreira, 2020).

2.5 Biomimetics

The term biomimicry comes from the Greek word ‘bios’, which means life, and ‘mimesis’, which symbolises imitation. This area of study aims to develop systems inspired by or imitating natural systems, which are advantageous in different areas of science. The principle behind biomimicry is that nature, which has evolved over millions of years and has exemplary productivity and functionality, is the best inspirational model for imitating systems (Narayan, 2024).

Some examples of structures used are fish scales, lobster claws, shell nacre and deer bones, as they are highly rigid and mobile.

The complexity of natural structures makes them difficult to manufacture using traditional design and manufacturing technologies, and additive manufacturing has played an important role in the progress of biomimicry studies. Some of these advances are the possibility of printing structures with reinforced, shape-shifting and hydrodynamic materials (Yang, Song, Li, & Chen, 2018).

As 3D printing progresses, it will be possible to manufacture next-generation materials and functional structures, inspired by the characteristics of biological beings, which millions of years in the making continue to enable optimised and original alternatives to engineering problems (Yang, Song, Li, & Chen, 2018).

The next subchapter will develop the idea of biomimicry using the structure of geckos' feet as a basis.

2.5.1 Gecko inspired Biomimetics

To understand the ability of geckos' feet to adhere, we need to understand the meaning of adhesion, which is defined as the force of attraction created by contact between two materials. Since the 19th century, the study of the phenomenon of lizard foot adhesion has led to the creation of various theories to explain it, such as electrostatic attraction, micro entanglement and suction, none of which have been proven to be the answer to the study (Liu, Wang, Li, & Pengyang Li, 2024).

The discovery of the scanning electron microscope has made it possible to discover insights into the lamellar structure of lizards' fingers. Each finger is made up of dozens of rows of bristles, each 30-130 micrometres long and 5 micrometres in diameter. At their ends, there are between 100-1000 spatulas, 300 nanometres long and with a flat tip approximately 280 nanometres wide. This structure gives lizards exceptional climbing ability (Liu, Wang, Li, & Pengyang Li, 2024).

Associated with the attempt to reproduce the adhesion properties of geckos' feet are difficulties related to the manufacture of the structure on a nanometre scale and the roughness of the surface, since this has an impact on both the macro and micro scales (Liu, Wang, Li, & Pengyang Li, 2024).

Dry adhesion systems based on lizards aim to mimic the bristle matrices found on lizards' fingers to produce van der Waals forces, which are sensitive to the distance between particles. The solution to achieving high adhesion lies in maximising the effective contact area between the artificial bristles and the surfaces (Ren, 2022).

There are various artificial bristle designs such as the cylinder shape which is considered the simplest method for replicating the adhesion properties of geckos' feet. There's also the mushroom shape, which allows for greater adhesive strength because the geometry of the tip prevents the concentration of tension at the contact boundary. Lastly, the wedge shape ensures a controllable adhesive force through shear movement (Ren, 2022).

A tilting mechanism is used to achieve controllable adhesion. When a shear force is applied in the direction of inclination, adhesion increases, and when the force is reversed, it decreases. This mechanism is essential for the practical application of gecko-inspired adhesives and is demonstrated in Figure 10 (Ren, 2022).

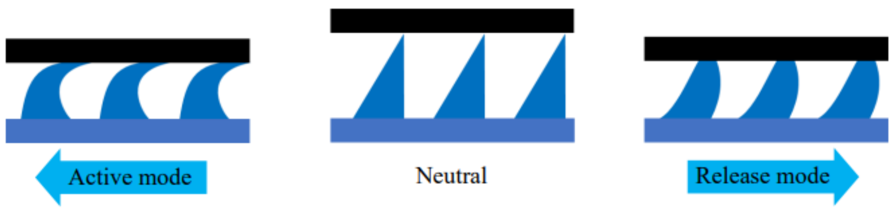


Figure 10:Example of active mode and release mode of the wedge-shaped artificial seta design (Ren, 2022)

In conclusion, the multiscale composite adhesive structure of geckos' feet, ranging from centimetres to nanometres, is what gives geckos their exceptional climbing abilities. By mimicking these natural structures and mechanisms, the researchers aim to develop innovative adhesive materials that take advantage of the same principles. However, replication challenges remain due to the intricate and precise nature of these biological systems.

2.6 Mechanical Tensile and Bending Tests

When carrying out the mechanical tests, I took into account two standards, ATSM D638.14 (ASTM D638-14 , 2022) in tensile tests and ASTM D7264/D7264M-21 (ASTM D7241/D7264M-21, 2021) for bending tests. The results of composite materials are influenced by the speed of the test, the length of the measurement, the cross-sectional area, the number of specimens and the type of component.

2.6.1 Tensile Test

The purpose of the pull test is to determine the tensile strength of composites. This is the most important mechanical property in the manufacture of various materials.

In order to obtain the material results, it is necessary to create specimens with their own geometry and apply the load data to the universal testing machine.

The geometry of the specimens is constructed in such a way that when they break, it occurs at the desired location, i.e. the shortest section. The most widely accepted geometry for these specimens is the ‘dog bone’ or ‘bell’ geometry, i.e. specimens with a conical width like the ASTM D638 standard. The correct alignment of the fibres is crucial for obtaining the correct elastic properties. Incorrect alignment of the fibres around the test axis can result in an error of up to 30%. Before placing the specimen in the machine, it is necessary to accurately measure the cross-sectional area and lengths. After this, we can place the specimen in the universal testing machine by placing the ends in the machine's clamps.

Unidirectional composites show linear behaviour. It should point out that at the start of the test, we should bear in mind that some non-linearities may be present, which can be characterised by sliding phenomena, machine backlash, etc.

2.6.2 Bending Test

In the bending test, we have various tensile, compressive and shear stresses. Therefore, flexural strength cannot be used directly in the design of composites. The aim of the bending test is to determine the maximum bending strength. There are two methods for carrying out the three-point and four-point bending tests.

The three-point bending test uses a flat beam-shaped specimen with a constant rectangular cross-section. The dimensions of the specimen are not exact, but only one should be chosen for the appropriate span thickness ratio (L/h). This ratio must be large enough for the specimen to break in bending.

The calculation methodology for each of these tests is presented in Chapter 3.

2.7 Taguchi Method

The Taguchi Method, developed to the world by Dr Genichi Taguchi inspired a new way of thinking about experimental design which aimed at optimizing processes and improving product quality. The methodology is distinguished from traditional methods such as factorial design by a new concept in efficient execution, where multiple system characteristics are simultaneously improved (Nabendu Gosh, 2017).

The foundation of the Taguchi Method lies in the use of orthogonal arrays, allowing for simultaneous study in one set-up (instead of individual experiments as seen above) of multiple input factors at once. This is what makes the method so powerful, as we can make optimisations without trying all combinations of variables. This leads to a faster and cheaper manufacturing process, which greatly benefits industrial product development (NIST/SEMATECH, 2012).

