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3D PRINTING OF TEMPORARY WORKS WITH FIBER REINFORCED POLYMERS

Birdcage Design

Thesis Report

PRESENTED BY: MAURICIO A. RAMOS

BAM INTERNATIONAL

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NOMENCLATURE

Additive Manufacturing: 3D Printing, building a structure in layers (as opposed to a mould).

Fused Deposition Modeling (FDM): The process by which a viscous liquid filament is extruded through a nozzle layer by layer and onto a base.

3D Printing Filament: Is the thermoplastic feedstock used for fused deposition modeling technique. It often comes rolled in reels/spools.

Composite: Material made of several parts or elements. In case of 3D printing, a composite is a plastic resin reinforced with any type of fibers.

Anisotropic: A quality of a cross section which has a different physical property when measured in different directions. One example of it is wood.

Infill Patterns: Is the infill density of filament printed inside the structure.

Nozzle: A cylindrical or round spout at the end of a tube to control a jet of liquid. In 3D printing is used a heated nozzle to heat up, soften the plastic, and the extrude the filament layer by layer.

Birdcage: Platform structure which is attach to the piles in the construction of jetties.

Buttress: A buttress is an architectural structure built against or projecting from a wall which serves to support or reinforce the wall. In this research the buttresses serve supporting the upper plate, transferring the loads to the core of the structure.

INTRODUCTION

BAM International is a subsidiary of Royal BAM Group, one of Europe's largest contracting companies active in construction, property, civil engineering, public-private partnerships, mechanical and electrical contracting and engineering in 30 countries across the globe. As an active member in the construction industry, BAM is always looking to improve and adapt its techniques or practices as the technology moves forward and newer materials are available.

BAM International is experienced in the near shore civil marine sector. Hence, when executing the projects, the efficiency and the time of these are depending on certain techniques and works needed to build the permanent works. If there is any structure which can simplify the work and reduce the overall time of the activity, then, it is first designed by the engineers and later sent to a subcontractor who will manufacture the final product to be used only during the execution phase. These structures/techniques are called temporary works. The current situation for these temporary works in remote locations, where the projects take place, have shown some disadvantages and/or nonefficient and unsustainable materials used when compared to 3D printing technologies and composite materials for example. The manufacturing process takes place at the subcontractors' facilities relatively far from the project location, and the delivery of these structures takes long periods due to the distance from suppliers to the sites; thus, the need for a more efficient technology and materials has arisen. This is the case for 3D Printing technologies and composite materials which are sustainable and innovative ideas that are growing and involving different industries as transportation, electrical, infrastructure, industrial and energy etc. The following plan purposes are to seek out the opportunity to introduce this technology in BAM practices. It will also consider the possibility to be introduced in other phases of the project to reduce overall costs, time, and the environmental footprint of the construction industry while increasing the economical profit and social acceptance of the company (BAM).

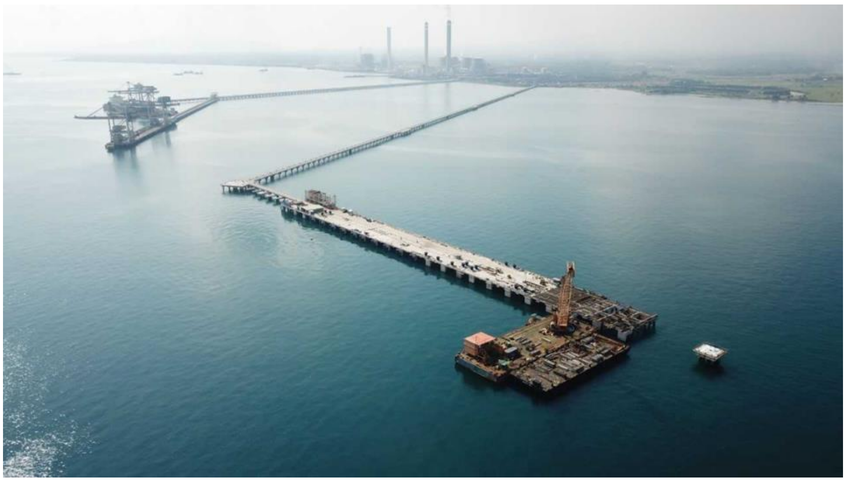


Figure 1 Tanjun Jati Project (study case)

Within BAM Infra (Netherlands) there is a 3D concrete printing facility already. This is the Europe's first commercial and industrial production location for 3D printing of concrete elements for bridges. The idea now for BAM (International) is to also include composite materials in the design of temporary works through 3D printing methods. Prior to this research, a feasibility study was done by Maximilian Foy where it was concluded that it is technically feasible to use 3D Printed birdcages, gangways, and handrails. Nevertheless, the commercial case of 3D printing of temporary works is dependent on the contributing factors such as the costs of the material used, including the productivity and the costs of the 3D printer itself. The following plan aims to optimize the current design (structural and economical wise) for the Tanjung Jati project study case (platforms, gangways, and handrails) and to investigate the required certifications and legal documents to produce such structures and tools. Furthermore, an investigation of 3D printable alternatives will be done within other Opco's like BAM Infra, BAM Belgium and BAM Nuttall to optimize the productivity of the 3D Printer.

PROBLEM STATEMENT

Unfortunately, the construction sector is considered as one of the main sources of environmental pollution in the world (Enshassi, 2014). The following design is based on the study case of Tanjung Jati project in Indonesia where birdcages were used to do the necessary adjustments on the piles. The material used is steel which is being manufactured and gathered from external parties. Depending on the production of such structures can cause problems in the development and duration of the project due to time delays in the delivery process.

Figure 2 Current steel birdcage

New technologies as it is 3D printing can be applied in the construction industry to tackle the different issues presented in each project and/or to improve the current practices, reducing time and implementing new materials like composites and thermoplastics. BAM international has started an innovative project to design these structures to be 3D printed and using fiber reinforced polymers (composites).

The current platforms used in marine projects are designed and made of steel. The lifting process of these platforms requires the use of a crane, and the platform itself is attached to the pile with a clamp system. To acquire these platforms in the Tanjung Jati project, a local subcontractor was contacted, and therefore, the logistics and delivery time was depending on an external party. The platforms presented above (figure 2) were only needed to do the required work on the piles for the final project and once the execution of the project is done, these platforms are stored for 5-6 years, to then be sent to a scrap yard.

