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Research of Enhancing Connection Reliability in Fused Filament Fabrication (FFF) Parts for URM Modular Robotic Arms

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Abstract— This paper discusses the Universal Rotary Module (URM), a device developed at the Technical University of Kosice, which is a main component for building a modular robotic arm capable of continuous rotation without the need to rotate back. The text highlights the advantages of the URM, such as its modular architecture, ability to create kinematic chains with varying degrees of freedom, and its potential for further development by reducing component weight. It explores the use of Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM) as an additive manufacturing technology for creating components The text addresses the challenge of connecting FFF parts with parts manufactured using different methods, specifically focusing on creating threads in parts. It compares two methods: tapping threads and using threaded inserts. The advantages and disadvantages of each method are discussed, considering factors such as tool life, breakage risk, skill requirements, load distribution, and ease of replacement. The text presents an experiment conducted to test the thread creation methods using different materials, including PLA, PLA Tough, PETG, and Nylon CF15 Carbon. The results show that the length of the thread significantly affects the strength of the joint, and the point of failure varies depending on the material and thread type. Inserts were found to be more reliable than tapped threads, and the overall strength and reliability of the joints were prioritized over maximum strength.

Index Terms— URM, Additive Manufacturing, Inserts, Threads

I. INTRODUCTION

URM is short-term for Universal Rotary Module. This device is developed at the Technical University of Kosice. It is based on a modular architecture, and it is important for a modular robotic arm. The main advantage is the ability to rotate continually without the need to rotate back. Communication between modules is wireless. The power delivery to each module is done from the previous module through contact pins and coils for wireless power transfer. Another advantage is building a kinematic chain with degrees of freedom depending on the required application. [1]

The second generation of these modules was manufactured in 2019. This generation consists of 3 different sizes named Large, Medium, and Small. All modules have a height identical to the outside diameter. Large is 128 mm, Medium is 108 mm and Small is 88 mm. For mechanical connection, they are requiring passive parts. This part does not have any mechanical parts, batteries, or logic. It only connects two active modules. However, it is necessary to have this part, as the servo with the gearbox is longer than the shell of the URM. An example of a kinematic chain assembled from Large URM modules is in Fig.1.[2]

For further development of this prototype, we are planning to reduce the weight of components. This will help us to further increase speeds and available loads of modular robotic arms. One option is to replace aluminum parts for a parts manufacturer with the FFF technique.

Fused Filament Fabrication (FFF), also known as Fused Deposition Modeling (FDM), is an additive manufacturing technology used to create three-dimensional objects. It is one of the most widely used and accessible 3D printing techniques available today. FFF offers several advantages, including affordability, ease of use, and versatility. It allows the production of complex geometries, functional prototypes, and end-use parts Additionally, a wide range of thermoplastic materials can be used, enabling different properties such as strength, flexibility, or heat resistance. All these properties are necessary for the development of our prototype. [3]–[5]

There is however a problem of connecting these parts to current assemblies. Currently, we do not know, how to reliably connect these parts with parts manufactured with different methods. We would like to use screws and threads.

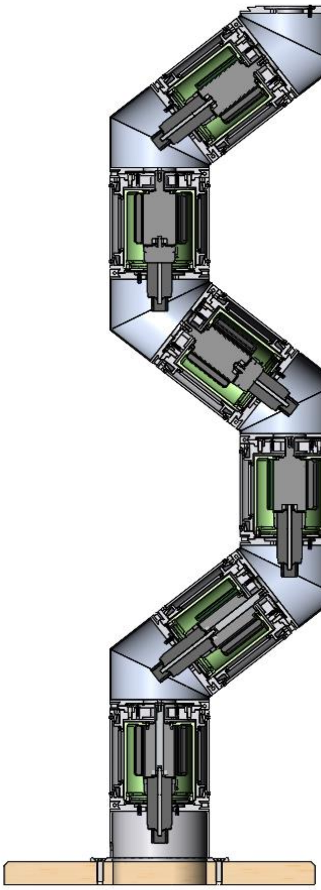

Figure 1 Example of Kinematic chain

II. TYPES OF CREATING THREADS IN PARTS

Thread is the most common type of removable joint. For our purposes, we will consider only metric-size threads. Based on material type, the ISO standard specifies a minimal depth of thread to ensure the secure connection of the bolt. The depth is derived from the main thread diameter. For steel is a multiple of 1, for aluminum alloys is 1.2-1.6 times more, than the diameter, and for plastics is 2. For example, the depth of thread in aluminum alloy for an M5 screw should be at least 7 mm, while for plastic it should be at least 10 mm. This norm is however from 1950. Since then, there was a huge leap in material science, composite materials, etc.