They can be used to perform a parameter study on variables and interactions between control parameters. Choosing the right dimension array will depend on how many arguments we have and their number of levels. This makes the method highly versatile, and applicable to various kinds of experiments, ranging in scope from small fractional tests to large full factorial experiments (Nabendu Gosh, 2017).

The Taguchi Method is advantageous as some of the most wanted benefits of this method are relatively low cost and high speed while providing significant improvement in final quality, for product or process optimization needs. The Taguchi Method's advantages, such as its ability to use fewer resources when installed at just the right levels and its higher efficiency and effectiveness compared to classical methods, make it widely applicable in many fields of engineering and manufacturing (Resit Unal, 1991).

2.7.1 Signal to Noise Ratio

The signal-to-noise ratio (S/N) represents a crucial concept in Taguchi’s methodology: it serves to evaluate the robustness of a process (or product) especially when faced with uncontrollable elements, referred to as noise factors. The basic aim of the S/N ratio is to assess the variation with respect to quality characteristic values concerning its target value without resources from some external parameters, not being accessible during production whereas they can be simulated experimentally (Costa, 2024).

Taguchi proposed the use of a loss function to quantify the deviation between a product’s actual performance and its ideal target value. Another one is the loss function obtained, which will then be transformed into a signal-to-noise ratio that brings to light the numerical results of variants between repetitions from each test and their analogical data. It is the process of identifying which control parameter can suppress noise factor to enhance consistency and improve the quality of this process (Rashid, 2023).

Three main quality categories determine how the S/N ratio is calculated, depending on the objectives of the experiment (Rashid, 2023):

1.Smaller is better: This strategy focuses on minimizing response, for instance reduction of defects or waste in a process. The Signal and Noise (S/N) ratio calculated in this category is:

$$S/N_S = -10 * \log\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right)$$

Where Y_i represents the observed data and n the number of observations.

2.Larger is better: Used when the aim is to maximise a quality characteristic, such as efficiency or material strength. The S/N ratio is calculated using the formula:

$$S/N_L = -10 * \log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{{y_i}^2}\right)$$

This formula focuses on ensuring that the observed values are as large as possible.

3.Nominal: Ideal target value used when it is expected to achieve an exact or nearly so number and there are well define specifications. Where the S/N ratio is determined by:

$$S/N_t = 10 * \log\left(\frac{\bar{y}^2}{{s^2}_y}\right)$$

Where $\bar{Y}$ is the mean of the observed values and σ is the standard deviation. This formula aims to minimise variation around a specific target.

In any category, a high S/N ratio signifies superior system performance; a higher signal-to-noise ratio also signifies a reduction in noise-induced well-being variation. However, when multiple quality characteristics are present, it can be challenging to optimize one without compromising the performance of another. To address this issue, we can employ the Taguchi method with Grey, which integrates various loss functions into a single performance metric. This method simplifies the search for parameter configurations by identifying those that can simultaneously improve all metrics (Nabendu Gosh, 2017).

The signal-to-noise ratio is therefore a very useful technique to detect the control parameters that improve quality and diminish variability in si process or product, providing them with greater robustness against uncontrollable factors. When used properly, it can help result in more predictable processes, less rework and waste as well as significant gains in overall performance.

2.8 ANOVA

The Analysis of Variance (ANOVA) is a statistical technique that assesses the effects of factors at different levels and is particularly utilized when the researcher wishes to establish the meaningfulness of differences between two or more group means. This technique is important in studies designed to determine whether the observed sample variation between the groups of subjects is due to chance or represents a true effect of the experimental treatment or the study variables (Gen'ichi Taguchi, 2005).

This process measures the spread of data around the average score which is known as the 'mean' of a certain population known as a sample. In ANOVA, however, the main objective is to measure whether the outcomes in the three and more groups differ significantly or not. Thanks to this, ANOVA allows for the evaluation of the data and clarifies whether the differences in the data are genuine differences between the groups or simply random noise or outliers.

To conduct ANOVA, an ANOVA table is created, which includes several key components (Costa, 2024):

1. Sequential sums of squares (SS): These indicate the part of the total variation in the data that can be linked to each factor in the model. It measures the total deviation for each group in relation to the overall mean.
2. Degrees of freedom (DF): This reflects the amount of information available in the model to estimate parameters. It is determined by the number of groups and the sample size.
3. Mean squares (MS): Mean squares are obtained by dividing the sums of squares by their respective degrees of freedom. The mean square provides an average measure of the variation between the sample means, offering a clearer understanding of variability.
4. F-value: This is a test statistic used to evaluate whether the variation seen between group means is greater than what would be expected by random chance. It compares the variability among groups to the variability within groups. A significantly large F-value suggests that the factor being tested has a strong impact on the outcome.
5. P-value: This represents the probability of obtaining an F-value as extreme as the one observed, assuming the null hypothesis is true (i.e., there are no significant differences between group means). A P-value less than 0.05 is commonly used as a threshold to reject the null hypothesis, indicating that there is less than a 5% chance that the observed differences are due to random variation alone.

If the ANOVA results show a significant difference (P-value < 0.05), it indicates that at least one group's mean differs from the others, which calls for further analysis, such as post-hoc tests, to pinpoint the specific groups that are different. Conversely, if the P-value exceeds 0.05, it suggests that there is no significant evidence of differences among the groups, and any variation observed is likely due to random noise rather than the experimental factors. (Bobbit, 2021)

ANOVA is particularly advantageous because it enables the comparison of multiple groups at once, minimizing the risk of errors that could arise from conducting several two-sample t-tests. Additionally, it sheds light on how various factors and their interactions affect the variable of interest, making it a valuable tool in experimental design and data analysis (Pereira, Ribeiro, & Queijo, 2018).

In summary, ANOVA is a powerful method for assessing whether significant differences exist between groups in a sample, and it is essential in both scientific and industrial research for improving our understanding of the factors that influence outcomes. By systematically analysing variance, ANOVA aids researchers in drawing valid conclusions from their data and supports decision-making grounded in statistical evidence.

Chapter 3

Mechanical properties of PLA specimens obtained by additive manufacturing process reinforced with glass and carbon fibres.

3.1 Material and Methods

This subchapter deals with the materials and methods used to make the specimens and carry out the tensile and bending tests.

3.1.1 Design of Experiments

As mentioned in the previous chapter, the additive manufacturing parameters influence the properties of the products obtained. For this reason, specimens were made with a 40% filler. The type of reinforcement used, in this case, glass or carbon fibre, was also used as a control factor. The amount of reinforcement was also studied using the existence of one or two holes in the specimens as a comparison. Finally, the influence of a bonding surface on the surface of the holes was also studied. Table 2 shows these factors with their respective levels.