As BAM International is always looking to improve its practices, the idea of this research is to study the possibility to design, produce, and recycle temporary works at the site (by using composite materials and being 3D printed at the project location), reducing cost and time in the manufacturing process and logistics. At the same time this method is far more sustainable, giving the opportunity to reduce the environmental footprint of each project carried by BAM (international).

RESEARCH OBJECTIVE

To determine (a) potential valuable business case (s) for BAM (International) to apply 3D printed products using composite materials on their (near shore Civil Marine) projects, by studying the technical advantages of the 3D printing technology and composite materials besides providing an structural optimization of the current platform used as temporary works as an initial study case to introduce the 3D printing technology in the construction industry of BAM.

MAIN QUESTION

What is the optimal design of 3D printed temporary works platforms (birdcages) made of composite materials which meet the structural requirements and is economically feasible for BAM International when being produced by means of additive manufacturing and used in near shore civil marine projects (Tanjung Jati study case)?

SUBQUESTIONS

To answer this question, the study will be divided into 3 different parts to ensure the accomplishment of the goals:

Material and equipment needed for production of platforms (birdcages).

- What is 3D printing?
- What are the different 3D printing techniques?
- What are polymer materials?
- What is the difference of thermosets and thermoplastics?
- What are 3D printing filaments?
- What is fiber reinforced polymers?
- What is the type of fibers used in FRP's?
- What is warping or shrinkage in 3D printing?

Design and production of the product (Platform/Birdcage).

- What is finite element analysis?
- What is linear material analysis?
- What is orthotropic material?
- What are the printing parameters for a birdcage design made by means of Fused deposition technique?
- What are the technical requirements for a birdcage design made by means of fused deposition modeling technique?
- What are the weather and chemical conditions for the platform?
- How does fused deposition modelling (FDM) manufacturing technique affects the cross-sectional resistance of the platform?
- What is the material physical and mechanical properties to be used in the design?

Disposal of the product/structure after finalization of the project.

- What happens with the current temporary works when the project is done?
- Can temporary works made of composite materials be re-used or recycled?

RESEARCH DESIGN STRATEGY

The design will be done taking into account the manufacturing technique limitations and requirements. Additive manufacturing has a special method to produce the 3D objects, therefore, an extensive desk research needs to be carried to understand the possibilities for a new design while fulfilling the current needs as a birdcage and not affecting the durability and performance of the structure. Along the manufacturing technique, there is the material which in this case is intended to be different to the current material used by BAM (steel). Thus, an understanding of the new material behavior is needed to achieve the main objective of this report.

The following report is structured for a clear understanding of the 3D printing technology, the material used, and the structural analysis of composite materials when using 3D printing as a manufacturing technique. It aims to improve the current practices and at the same time reduce the costs and negative environmental impact of temporary works used in projects.

This report is divided into the following chapters:

Introduction: The company background, problem statement, main questions and sub questions.

Theoretical Framework: Desk research of important subjects required for the design of a birdcage.

Methodology: Describes the strategy used for the design of the structure (birdcage).

Results: Final design (3D modeling, prototyping, and structural analysis).

Discussion: The study of the design process and its possible variants for further designs for 3D printing.

Conclusion: An analysis of the development and results of the research design.

THEORETICAL FRAMEWORK

This project includes different aspects that need to be analysed in order to fully understand the advantages and differences of the proposed method and material compared to the current practices.

To understand the design process, the topics in this research are divided into three main groups.

1. 3D Printing technology (Additive manufacturing techniques).
2. Composites materials FRP (fibre reinforced polymers).
3. Structural analysis of 3D printed structures.

The three groups have an important influence in the stability and functionality of the final structure. Therefore, it is important to have a good understanding of the qualities of each group to achieve the desired goals and to answer the research questions for this project.

The focus of this report is the design of a birdcage (platform), used in the Tanjun Jati project in Indonesia, but it also looks into the best way of producing this structure, to later apply this method in other printable alternatives.

To start, will explain the manufacturing method which in this case is 3D printing and the different techniques that it has, to define the most suitable for the production of birdcages. Then an overview of the material properties and behaviour, to finally explain how to approach and proceed for a structural analysis.

INTRODUCTION TO 3D PRINTING

There are different 3D printing methods with plastics and used worldwide. These methods have been developed to cover a wide range of applications and part geometries. It is important for any designer or engineer to be familiar with the manufacturing options and the latest developments in technology to be able to choose the right technique and type of plastic used for the final product. The following table illustrates the current techniques used in 3D printing, linked to the current design of a birdcage:

3D Printing Technique	Material form	Equipment Costs	Fibers reinforcement	Advantages
Stereolithography (SLA)	Resin	€200 – €500	Yes (Uncommon)	Good for prototyping and medical end-products
Powder bed and inkjet head 3D printing (3DP)	Powder	€50.000 – €2.000.000	No	Can use different type of materials, not only polymers
Selective Laser Sintering (SLS)	Powder	€5.000 – €10.000	Yes (Uncommon)	Reliable mechanical properties
Fused deposition modeling (FDM)	Filament/pellet	€250.000 – €500.000	Yes	It is possible to produce large scale end-products

Due to the functionality of the birdcage and to be able to produce it on-site **the method chosen for this design is Fused deposition modeling (FDM)** since it allows to have all the equipment and material near by the project location avoiding the need for an external company to manufacture it, and also can provide the desired shapes while meeting the structural requirements. Regardless of its high initial investment, overtime it is still economically feasible for the project only if the birdcages can be recyclable or reusable. This manufacturing method will be explained in the next sub-chapter. <u>However, the other 3D printing techniques will also be described in the following sub-chapter to take into account for further designs used in the construction industry.</u>

The idea of making a three-dimensional printed model has been around for fairly a long time but is only now when is being introduced in large scale in different industries. 3D Printing or additive manufacturing (AM) is the process of making three dimensional objects from a digital file. The creation of the 3D object can be by means of different techniques as it is fused deposition modelling, stereolithography, digital light processing, etc. And using certain materials which are extruded or shaped according to the chosen technique. (What is 3D Printing?, n.d.)There is a variety of materials that can be used to 3D print, including plastics (polymers), powders, filaments and paper, but nowadays is being introduced the use of fibbers (e.g. glass, carbon) to reinforce and improve the mechanical properties of the pure polymer materials. For this design the material used will be a polymer reinforced with a type of fibers, to assure it is strong enough to withstand the applied forces.