Use metric bolts, there are also multiple ways of creating threads. One of them is to use tapping to cut the thread inside the hole. Tapping involves cutting threads directly into a pre-drilled hole using a tap. In tapping, a tap is used to cut the threads by rotating them into the pre-drilled hole. The tap has flutes that help remove chips and create the desired thread profile.

The main advantages are, that this process is simple, especially for small-scale or one-off productions. It is also cost-effective for low-volume production or repairs, and it can be performed using standard taps readily available in various thread sizes. This process has however few disadvantages. One of them is limited tool life. Repeated use of the tap can lead to wear and eventual replacement. There is also a risk of tap breakage, especially in harder materials or if proper tapping techniques are not followed. Additionally, greater skill and experience are required for precision tapping.

Inserts, also known as threaded inserts or helicoil inserts, are pre-manufactured threaded components that are inserted into a pre-drilled hole. They are typically made of metal and are threaded internally and externally. They are inserted into a pre-drilled hole using specific tools such as insert installation tools or mandrels. Some inserts can be installed at high temperatures or using ultrasonic tools. This is typical for inserts used in plastic. Once installed, they provide a threaded surface for mating fasteners. Inserts distribute the load and prevent thread stripping or wear, especially in softer materials or high-stress applications. They are also allowing for the creation of threads in materials that are difficult to tap, such as castings, composites, or thin-walled structures. Inserts can be used to repair damaged threads in existing holes by providing a new thread surface. Inserts can be used multiple times and worn, or damaged inserts can be easily replaced.[6]

Inserts themselves add cost compared to tapping alone, as they are separate components. Insert-specific tools and equipment are required for installation. They also may require more space or clearance around the hole due to their dimensions.

The choice between tapping and inserts depends on factors such as the application, material, production volume, and specific requirements of the threaded connection. Because of our unique construction of the prototype, the best option is currently unknown. Our main objective is to verify the applicability of these methods for use in our prototype URM. An example of this connection is in the next Figure.

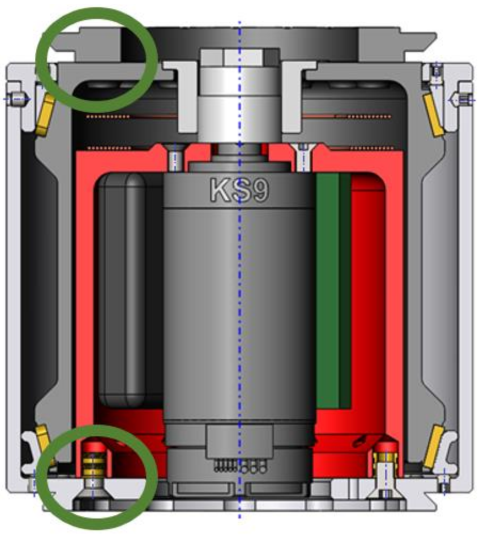

Figure 2 Section view of URM

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Our prototype can use these connections in multiple locations. While the current design can accommodate both solutions, we would like to select and implement the best one as soon as possible.

III. PARAMETERS OF EXPERIMENT

A. Dimensions of samples

We used a custom design for creating test samples. The threads were made size M5x0.8. The depth of the threads was 7 and 14 mm for tapped threads and 7 mm for the inserts (dimension *h*). For tapping the thread, we created a hole 4.5 mm (dimension *d*) and a standard tapping tool.

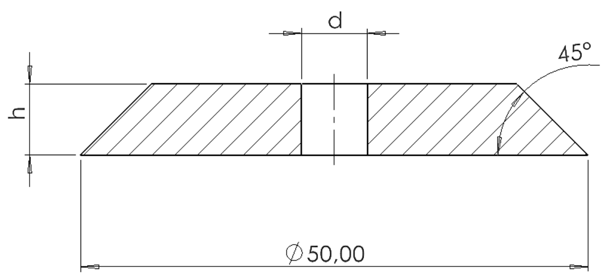

Figure 3 Sample model

In the case of inserts, the height of a sample was 7 mm. That is also the height of an insert, therefore bigger depth does not have any advantage. The hole needed to be enlarged to accommodate the insert to 6.5 mm. The size of the hole was selected from a recommendation from the manufacturer of inserts. All samples were manufactured 5 times from each material.