Table 2:Control factors

Symbol	Control factor	Level 1	Level 2	Level 3
A	Reinforcement	Carbon Fiber	Glass Fiber	No reinforcement
B	Surface	With Grip	Without Grip	
C	Holes	1	2	0

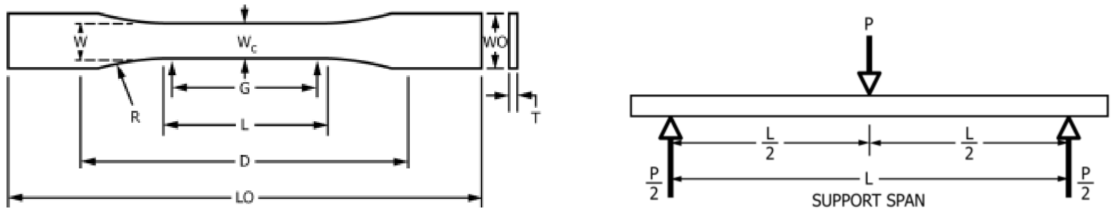
With the data in Table 2, a Taguchi L9 orthogonal array was created (Table 3).

Table 3:Taguchi L9 orthogonal array

Test number	A	B	C
	Reinforcement	Surface	Holes
1	1	1	1
2	1	1	2
3	1	2	1
4	1	2	2
5	2	1	1
6	2	1	2
7	2	2	1
8	2	2	2
9	3	2	0

3.1.2 Specimens Manufacturing

The standards used to carry out the tensile and bending tests are ASTM D638.14 (ASTM D638-14 , 2022) and ASTM D7264/D7264M-21 (ASTM D7241/D7264M-21, 2021), respectively. The geometries and dimensions of the specimens must therefore be following the standard. Figure 11 shows drawings of the specimen types.



(a) (b)

Figure 11: (a) Tensile specimen geometry in agreement with ASTM D638.14 standard and (b) Flexural specimen geometry in agreement with ASTM D7264/D7264m-21

Table 4 shows the dimensions of the specimens studied.

Table 4:Dimesions of (a)tensile and (b) flexural of the test pieces

Tensile test piece dimensions[mm]	
LO	165
D	115
L	57
G	50
R	76
T	7
W	13
Wc	4
WO	19

Flexural test piece dimensions [mm]	
L	128,7

As previously mentioned, certain specimens feature holes with an adhesive structure, which is consistent with the structure of the geckos' feet. In the upcoming chapter, we will showcase our efforts to achieve the desired outcome. Figure 12 displays the achieved result.

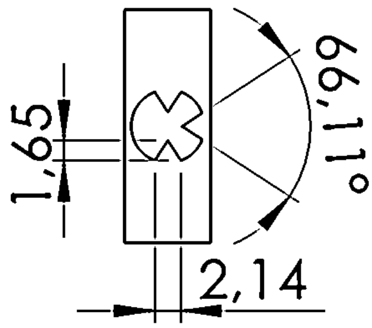


Figure 12: Dimension of adhesive structure

The materials and equipment used to manufacture the specimens were:

- EasyFil PLA;
- Anycubic 3D printer
- Glass fibres
- Carbon fibres

Glass and carbon fibres were used to reinforce the printed specimens. The thermoplastic biopolymer PLA (or polylactic acid) was used to manufacture the specimens and then reinforced with glass or carbon fibres. Table 5 shows the number of fibres used in each specimen.

Table 5:Number of fibres

Test number	Number of fibers
1	40
2	80
3	55
4	110
5	26
6	52
7	17
8	34
9	0

3.1.4 Bending Test

The bending tests were carried out in the laboratory of structures and strength of materials. The material required was as follows:

- Specimens

- Shimadzu universal testing machine
- Computer

The first step is to switch on the computer and the machine and enter the data on the specimen measurements, the speed and the type of results desired. The standard used was ASTM D7264/D7264M-21 (ASTM D7241/D7264M-21, 2021), and the speed used was 4 mm/min.

$$R = \frac{Z \times L^2}{6 \times d}$$

Where:

R = rate of crosshead motion, mm (in.)/min,

L = support span, mm (in.),

d = depth of beam, mm (in.), and

Z = rate of straining of the outer fibre, mm/mm/min (in. /in. /min). Z shall be equal to 0.01.

After the tests have been carried out, the graphs and data obtained can be seen.

The procedure used was A (or the three-point bending test), the maximum bending stress at the outer surface occurs at mid-span is given by:

$$\sigma = \frac{3PL}{2bh^2}$$

Where:

σ = stress at the outer surface at mid-span, MPa [psi],

P = applied force, N [lbf],

L = support span, mm [in.],

b = width of beam, mm [in.],

h = thickness of the beam, mm [in.].

The equation to calculate strain is:

$$\varepsilon = \frac{6\delta h}{L^2}$$

Where:

ε = maximum strain at the outer surface, mm/mm [in./in.],

δ = mid-span deflection, mm [in.],

L = support span, mm [in.],

h = beam thickness, mm [in.]

3.1.5 Tensile Tests

The tensile tests were carried out in the same laboratory as the bending tests. The material required was as follows:

- Specimens
- Shimadzu universal testing machine
- Computer

Like the previous test, the first step involves turning on the computer and machine, then entering the specimen measurements, speed, and desired results. The standard used was ASTM D638.14 (ASTM D638-14 , 2022), and the speed used was 5 mm/min with a gauge length of 115 mm. Figure 13 shows the type of specimen used in tensile testing.

Figure 13: Specimen for tensile testing

Chapter 4

Results

This chapter aims to present the results of each experimental test relating to the tensile and bending tests, using the initial data from the Taguchi Method.

4.1 Adhesive structure

This subchapter will present the design stages of the structure, which aim to mimic the properties of gecko feet. This is because a faithful copy of the microstructure is too difficult due to nanoscale manufacturing and the hierarchical structure. Figure 14 shows a picture of the gecko's foot and a detailed view of it.

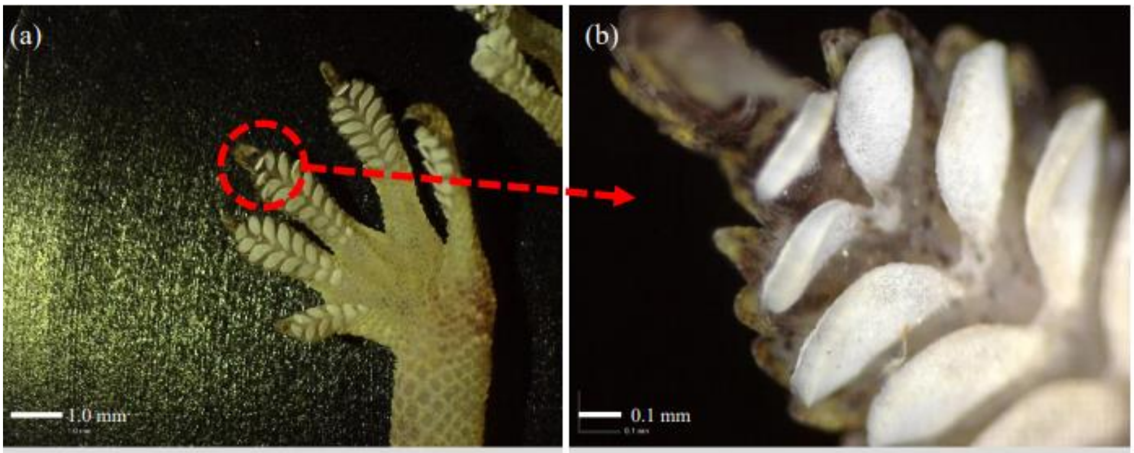


Figure 14: (a) Gecko's foot and (b) detail of its toe (Ren, 2022)

As a first attempt, a mushroom-shaped design (see Figure 15) was replicated along the specimen every 3 millimetres. Along the circumference of each hole, the design was multiplied by 10 with equal spacing between them. The printer was not precise enough to print this structure.