The materials used in FDM technique are polymers (plastics) in the form of filaments or pellets. They are the most common materials for producing end-use parts and products (Wang, Jiang, Zhou, Gou, & Hui, 2016), but in the past decades these materials and resources have not had a proper administration since they have been used in a linear economy, causing critical problems in the environment which are prompt to worsen with time if nothing is done to change the current situation. This research intends to reduce the negative environmental impact by recycling the material after each project is completed.

3D Printing technology is in its early stages in the construction sector but has shown a strong potential to overcome environmental, economic, and efficiency problems that the industry might face in the current and future stages. There are already examples of how this technology (additive manufacturing) is being used in large scales where companies have printed as for example: One level houses, concrete and composite bridges, and composite boats; showing the possibility and availability to acquire the required equipment to produce and replace the current temporary works used by BAM. In these examples, the technique implemented is Fused Deposition Modeling (FDM) which is the same technique that will be applied for the birdcage and will be explained in the next sub-chapter.

Until recently, the main functionality of the 3D printed models is for conceptual prototyping rather than functional components. This is because 3D printed parts made of homogenous polymers have mechanical properties relatively weak to withstand larger forces due to its flexibility. Such disadvantages were restricting the wide industrial application of 3D printed polymers (Wang, Jiang, Zhou, Gou, & Hui, 2016). Yet, the use of composite polymers with different type of reinforcement fibbers are being developed and improved to overcome these disadvantages. Even though this technology is rarely new, other materials are currently under studies to be able to increase the functionality of the end-products fabricated by 3D printing methods.

Additive manufacturing is rapidly growing in different industries providing a reduction in time and costs in the production phase. As an example in China, Yingchuang Building Technique (Shanghai) Co.,Ltd. (Winsun) has achieved enormous ideas within the construction and architecture industry worldwide. Winsun has developed a series of new materials for the past 17 years since it was founded in 2003 (Hahn, 2018). Since then, the materials have been improved to be applied in the 3D printing industry. These methods (3D printing -FDM) can also be applied by BAM in the production of temporary works and spare parts to reduce the costs of its projects.

Many other companies have now started to introduce this technology to enjoy the advantages that additive manufacturing can offer. In this research the technique used for design is FDM (fused deposition modelling) as stated before. The type of material chosen is fiber reinforced polymers it will also consider the possibility to use recycled plastics. Aiming to start circularity in the practices carried by BAM International and other Op'Cos.

The construction sector is considered as one of the main sources of environmental pollution in the world, therefore, the companies and any entity involved should start adapting to more sustainable methods and materials to use in the industry, and that is the intention with this research: to propose a more efficient, economically feasible, and more sustainable approach of designing temporary works as for the study case. In the following sub-chapters will be described the 3D printing techniques, the material used in fused deposition modeling (FDM), and the possible reinforcement particles which can be added to the plastic to improve its mechanical and physical properties.

3D PRINTING TECHNIQUES

A summary of stablished printing techniques (Wang, Jiang, Zhou, Gou, & Hui, 2016):

Technique	State of starting materials	Typical polymer materials	Working principle
FDM	Filament	Thermoplastics, such as PC, ABS, PLA, and nylon	Extrusion and deposition
SLA	Liquid photo-polymer	Photocurable resin (epoxy or acrylate based resin)	Laser scanning and UV induced curing
SLS	Powder	PCL and polyamide powder	Laser scanning and heat induced sintering
3DP	Powder	Any materials can be supplied as powder, binder needed	Drop-on-demand binder printing
3D plotting	Liquid or paste	PCL, PLA, hydrogel	Pressurized syringe extrusion, and heat or UV-assisted curing

Figure 3 Printing techniques summary

FUSED DEPOSITION MODELING (FDM)

This method produces objects layer by layer when heating the extruded filament. The design is made with a CAD (computer aided design) software which sends the file to the printer. This method is one of the most widely used additive manufacturing processes to 3D print objects. Many types of polymer materials can be used with FDM techniques. These materials will be explained in the 3D Printing materials chapter.

FDM technique is the most commonly method to print polymer composites (in small and large scales). Thermoplastics (which is a type of polymer) like PC, ABS, and PLA are among the most common materials for this method due to their low melting temperature (Xing Wang, 2016). The filaments go into a heated end (nozzle) and just past its glass transition temperature is then extruded and deposited on a heated bed. One of the main advantages of this method is the capability to scale the designs according to the reach of the printer gantries. **In this study case this FDM technique method will be used for the design of the temporary work (birdcage).**

The process of 3D printing by means of FDM technique starts in the design by using a CAD (computer aid design) software, then is the slicing process which divides the 3D model into small parts (horizontal layers) drawing the path that the nozzle will take to extrude the material layer by layer (Grames, 219). And finally, the material is extruded and deposited in the printing bed. The slicing stage is done with a special slicing software.

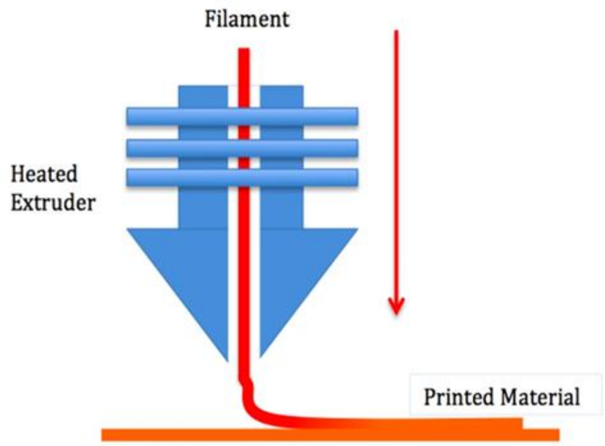


Figure 4 Fused deposition modeling (FDM)