B. Materials

For testing, we are going to use materials PLA, PLA Tough, PETG, and Nylon CF15 Carbon. These are materials that we are familiar with, and we already have experience with manufacturing parts from them.

1) PLA (Polylactic Acid)

PLA is derived from renewable resources such as cornstarch, tapioca roots, or sugarcane. It falls under the category of biodegradable and biocompatible polymers. It is known for its ease of use in 3D printing. It has a relatively low melting temperature compared to other filaments, typically around 180-220 °C. This makes it compatible with a wide range of consumer-grade 3D printers. It is considered an environmentally friendly filament due to its renewable source material and biodegradability. It is compostable under the right conditions, making it a preferred choice for those seeking sustainable and eco-friendly 3D printing options. PLA also exhibits good printability, low warping, and minimal odor during printing. It has a relatively low shrinkage rate, making it suitable for printing intricate and detailed objects. PLA prints tend to have a smooth surface finish. It is commonly used for a variety of applications, including prototypes, artistic models, architectural models, household items, and educational projects. It is not recommended for functional parts that require very high strength or heat resistance. It can be easily post-processed through sanding, painting, or even acetone smoothing to achieve a desired finish. It is also compatible with various post-printing techniques like gluing, drilling, and threading. While PLA is a versatile and user-friendly filament, its specific properties and performance may vary depending on the manufacturer and the specific blend of PLA being used. It's always advisable to refer to the manufacturer's guidelines and recommendations for optimal printing settings and applications.[7]

2) PLA Tough

Both PLA and PLA Tough are derived from the same base material, polylactic acid. They share similar chemical properties, including biodegradability and biocompatibility. PLA is known for its ease of use and good printability. PLA Tough, on the other hand, is specifically formulated to enhance certain properties, such as impact resistance and durability. PLA Tough typically requires higher printing temperatures compared to regular PLA, often ranging from 200-230 °C. PLA is known for its rigidity and can be brittle, making it prone to breaking under stress or impact. PLA Tough, as the name suggests, is formulated to improve toughness and impact resistance. It has higher flexural and tensile strength, making it more resilient and less likely to fracture under pressure. PLA is suitable for a wide range of applications, including prototypes, artistic models, and household items. However, due to its relatively lower mechanical properties, it may not be the best choice for functional parts that require high strength and impact resistance. PLA Tough is specifically designed for applications that demand greater durability, making it a better choice for functional parts, engineering prototypes, and objects that require additional toughness.[8]

3) PETG (Polyethylene terephthalate)

PETG is a thermoplastic copolyester composed of polyethylene terephthalate. It is a transparent and strong material commonly used in various applications, including 3D printing. PETG is known for its excellent printability and ease of use. It has a higher melting temperature compared to PLA, typically ranging from 220-250 °C. This requires a 3D printer with a heated bed and a nozzle capable of reaching higher temperatures. This filament offers enhanced strength and durability compared to PLA. It has good impact resistance, making it less prone to cracking or breaking. PETG is known for its flexibility, allowing it to withstand bending and deformation without snapping. It is also exhibiting high chemical resistance, making it suitable for applications that involve exposure to various chemicals, oils, and acids. It is less prone to degradation or deformation when exposed to these substances, making it a suitable choice for functional parts and containers. It has inherent transparency, making it ideal for projects that require a clear or translucent appearance, however different coloring may be added. This material is widely used in a variety of applications, including functional prototypes, mechanical parts, enclosures, medical equipment, and food-safe containers. Its combination of strength, flexibility, and chemical resistance makes it a versatile choice for both functional and aesthetic prints. PETG can be post-processed through techniques such as sanding, painting, and polishing to achieve the desired finish. It is also compatible with chemical smoothing techniques using substances like acetone or ethyl acetate, although the effect may be less pronounced compared to ABS.[9]