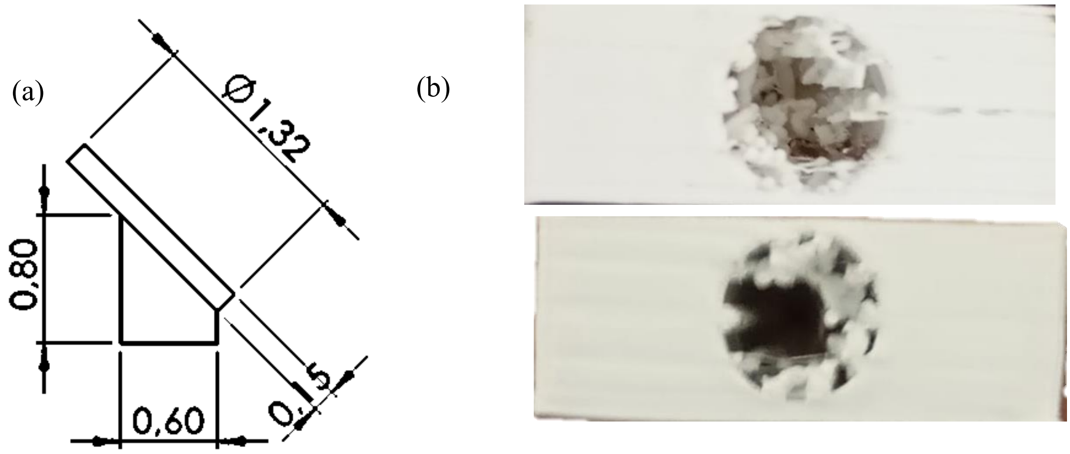


Figure 15: (a) Dimensions of the structure (b) Photo of the result

In the next step, the design was simplified to a wedge shape (see Figure 16) and projected continuously along the specimen. The use of this structure was unsuccessful due to the printer's inability to print the upper 90º without supports, as with the previous attempt.

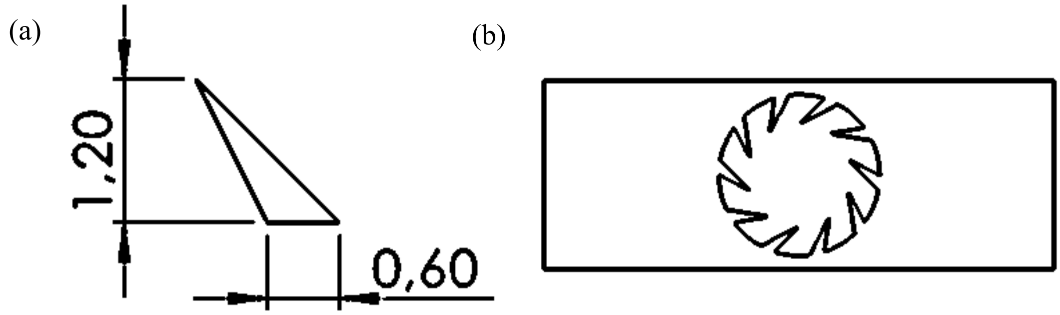


Figure 16: (a)Dimension of the structure (b) View of specimen

Finally, we chose a triangle-shaped structure (see Figure 17) to enable the printer to print without support. We multiplied the design three times along its circumference, leaving the top smooth.

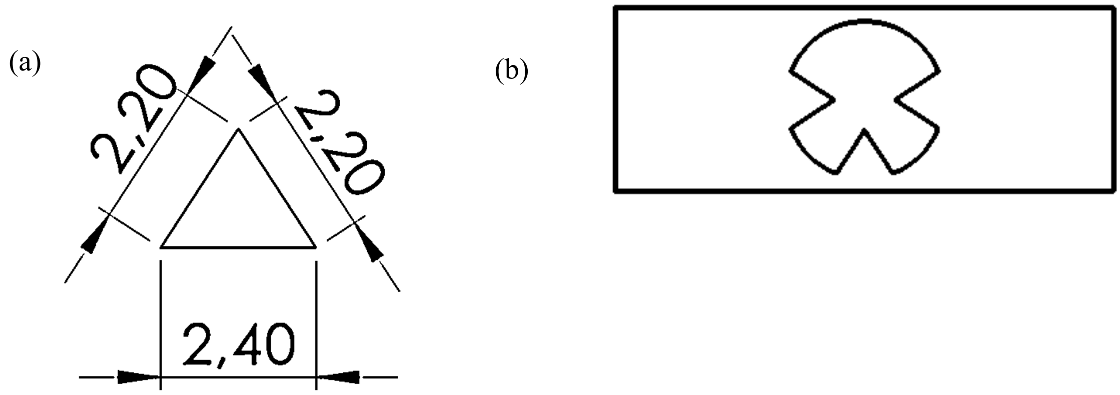


Figure 17: (a) Adhesive structure (b)View of specimen

4.2 Results of tests

This subchapter will present and then discuss the results obtained from the tensile and bending tests.

Utilizing the test data, we computed the stress and strain values and generated graphs for the glass- and carbon fibre-reinforced specimens.

Figure 18 shows the stress and strain values for the carbon fibre-reinforced test specimens for bending tests. It shows that test 4 gives the best results, corresponding to the specimen with a hole and the presence of an adhesion structure.