One disadvantage of this technique is that the composite materials in a filament when being extruded is difficult to equally spread the reinforcements (fibers). It is quite important to pay attention to the cooling process of each layer since a rapid change in temperature can aggravate deformation (warping) on the printed layers. For this, many printers have included a heated printing bed to keep a constant temperature within the printing room, and the cooling happens also in an enclosed space with the temperature regulated reducing the warping effects. At the same time, it is also difficult to evade but FDM double extrusion technique can remove the voids formed during the manufacturing process. Nevertheless, new technologies and printer providers are assuring methods against these difficulties. The most important factor when choosing which material to use as filament is that it needs to have a suitable viscosity: should be high enough for structural support but low enough to enable extrusion (Xin Wang, 2016). Composite materials not only have disadvantages, but some big advantages are that is widely used due to their low cost, high printing speed, and they are commonly simple to manage. FDM also allows the deposition of different materials by incorporating multiple extrusion nozzles.

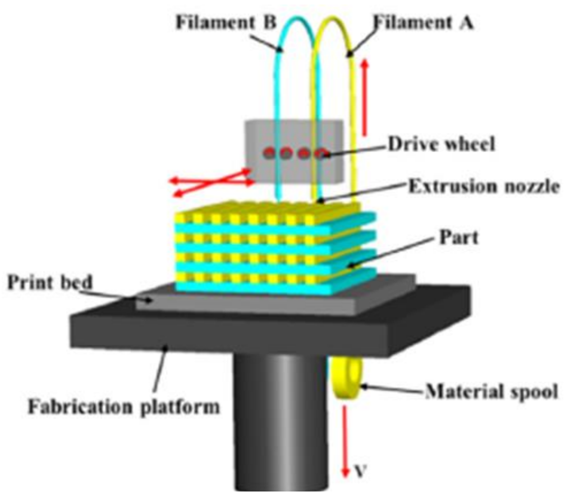


Figure 5 Double extrusion in FDM

In large scale/industrial 3D printing the recommended and most efficient method due to its simplicity and low cost is FDM (fused deposition modeling). This technology shows the benefits that it could bring to the construction industry by producing structural parts as BAM Infra is currently doing with one of the newest and largest concrete 3D printers.

The following are the two optional companies which are developing 3D printing (FDM technique) in large scale and are incorporating fiber reinforcement within their printing materials.

COLOSSUS S.A

Provides a large-scale containerized 3D Printer which allows to print products up to 4m*2m dimensions by means of FDM technique. Colossus printers are based in Belgium and are willing to work with BAM International to both develop and test the birdcage design provided in this report. The main focus of COLOSSUS up to 2019 was to produce end-products in the Art industry, like sculptures. The company is scaling up to start introducing new technology which allows the printer to print fiber reinforced polymers.

Figure 6 Colossus 3D Printer

CEAD GROUP

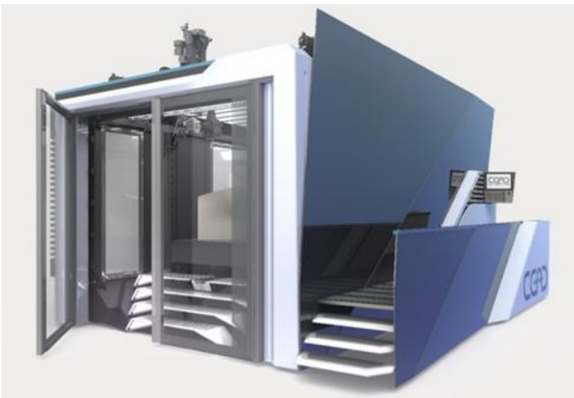


Figure 7 CEAD Printer

CEAD printers are more experienced with the printing of fiber reinforced polymers using FDM technique. They have carried projects in which large-scale products were used in the construction industry but one of their disadvantages is the high initial investment needed per printer. CEAD not only offers a 3D printer itself but also offers the different components separately (robotic arm, extruder, and a separate gantry system). One of the projects which they have carried and is similar to the birdcage design, is the printing of composite parts for a bridge.

STEREOLITHOGRAPHY (SLA)

This method makes use of a liquid plastic (thermoset resins) as the prime material which is transformed into a 3D object by using an UV (ultraviolet) laser which solidify the material layer by layer (Types of 3D printers or 3D printing technologies overview, sd). The platform lowers and then another layer can be solidified by the UV laser. Typical materials used in this technique are polymers like: acrylic and epoxy resins (Wang, Jiang, Zhou, Gou, & Hui, 2016). Yet, this technology is used in small scale and mainly for prototyping. For the 1:1 scale birdcage, the equipment used in SLA does not allow the production of large-scale parts. Thus, this technique cannot be applied for the production of birdcages but perhaps it can be used for spare parts.

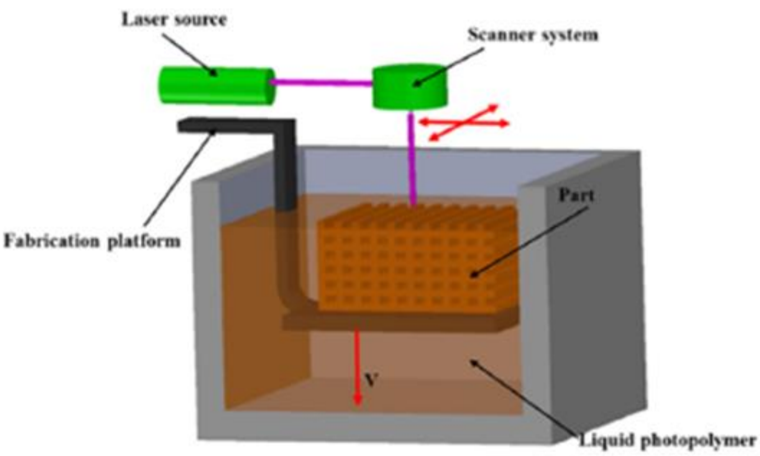


Figure 8 Stereolithography (SLA)

POWDER BED AND INKJET HEAD 3D PRINTING (3DP)

First developed at the Massachusetts Institute of Technology (MIT) in 1993 as a rapid prototyping technology. This technology is based in powder processing. The powders are first spread on the printing bed and then the inkjet printhead deposits liquid binder which solidify the 3D model (Xin Wang, 2016). Same as SLA technique, the equipment needed to produce the 3D objects only allows up to certain dimensions, no larger than one meter, and to be able to produce on-site this technology will not be suitable for this design. Instead, it can only be used for the production of prototypes.