4) Nylon CF15 Carbon

Nylon CF15 Carbon is a composite filament that combines Nylon (polyamide) with chopped carbon fiber. Carbon fiber, known for its exceptional strength-to-weight ratio, is embedded within the Nylon matrix to enhance the filament's mechanical properties. This material typically requires a heated bed and a nozzle capable of reaching higher temperatures, as the printing temperature can range from 240-280 degrees Celsius There is also a requirement for a nozzle to withstand the abrasive properties of this material. The addition of carbon fiber provides significant strength and rigidity to the Nylon filament. Carbon fiber is renowned for its high tensile strength, allowing the composite filament to exhibit improved structural integrity and resistance to deformation. The resulting prints are stronger and more durable compared to standard Nylon prints. Despite its enhanced strength, Nylon CF15 Carbon remains relatively lightweight. This makes it suitable for applications where strength is essential, but minimizing weight is also a consideration. This material also demonstrates improved heat resistance compared to regular Nylon. The presence of carbon fiber aids in dissipating heat, allowing the printed parts to withstand higher temperatures without warping or deforming. It is well-suited for demanding applications that require high strength, rigidity, and durability. It is commonly used in engineering prototypes, functional parts, tooling, robotics, aerospace components, and automotive applications. Its combination of strength, lightweight properties, and heat resistance makes it suitable for applications that require both structural integrity and performance.[10]

We choose PETG, PLA, PLA Though, and Nylon CF15 Carbon for material selection. This represents the material used for manufacturing selected parts as well as materials used in other projects. The tensile strength of each material is in the figure below.

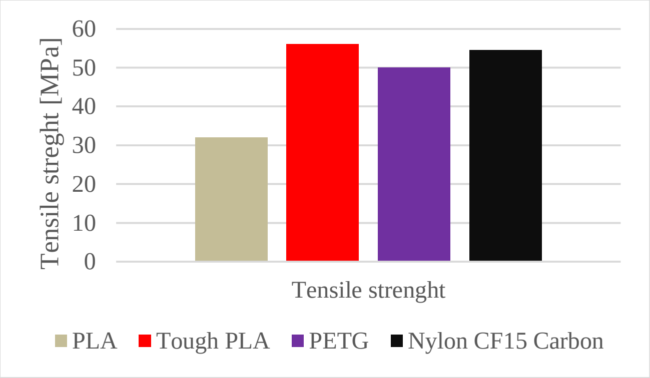

Figure 4 Tensile strength of tested materials

C. Equipment and specimen manufacturing

For each material, we used different printing parameters to achieve the best mechanical properties. One of the main parameters was changing the number of walls during manufacturing to 3 to ensure enough material during tapping. We also used 50-70 % infill, based on our previous experience with these materials.

For the tests themselves, we used the stress measuring tool for figuring out the force required to pull out the screw from a specimen. For that, we fixed a special fixture in the top clamps and a long M5 screw into the bottom clamps. The testing assembly is in the picture below. Each test was done with the same parameters.

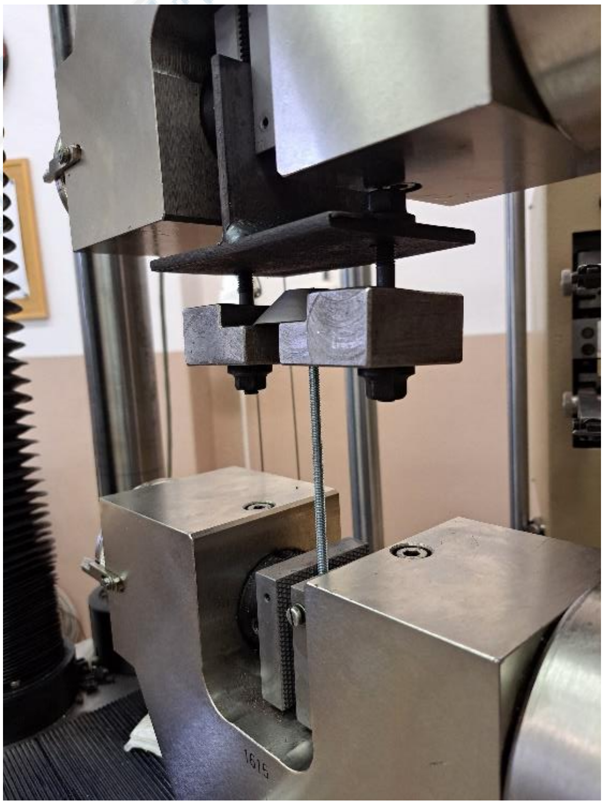

Figure 5 Testing setup

IV. TESTING AND RESULTS

In the case of the threaded samples, the pulling force from the materials varied based on the mechanical properties of the material. However, the double length did not provide double the strength for joints. The longer thread however provided a stronger holding force for all samples. What changed however was the point of failure. While for the samples from PLA with a tread depth of 7 mm the point of failure was the thread itself, for 14 mm it was the merge point of outside layers with infill. That suggests that during the manufacturing process, the material anisotropic properties are bigger concerns than the thread force itself. That means for this case the ISO norm is still applicable.