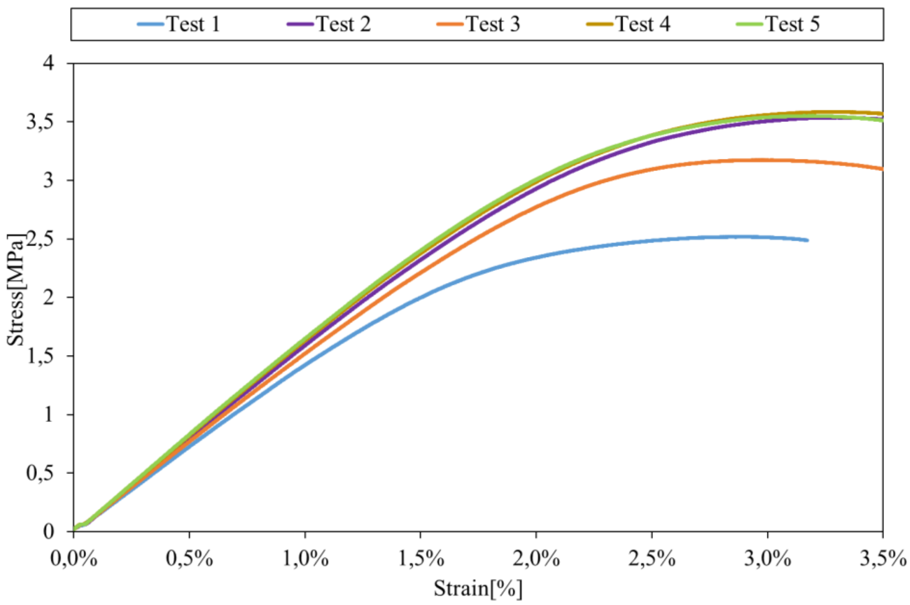


Figure 18: Stress-strain for flexural strength (specimens reinforced with carbon fibres)

Figure 19 shows the stress and strain values for the glass Fiber-reinforced test specimens. Test 8 shows the best results corresponding to the specimen with one hole and the presence of an adhesion structure.

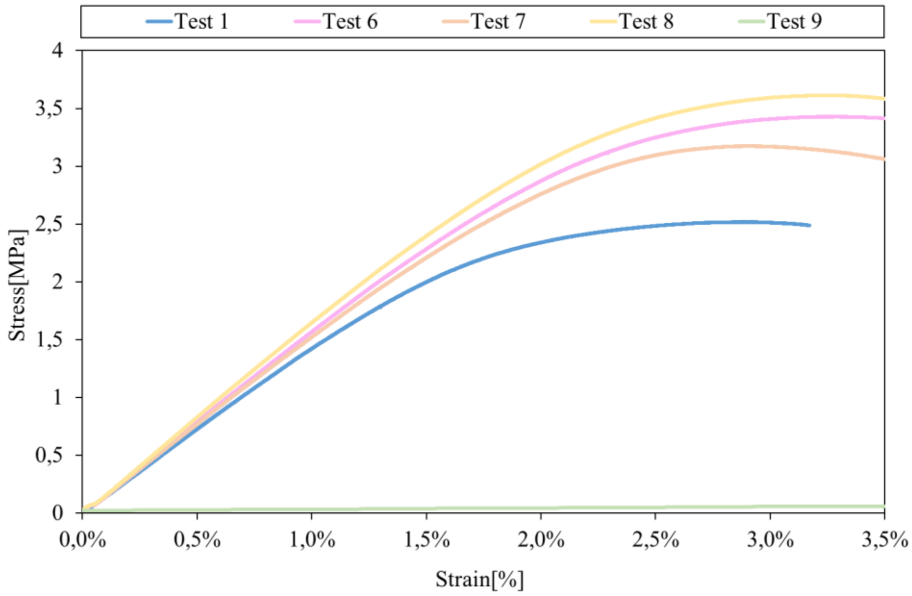


Figure 19: Stress-strain for flexural strength (specimens reinforced with glass fibres)

Figure 20 compares the best results from the two previous graphs. Test 8 shows considerably better results than test 4.

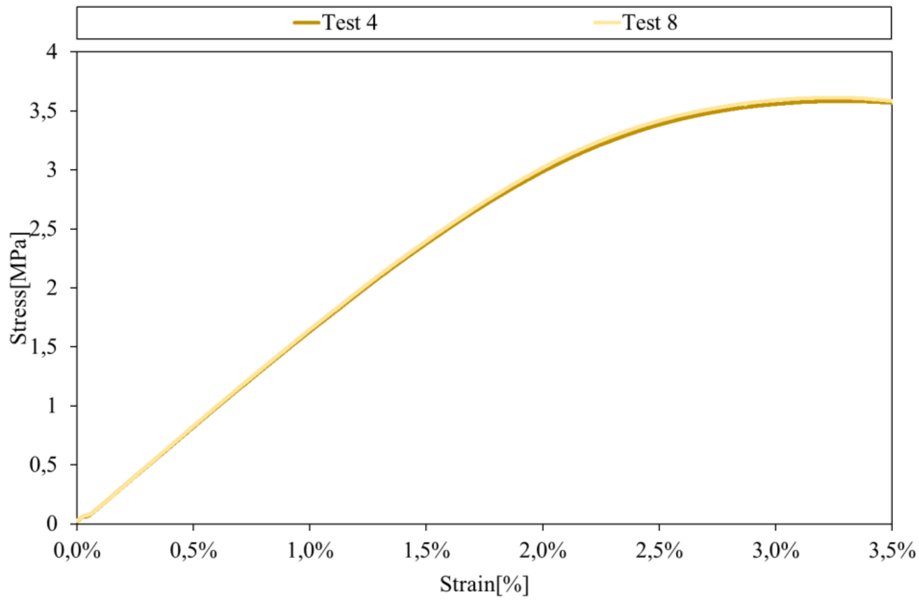


Figure 20: Best results from graphic's 1 and 2

Figure 21 shows the stress and strain values for the carbon fibre-reinforced test specimens for tensile tests. Test 4 shows the best results, corresponding to the specimen with one hole and the presence of an adhesive structure.

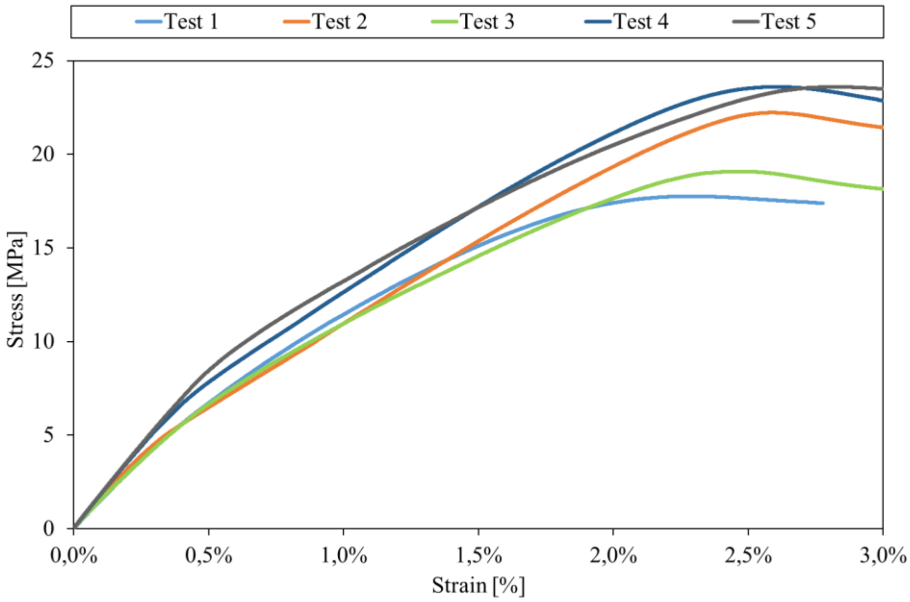


Figure 21: Stress-strain for tensile strength (specimens reinforced with carbon fibres)

Figure 22 shows the stress and strain values for the glass fibre-reinforced test specimens. Test 8 shows the best results, corresponding to the specimen with one hole and the presence of an adhesion structure.