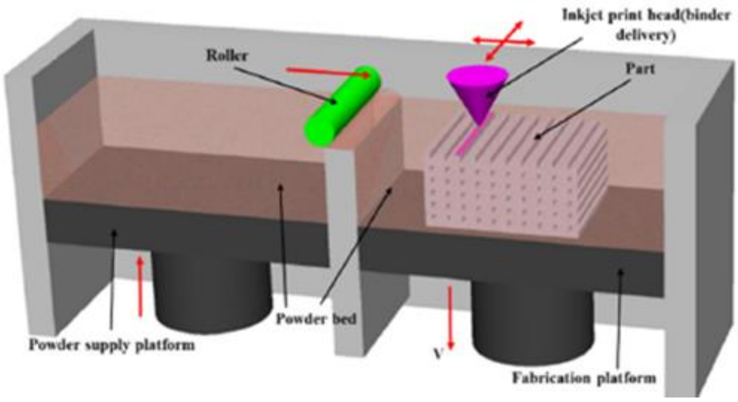


Figure 9 Powder bed and inkjet head 3D Printing (3DP)

SELECTIVE LASER SINTERING (SLS)

This technique is similar to the last mentioned 3DP technique since they both are based on powder processing. But instead of using a liquid binder, SLS technique uses a laser beam that scans the powders and sinter them by heating. The neighboring powders are fused together through molecular distribution. Once is done the processing of the next layers starts. (Xing Wang, 2016). It is one of the most used techniques used in the small-scale market for production of 3D objects, but since the birdcage dimensions and usage is larger than what is allowed with the SLS equipment, this technology can also not be used. It is possible that in the near future, new equipment will be released with the possibility to scale up its products and be considered to produce birdcages or other temporary works used by BAM International.

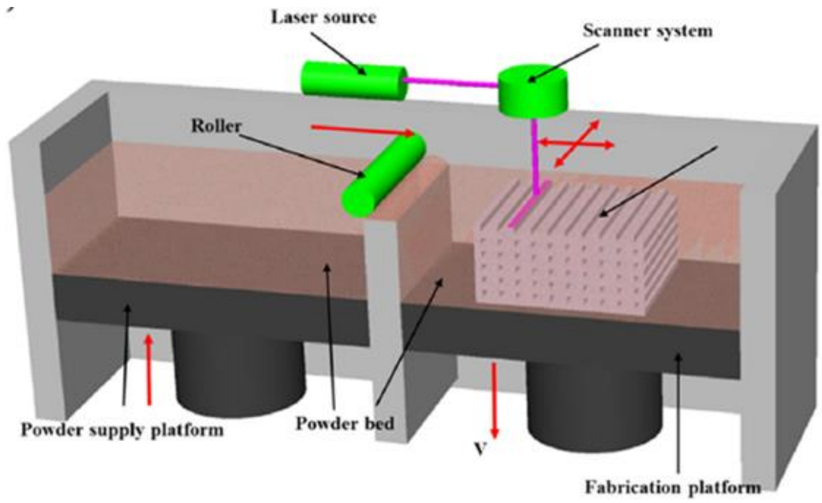


Figure 10 Selective laser sintering (SLS)

PRINTING PARAMETERS

To be able to 3D print such structures as birdcages, there are certain printing parameters to take into account when designing. The output variables will include the values and information alongside the printing parameters:

Printing parameters	
Max. Height, Shrinkage	*<1.5 meters*
Max. Width	*2 meters*
Max. Length	*4 meters*
Cantilevering, Max. Overhang	*45 degrees*
Layer dimensions	*Multiples of 10*

LAYERS DIMENSIONS

The end structure is comprised of multiple filament layers extruded by a nozzle; thus, each filament layer is constant in height and the end structures dimensions multiples of that height. The 3D printer will use a nozzle either of 5mm or 10mm diameter.

PRINTING PROCESS

The design and production of a model to be 3D printed after having selected the material and manufacturing technique, starts in the 3D modeling of the product in a CAD software which then produces a STL file with all the digital information required for the printing instructions of the 3D printer. After the creation of the STL file the model is processed by a slicing software which will determine the path the printer nozzle will follow to produce each layer. In the slicing process, the infill density and style can be determined to adjust the volume and printing time of the final product (Hu, 2017).

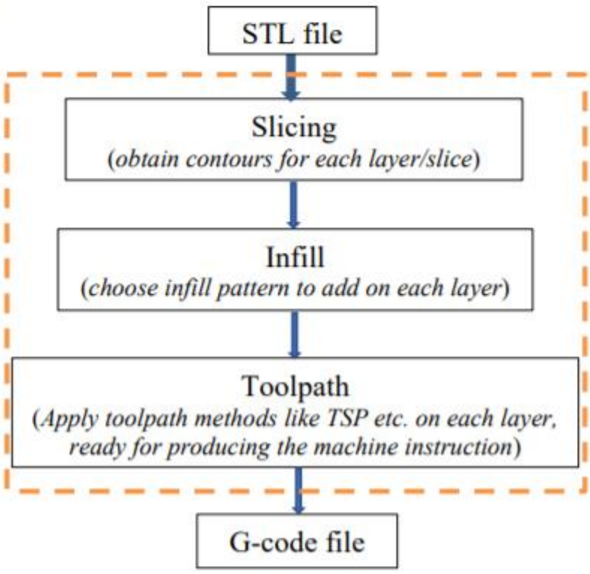


Figure 11 Printing process

INFILL PERCENTAGE AND PATTERNS

One of the main advantages of fused deposition modeling is the possibility to define the inner density of the structure. Infill is simply a repetitive structure used to take up space inside the model (Siber, 2018). By reducing the infill percentage, it also reduces the printing time and amount of material used. Deciding what infill to use will depend upon the final functionality of the structure since it will also affect the shear and flexural strength. Yet, the 3D model can also be modified with a slicer software to have a specific infill pattern.