For Nylon CF15 Carbon and some samples from PETG however was the point of failure the thread itself. The material could not hold the small, detailed thread.

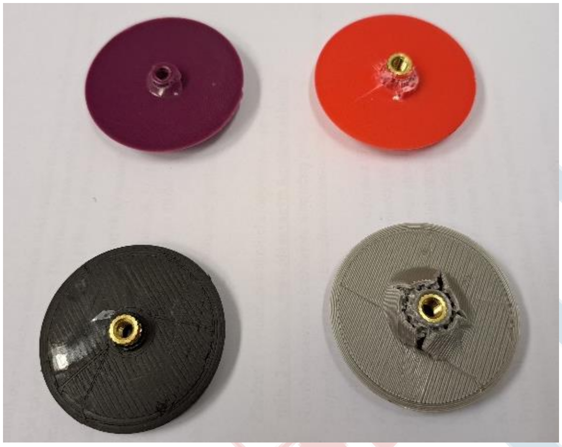

Figure 6 Example of tested samples

In the case of using the inserts, the point of failure was the material around the inserts, never the insert itself. There were two cases of failure, one of them was pulling up the insert from the material, and the other case was failure between the wall section and infill section of a specimen. However, these types of failures appeared to be random, but they are not affecting the results. The overall comparison is in Fig. 11 and detailed results for each tested material are in Fig. 7-10.