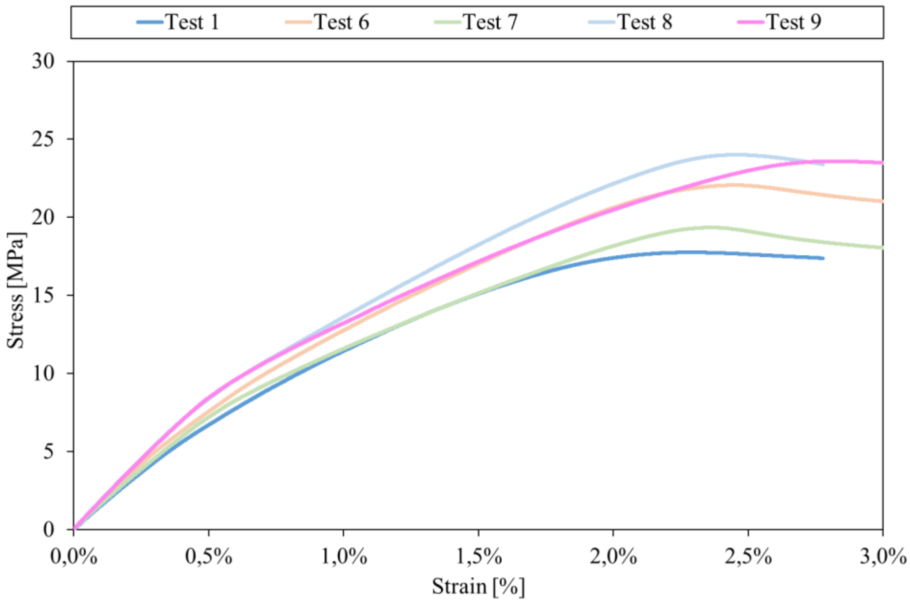


Figure 22: Stress-strain for tensile strength (specimens reinforced with glass fibres)

Figure 23 compares the best results from the two previous graphs. Test 8 shows considerably better results than test 4.

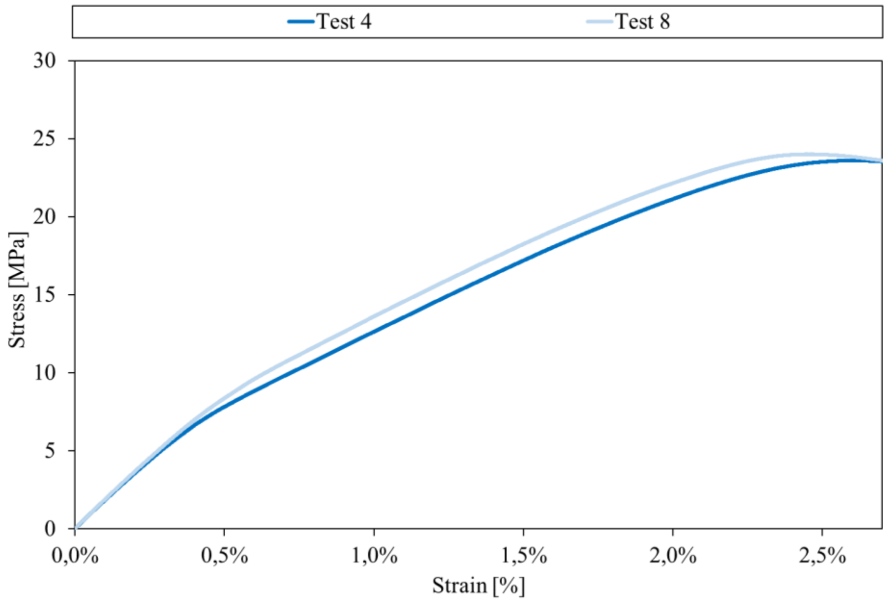


Figure 23: Best results from graphic's 5 and 6

Table 6 and Table 7 show the mean values of the maximum stresses for the 9 specimens in each test, as well as their standard deviation. Test 9 achieved the highest maximum tensile stress value in the tensile test, with a value of 24.436 MPa and a standard deviation of 0.182 MPa. In the bending tests, Test 8 yielded the highest stress, measuring 30.701 MPa with a standard deviation of 1.857 MPa.

Tabel 6:Values of the mean maximum stresses and their standard deviation for tensile tests

EXPERIMENT NUMBER	MAXIMUM STRESS AVERAGE [MPa]	STANDARD DEVIATION [MPa]	RUPTURE STRESS [MPa]	STANDARD DEVIATION [MPa]
1	17.877	0.611	17.190	0.626
2	22.237	0.210	19.452	0.225
3	19.266	0.339	14.321	0.802
4	23.766	0.534	21.442	0.931
5	23.747	0.472	19.688	0.795
6	22.255	0.506	19.415	1.085
7	19.407	0.289	15.911	0.240
8	24.148	0.509	21.629	0.789
9	24.436	0.182	20.409	0.896

Tabel 7:Values of the mean maximum stresses and their standard deviation for flexural tests

EXPERIMENT NUMBER	MAXIMUM STRESS[MPa]	STANDARD DEVIATION [MPa]	RUPTURE STRESS [MPa]	STANDARD DEVIATION [MPa]
1	26.301	0.502	19.127	0.850
2	30.050	0.179	24.159	2.350
3	26.984	0.443	17.592	-
4	30.447	0.471	-	-
5	30.184	2.297	-	-
6	29.126	0.277	15.065	1.631
7	26.981	0.447	-	-
8	30.701	1.857	-	-
9	28.866	0.599	-	-

Chapter 5

Analysis and discussion of results

This chapter analyses the results using the Taguchi analysis method and analysis of variance (ANOVA) for the tensile and bending tests.

5.1 Signal-to-Noise ratio

Like any other technology, additive manufacturing primarily aims to optimize the mechanical properties of the part it produces. The critical control factor is the 'higher-better' signal-to-noise ratio, with bigger values signifying superior performance levels. In this context, the principal control factor is the 'higher-better' signal-to-noise ratio, with bigger values signifying superior performance levels. The ratio equation can be found in subchapter 2.7.1. The following table (Table 8) shows the S/N values, where S/N_{ts} are the values corresponding to the tensile tests and S/N_{bt} are the values for the bending tests.