Figure 12 Infill densities

Some 3D printed structures can be hollow in the inside, with a horizontal shell made of layers built up in the Z direction and another shell in the top and bottom layers, but depending on the direction of the forces applied the structure will need supports in the inside. Therefore, there are several infill styles, and each of them have strengths and weaknesses. As long as the density is set correctly, these patterns give

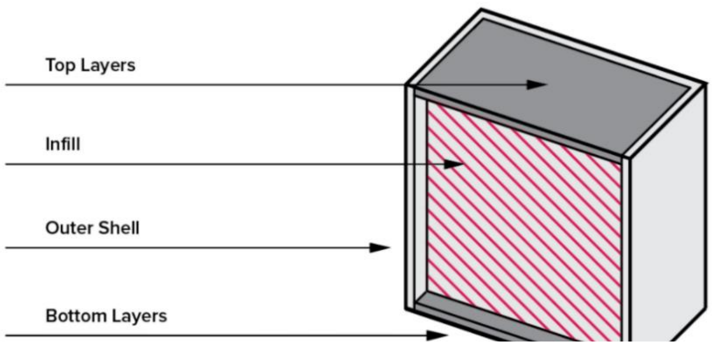


Figure 13 Infill example

enough volume for printing between the gaps. This allows the printer to print over empty space more accurately, and with less error. 3D printing infill like the "octi" and "archi" designs in the image are more suitable for circular or rounded designs. Meanwhile the "Hilbert" and "3D honey" designs are better for block-oriented prints.

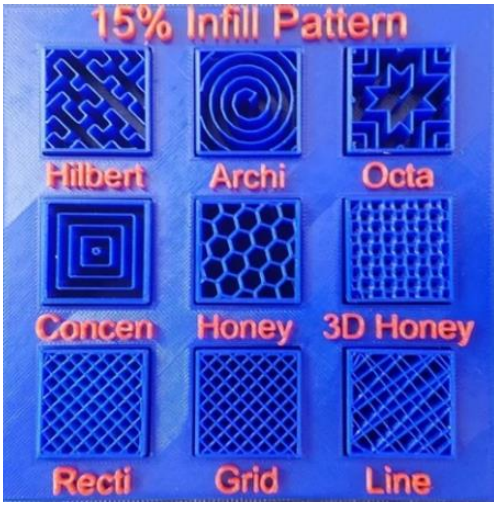
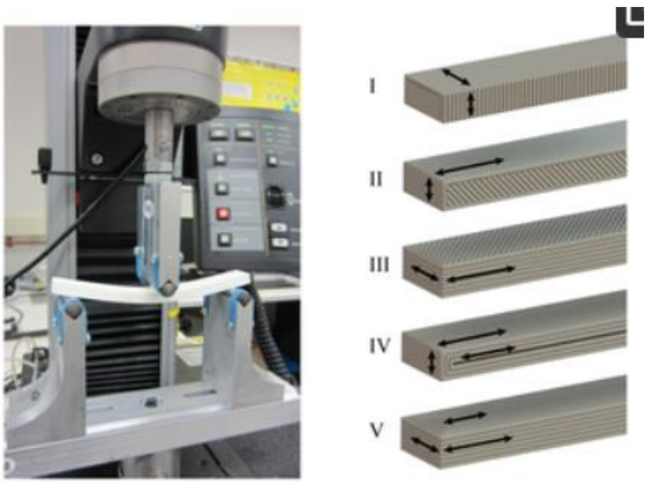


Figure 14 Infill patterns

COMPARISON OF FILL COMPOSITING TECHNIQUES

The currently methods used in fused deposition modeling are nowadays under studies to define their application in larger scale 3D printed structures. Functional load bearing structures can be improved by deciding the correct fill style and infill density. A study done by Joseph T. Belter and Aaron M. Dollar shows the increasing strength of the material fused deposition manufactured when including voids in the printed parts. The 3D printed parts were subjected to three-point bend testing methods of specimens with different infill patterns. The study did not only test different infill but also testing was done on different print orientations and printer parameters as shown in the following pictures:



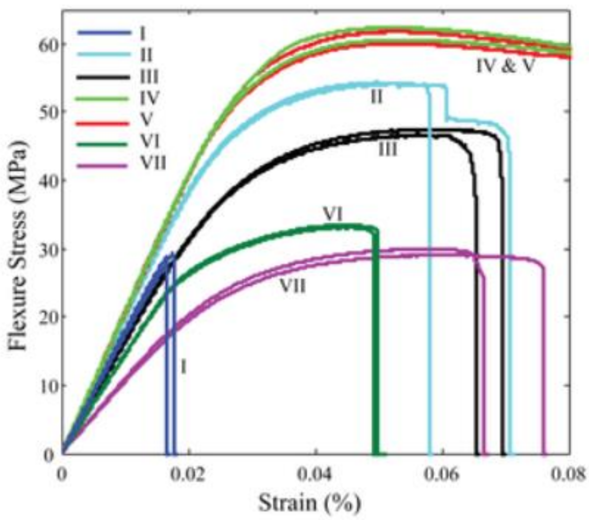


Figure 16 Testing variables

Figure 15 Testing results

It can be seen from the flexure stress curves that the print orientation at 90° leads to a greater strength when the load is acting perpendicular to the 3D printed part (Belter & Dollar, 2015). This is the case for the birdcage which acts as a platform and the loads are derived from the workers standing on it. Thus, the desired printing orientation should be 90°.

INFILL PERCENTAGE AND INFILL PATTERNS INFLUENCE IN THE MECHANICAL PROPERTIES

In fused deposition modeling the mechanical properties of the final product are affected by different printing parameters. The mechanical properties of the layered components should meet the service loading and operational requirements and must be comparable with parts produced by traditional manufacturing techniques. Compared with the conventional manufacturing processes, additive manufacturing part properties can depend on structural and process parameters rather than purely on material properties. This is also the main disadvantage of utilizing FDM printed parts for functional components. Due to this process effects as delamination of the component layers or materials anisotropy can occur. Additionally, printed components typically have lower elastic properties than injection molded components of the same thermoplastics, thus the designers cannot rely on values from static material databases, the material selection becoming a complex process (Dudesco & Racz, 2017).