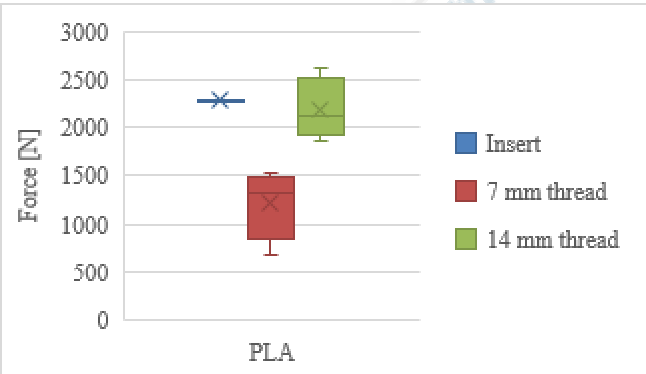

Figure 7 Results PLA

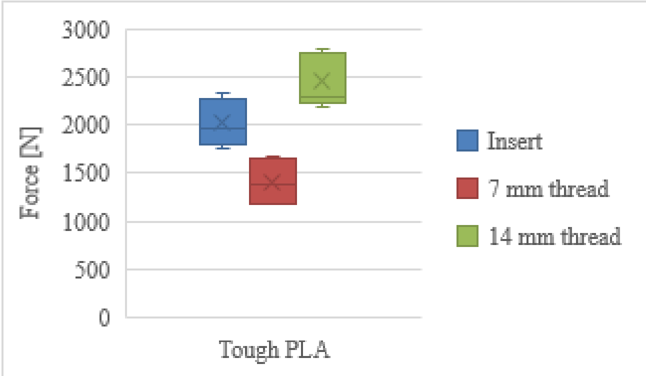

Figure 8 Results Tough PLA

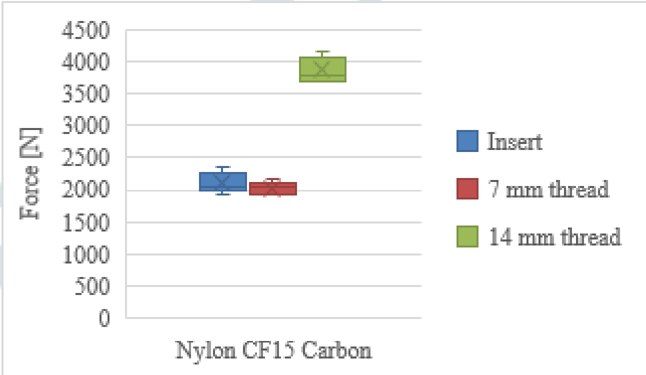

Figure 9 Results Nylon CF15 Carbon

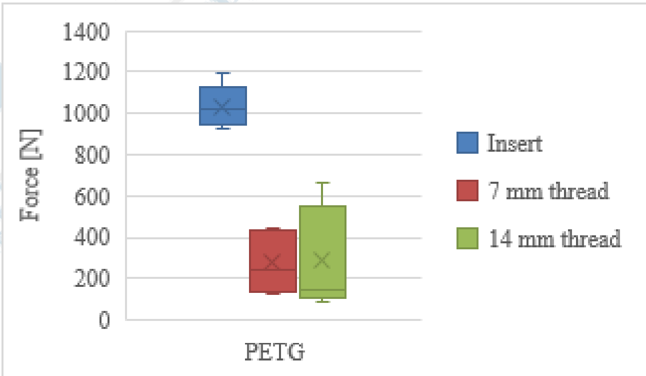

Figure 10 Results PETG

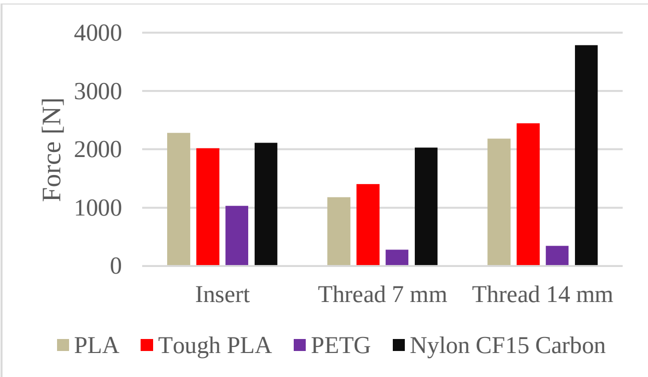

Figure 11 Results – average strength, an overall comparison

As mentioned before, one of the types of failure was between the wall section and the infill section of the specimen as shown in Fig. 12. This type was specific to PLA material 14 mm threads. That suggests that the overall strength of the joint could be higher if we used different types of infill. In either case, each material had a higher range of measured force for a tapped thread.

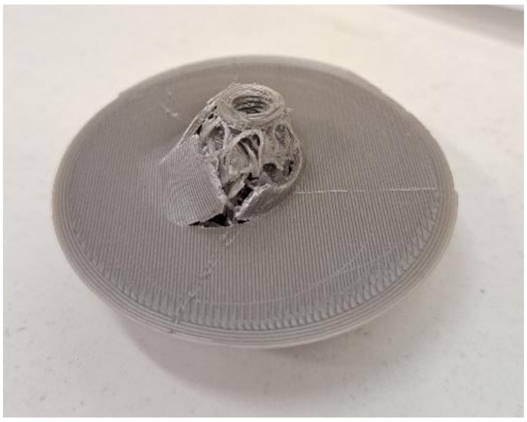

Figure 12 Tested sample - PLA with 14 mm thread.

For PETG using inserts is the only way for achieving reliable joints. In the case of PLA and Tough PLA using Inserts can reduce the overall height of the part, while achieving the same strength. For Nylon CF15 Carbon we can achieve higher strength if use a longer thread.

These results however considered only successful tests. During testing, we also must remove some specimens with faulty tapped threads. There was not a single faulty specimen with an insert. Because the reliability of manufactured joints is in our case the highest priority, we are going to use inserts in all our prototypes, even when it means lower strength.

V. CONCLUSION

This study aimed to investigate the effectiveness of different thread creation methods for parts manufactured using Fused Filament Fabrication (FFF) techniques. The study focused on two main approaches: tapping threads directly into pre-drilled holes and using threaded inserts.

The results of the experiments revealed several key findings. When using tapped threads, the length of the thread was found to significantly affect the strength of the joint. While longer threads provided stronger holding forces, the point of failure shifted from the thread itself to the merge point between outside layers and infill. This suggests that the anisotropic properties of the material during the manufacturing process play a significant role in joint strength.

On the other hand, the use of threaded inserts proved to be a reliable method, with no failures observed in the inserts themselves. Failures occurred either at the material around the inserts or at the interface between the wall and infill sections of the specimens. However, these failures did not significantly impact the overall results.

The choice between tapping threads and using inserts depends on various factors, including the application, material, production volume, and specific requirements of the threaded connection. In this study, inserts demonstrated higher reliability, as no faulty specimens were observed, compared to some faulty tapped threads. Therefore, the researchers decided to prioritize the reliability of the joints and opted to use inserts in all their prototypes, even if it meant sacrificing some strength.

It should be noted that further investigation can be done to explore the effect of different infill patterns on joint strength for parts with tapped threads, as it was observed that failures occurred at the interface between the wall and infill sections for some specimens.

Overall, this study provides valuable insights into the selection of thread-creation methods for FFF-manufactured parts. The findings can guide future researchers and practitioners in choosing the most suitable approach based on their specific requirements for joint strength and reliability.

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