Table 8: Values of S/N

TEST NUMBER	A	B	C	S/N_{bs} ratio [dB]	S/N_{ts} ratio [dB]
1	1	1	1	19,854	-41,168
2	1	1	2	16,904	-14,595
3	1	2	1	16,795	-20,616
4	1	2	2	16,241	-37,465
5	2	1	1	14,612	-18,386
6	2	1	2	16,528	-11,245
7	2	2	1	14,749	4,598
8	2	2	2	16,236	-4,874
9	3	2	0	-6,146	-13,143

The highest S/Nbt ratio is found in Test 1 (A1, B1, C1), which has a value of 19.854 dB, showing that this setup offers the best bending performance among all the tests. In contrast, Test 9 (A3, B2, C0) demonstrates the poorest bending performance, with a notably negative S/Nbt ratio of -6.1458 dB, indicating that this combination is not suitable for achieving strong bending results.

Other tests, like Test 6 (A2, B1, C2) and Test 2 (A1, B1, C2), also present relatively high S/Nbt ratios (16.528 dB and 16.904 dB, respectively), suggesting good bending performance. However, there is a noticeable trend of decreasing bending performance as we progress away from the initial test configurations, particularly when factor A reaches level 3 in Test 9.

For tensile performance, the S/Nts ratio reveals a distinct trend. The highest tensile value is observed in Test 7 (A2, B2, C1), which boasts a positive value of 4.598 dB. This is the only test that yields a positive S/Nts ratio, underscoring that this configuration offers significantly superior tensile strength compared to all other tests.

On the other hand, Test 1 (A1, B1, C1), which excelled in bending performance, exhibits the poorest tensile performance, with an S/Nts ratio of -41.168 dB. This notable disparity highlights a clear trade-off between bending and tensile performance for this configuration. Likewise, Test 4 (A1, B2, C2) also demonstrates weak tensile performance (-37.465 dB), despite having reasonable bending strength.

A key takeaway from the table is the trade-off between tensile and bending properties. Test 1, which demonstrates excellent bending performance, has the poorest tensile performance, whereas Test 7, which showcases the best tensile performance, only provides moderate bending strength. This illustrates the difficulty of optimizing both mechanical properties at the same time, as enhancing one often results in a decrease in the other.

A possible compromise between tensile and bending performance is observed in Test 6 (A2, B1, C2). This configuration offers good bending strength (S/Nbt = 16.528 dB) and better tensile strength (S/Nts = -11.245 dB) compared to most other tests. While it may not excel in either property, it presents a more balanced outcome than some of the more extreme results.

The table analysis shows how difficult it is to maximize mechanical properties through additive manufacturing. The selection of control factors (A, B, and C) is key in the mechanical properties of the parts that are produced. So, Test 1 (A1, B1, C1) for best bending performance, and Test 7 (A2, B2, C1) for tensile strength. However, achieving a balanced configuration that offers both strong tensile and bending properties may require selecting a middle-ground approach, as seen in Test 6 (A2, B1, C2). In the end, though, the best layout will be determined by whether the emphasis is on tensile strength bending strength, or a balance of the two.

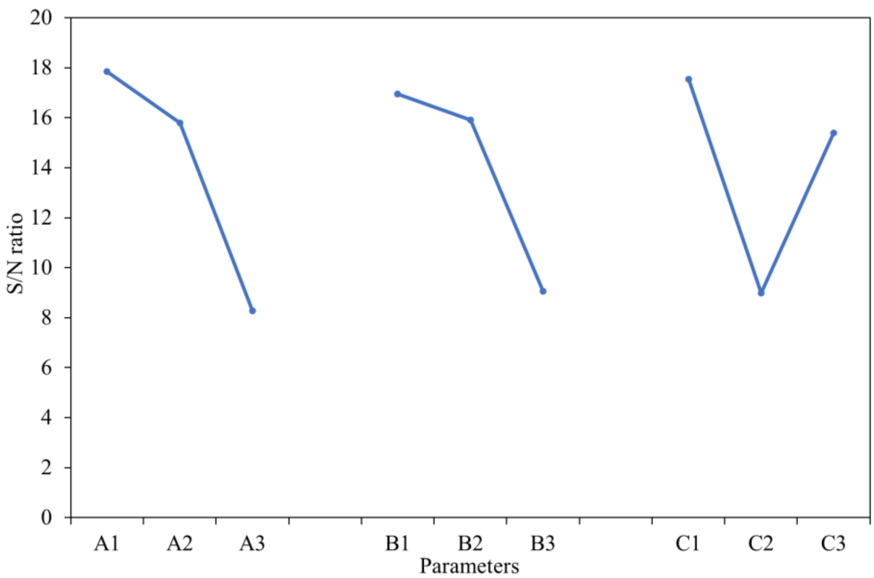


Figure 24: S/N ratio response for bending test

Through the analysis of Figure 24 it is possible to determine the optimal combination to increase the flexural strength of composite. Regarding the bending tests, the ideal combination is A1, B1, C1, i.e., reinforced with carbon fibre, with grip and one hole.

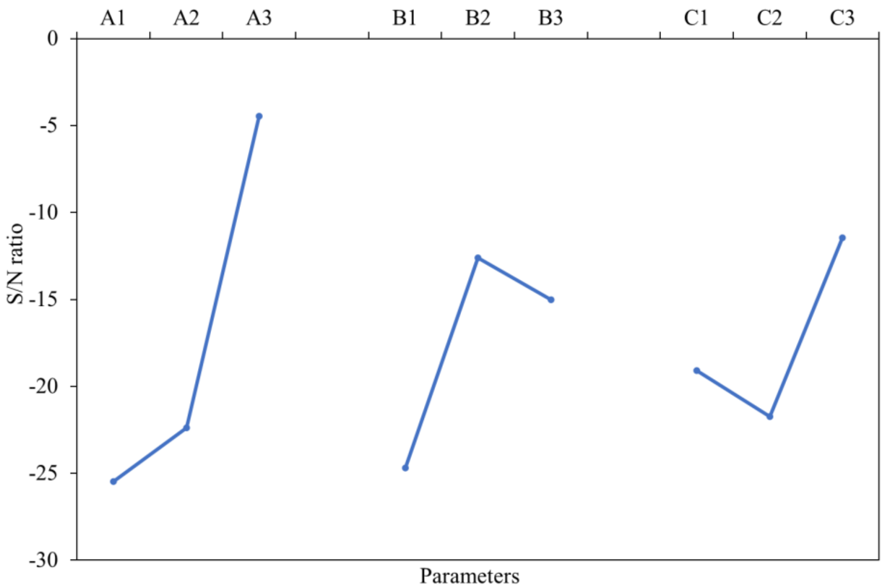


Figure 25:S/N ratio for tensile test

Through the analysis of Figure 25, it is possible to determine the optimal combination to increase the tensile strength of the composite. Regarding the tensile tests, the ideal combination is A3, B2, C3, i.e., reinforced with no reinforcement, without grip and no holes.