To determine if 3D printed materials can be used for functional components, the mechanical properties need to be determined and is also important to predict not only the strength, but also the stiffness and how they relate to process parameters. Therefore, in 2017 a research study was done at the university of University of Cluj-Napoca in Romania, where different 3D printed specimens were tested with different printing parameters.

Three different types of specimens were manufactured by varying the following parameters:

- Infill rate/percentage.
- Infill patterns (Honeycomb, Full Honeycomb, Wiggle, Triangular, Grid and Rectilinear).
- Raster orientation.

Since this research was done on small scale 3D printing and there are not yet public researches on large scale, the results can be taken into account as representative orientation on the possible outcome behavior for the structure designed in this report. Yet, the design propose in this report must be tested in 1:1 scale prototype before being used on site.

According to the research done by the University of Cluj-Napoca in Romania, the tests done with different infill rates were as expected, the specimen strength increases with the infill rate, from 16.1 MPa at 20% to 28.9 MPa at 100%, the evolution is not linear. The apparent E-modulus has also in increase with the infill percentage from 982 MPa at 20% to 1503 MPa at 100%, the increase per percentage point of infill also changes non-linearly, the higher the infill rates the smaller the increase. The E-modulus behaviour is due to the approximate formula to calculate the real cross-sectional area. Because the specimen, excepting the 100% infill rate, is porous, the E-modulus can be calculated considering apparent cross section (ignoring the void inside the part) or the calculation can be adjusted by multiplying the cross-section area by the infill rate. In this case the adjusted E-modulus can be obtain similarly as with the rule of mixtures by multiplying the apparent modulus with the (1-Infill_rate) (Dudesco & Racz, 2017).

$$E\ \text{adjusted} = (1 - \text{Infill rate}\ \%)\ E\ \text{apparent}$$

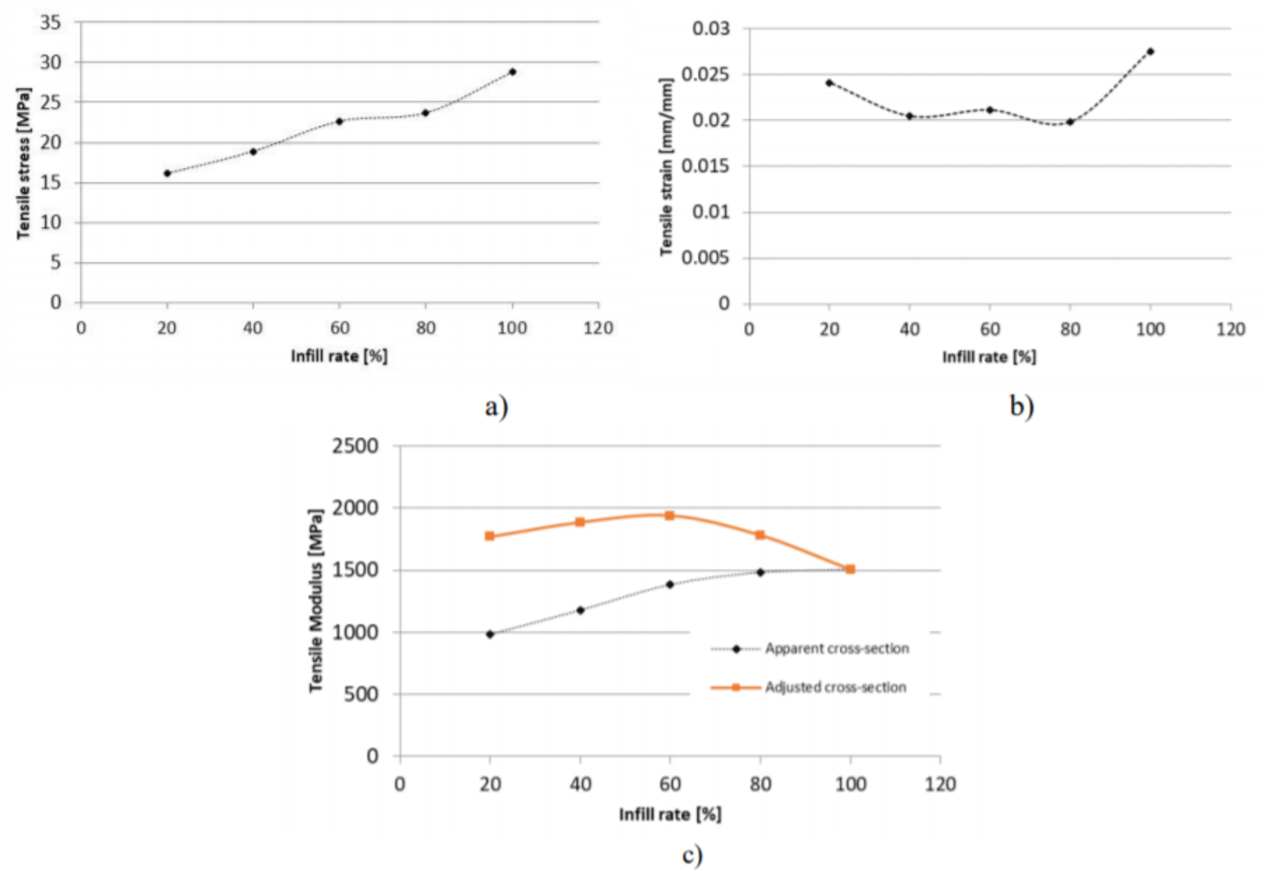


Figure 17 Variation with the infill rate: a) tensile stress, b) tensile strain at maximum stress and c) Young's modulus (Dudesco & Racz, 2017)

Due to the complexity that each infill pattern has at the time of calculations, for this design the rectilinear pattern will be used since it will have more constant mechanical properties measured in different directions.

ANISOTROPIC MATERIALS

Anisotropic materials are materials whose properties vary when measured in different directions. Fiber-reinforced materials such as composites frequently display anisotropic properties and can demonstrate great strength when force is applied in the same direction as the fibbers, and much less strength when force is applied in the opposite direction (Anisotropic or Anisotropy, n.d.).