5.2 ANOVA Analysis Results

In this chapter, ANOVA will be used to evaluate the effectiveness of the various factors on the performance of the variable considered, which is the signal-to-noise ratio (S/N). The purpose of this analysis is to ascertain if there are any differences in the means of the considered groups and all the possible factors which affect the differences in the values of the results within the groups. In achieving this, different statistical measures are employed. DF (Degrees of Freedom) refers to the number of values in the analysis that are free to vary; Seq SS quantifies the contribution of each factor (or independent variable) in explaining the variability observed in the data (dependent variable).; Adj MS (Adjusted Mean Squares) refers to the adjusted sum of squares divided by the corresponding degrees of freedom and refers to the average diversity for every degree of freedom; F-value is a statistical value that contrasts the intergroup differences and differences within groups, enabling evaluation of how important the factor in question is. The P-value, which indicates the likelihood of obtaining a value as deviant as the observed value under the null hypothesis, often interprets yields below the 0.05 level of risk as significant differences. contribution (%): presents the contribution of each factor to the overall variation, giving a straightforward indication of the effect of every factor. This analysis plays a crucial role in improving the manufacturing process and the mechanical properties of the product. The next subchapters analyse the data from the bending and tensile tests with this method.

*5.2.*1 Flexural Test

The analysis of variance (ANOVA) table (see Table 9) provides significant details concerning the influence of three factors, labelled as A, B and C, on the S/N ratio.

Table 9:ANOVA for flexural test

Source	DF	Seq SS	Adj MS	F-Value	P-Value	Contribution [%]
A	2	342,47	171,24	2,35	0,19	40,53%
B	1	207,66	207,66	3,52	0,119	24,57%
C	2	0,78	0,39	*	*	0,09%
Error	3	294,21	98,07			34,81%
Total	**8**	**845,13**				**100,00%**

With a Sequence SS of 342.47, or 40.53% of the entire variability, the analysis showed that Factor A contributes the most to the overall variability. According to the p-value of 0.19 and the F-value of 2.35, Factor A is not statistically significant at the 0.05 level. However, given its significant contribution, it appears to be a major factor in determining the material's mechanical characteristics, necessitating additional research to optimize the parameters involved.

In contrast, Factor B contributed 24.57% of the total variability with a Seq SS of 207.66. Factor B comes close to significance but falls short of the threshold for statistical significance with an F-value of 3.52 and a p-value of 0.119. This implies that although Factor B has some influence, it is not consistent enough or has a relatively moderate effect to warrant giving Factor A priority. Possible interactions between Factor B and other factors might be investigated in more detail.

With a Seq SS of 294.21, the error term accounted for 34.81% of the variability. This demonstrates that the factors included in the study are unable to account for a sizable amount of the data variability.

In conclusion, a significant amount of the observed variability may be explained by Factor A, which is found to be the most influential variable. Significant improvements in the material's mechanical characteristics could result from optimizing the factors related to Factor A. To improve performance in additive manufacturing processes, the emphasis should continue to be on improving the conditions linked to Factor A, even while Factors B and C contribute only modestly.

*5.2.*2 Tensile Test

ANOVA findings demonstrated that tensile strength is governed by three main factors A, B, and C, in addition to error and total variation. The findings can be seen in Table 10.

Table 10:ANOVA for tensile test

Source	DF	Seq SS	Adj MS	F-Value	P-Value	Contribution [%]
A	2	12,351	6,1755	0,8	0,5	25,76%
B	1	0,0278	0,0278	0	0,953	0,06%
C	2	18,3245	9,1623	1,29	*	38,21%
Error	3	17,2527	5,7509			35,97%
Total	**8**	**47,9561**				**100.00%**

With a sequential sum of squares (Seq SS) of 12.351 and an F-value of 0.8 ($p = 0.5$), the research showed that Factor A has an impact on tensile strength. Of the overall variability observed, 25.76% was attributed to Factor A. The percentage contribution indicates that Factor A has a significant effect on tensile strength, even though it did not show statistical significance at the $p < 0.05$ level. This calls for a more thorough examination of the conditions related to this parameter. However, Factor B showed a p-value of 0.953, an F-value of 0, and a sequential sum of squares (Seq SS) of 0.0278. This factor's negligible contribution of 0.06% to the overall variability suggests that it has little effect on tensile strength.

With a sequential sum of squares (Seq SS) of 18.3245, Factor C had the highest value and accounted for 38.21% of the variability. Although the F-value of 1.29 points to a potential trend of effect, a conclusion on its statistical significance cannot be drawn because no precise p-value is provided.

Lastly, the error variability, which accounted for 35.97 percent of the overall variability, shows that the components evaluated in this study have not yet been able to account for a sizable portion of the variability in tensile strength.

Chapter 6

Conclusion

We can conclude from this study's analysis that the highest recorded tensile stress was 24.436 MPa, with a standard deviation of 0.182 MPa, in the specimen with two holes, reinforced with glass fibre and the adhesion structure. The highest flexural stress was 30.701 MPa, with a standard deviation of 1.858 MPa, in the specimen with one hole, reinforced with glass fibre and the adhesion structure.

The application of the Taguchi method allowed for the identification of the optimal factor combinations to maximise tensile and flexural strength. For tensile strength, the optimal combination was A1, B1, and C1, which corresponds to reinforcement with carbon fibre, an adhesion structure, and one hole. For flexural strength, the ideal configuration was A3, B2, and C3, which corresponds to no reinforcement, no adhesion structure, and no holes. This highlights the importance of specific factors in enhancing the mechanical performance of the tested material.

ANOVA showed that the type of reinforcement (Factor A) explained 40.53% of the total variation in the S/N ratio for the flexural strength tests, making it the most important factor. In contrast, the type of surface (Factor B) and the number of holes (Factor C) contributed significantly less, at 24.57% and 0.09%, respectively. These findings indicate that Factor A plays a critical role in influencing the material’s flexural properties.

The ANOVA test further revealed that Factor A had the largest effect on the variation in the S/N ratio for the tensile strength tests, accounting for 25.76% of the total variation. In comparison, Factor B and Factor C showed smaller contributions, at 0.06% and 38.21%, respectively. These results underscore the pivotal role of Factor A in determining the material’s tensile properties.

Confirmation tests using the optimal factor combinations validated the maximum tensile strength of 24.436 MPa and flexural strength of 30.701 MPa. These results confirm the effectiveness of the Taguchi method and ANOVA in optimising the mechanical properties of the material.

In summary, the present study demonstrated that the specimen has higher flexural strength (30.701 MPa) when reinforced with glass fibre, with two holes and the adhesion structure, compared to its tensile strength (24.436 MPa) when reinforced with glass fibre, with one hole and the adhesion structure. Moreover, the Taguchi method successfully determined the best factor combinations to enhance the tensile and flexural strength of the materials. Factor A consistently influenced both tensile and flexural performance. The ANOVA analyses confirmed that Factor A had the most significant contribution, further emphasising its critical role in improving the material's mechanical performance.

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