A subset of anisotropic materials are orthotropic materials which have different material properties in three different axes. In fused deposition modeling, the end product has layers deposited in different directions and therefore it has a orthotropic behavior. In this design, these mechanical properties will be taken into account by using the stress analysis tool of Autodesk Inventor.

3D PRINTING MATERIALS

The first materials used in 3D printing were pure polymer resins as it is ABS (Acrylonitrile butadiene styrene) or PETG (polyethylene) but in the form of filament and rolled in reels/spools as shown in the figure below. The main advantages of these resins are low melting points and when in liquid state, they are easier to extrude and produce the desired forms (filaments or pellets in case of fused deposition modeling technique). Polymer materials compared to steel or concrete have low weight, low cost and low processing flexibility. Therefore, they are widely used in the 3D printing industry for small scale designs. On the contrary, the disadvantage of pure polymer resins is the low mechanical strength to withstand larger forces.

Figure 18 3D printing filaments rolled in spools

Nowadays the industry is scaling up and new large-scale 3D printers are being developed, creating the opportunity to increase the functionality of bigger designs. But due to the lack of strength in the polymer itself, different types of particle reinforcements are being added to enlarge the mechanical strength and the required functional properties to compete against concrete or steel materials used in the construction industry.

Due to the low cost, particle reinforcements are widely used to improve the material behavior, but not until recently, these particles were combined with a polymer matrix to create filaments used in a 3D printing technique called FDM (fused deposition modelling) techniques.

Therefore, for the production of birdcages pure polymers can have major disadvantages when exposed to extreme chemical and climate conditions. But when reinforced, will increase the mechanical strength and physical properties. So, for this design the material must be a fiber reinforced polymer.

3D PRINTING FILAMENTS

It is important to know the final product functionality to be able to decide which 3D printing filament is suitable for the job at hand. To find out this functionality it should be known how flexible the final product needs to be (flexibility), what forces does it need to withstand (strength), and what level of detail and precision is needed when 3D printing (accuracy). Once these questions are answered, then the type of filament can be chosen. Each filament will have different mechanical properties depending on the type of resin. The following table shows the most used and current filaments (non-reinforced) available for 3D printing:

Filament	Applications	Average Costs	Advantages	Disadvantages
ABS	Automotive Parts, musical instruments, kitchen appliances	€18/kg	Durable, strong, flexible, lightweight	Non-biodegradable material, high temperature for melting
PLA	Mostly in the medical sector as surgical implants	€20/kg	No harmful fumes, easy to work with, less warping	It is susceptible to clogging the printer nozzle
PET	Food containers and kitchen utensils	€24/kg	Strong, flexible, low warping, low shrinking	Not an easy material to work with, 3D printer needs fine-tuning
PETT	Food containers and kitchen utensils	€26/kg	Biocompatibility, strong, flexible	Not an easy material to work with, 3D printer needs fine-tuning

COMPOSITE MATERIALS

Composite materials are the combination of two components or more with different physical and chemical properties, which enables to enlarge the functionality of the final fiber composite matrix. Some examples of composite materials used nowadays are concrete, mud bricks, and fiber reinforced polymers but unlike conventional materials, composites can have multiple properties not often found in a single material without dissolving or blending them into each other. In this research the focus will be fiber reinforced plastic filaments. They are composed by a polymer resin as it is ABS (acrylonitrile butadiene styrene) or ASA (acrylonitrile styrene acrylate), combined with a type of fibers like glass or carbon. There is an enormous variety of composite materials used nowadays in different industries such as aerospace, infrastructure, automotive, energy, etc. However, these materials have certain limitations when the manufacturing process is 3D printing. For the Tanjun Jati study case, the material to be studied is fiber reinforced polymer since the mechanical properties are suitable for large scale 3D printing as explained further in this report. In this type of filament, the matrix protects and transfer the loads between fibers.

The matrix at the same time protects the fibers from environmental and external damage, while the fibers provide the strength and stiffness needed to withstand the carried loads, reducing the risk for cracks and fractures. There are two major groups of resins that make up polymer materials: *Thermosets and thermoplastics*. These resins consist of large molecules made up of long chains of smaller molecules or monomers.

Thermoplastics can be melted, formed, re-melted and re-formed. Therefore, for 3D printing technology this is the type of resin that is used to produced filaments or pellets. Solid thermosets on the other hand cannot be converted back to their original liquid form, and when 3D printing the material will not reach its melting point in the extrusion process.

The material will be exposed to certain climate, environmental, and chemical conditions. Thus, additives and coats need to be added to protect the surface and provide the needed quality properties. The following are the most important protective guidelines to be used in the design of the birdcage.

PROTECTION FOR UV RADIATION

The structure should be protected against UV radiation through the use of additives in the material or by means of surface protection. UV radiation can cause degradation of polymers and reduce the strength of the resin. Therefore, glass fibers or carbon fibers can be used to increase the resistance to UV radiation. The following measures can be adopted to protect the material:

- The application of a gel coat, top coat or layer of paint.
- The use of a UV resistant resin.
- The addition of pigment or UV absorbers to the resin.

THERMAL PROTECTION

To prevent failure due to degradation in the material properties under influence of raised temperature the use of a partial conversion factor for temperature can be used in the design.

Since the study case for the birdcage design is in Indonesia, the average temperature which the birdcage is exposed is higher than 40 °C the safety factor for temperature effects should be determined based on testing.

HUMIDITY, WATER, AND CHEMICALS

The resistance of FRP's to humidity, water and other chemicals is determined mainly by the resin. The resins and fibers considered in this design are generally well resistant to chemicals. Good embedding in a resin isolates and protects the fiber and will reduce the degree of penetration. Carbon fiber is resistant to both acidic and basic environments. Glass fiber is resistant to acids but may (except for especially resistant types) degrade in a basic environment (Wang, Jiang, Zhou, Gou, & Hui, 2016).

FIBER REINFORCED POLYMERS (FRP'S)

Fiber reinforced polymers in 3D printing are filaments composed by a single resin with nanoparticles reinforcement which improve the mechanical properties of the material. Since these materials are rarely new, and are anisotropic due to the 3D printing technique FDM (fused deposition modelling**) the final mechanical properties should be acquired by testing of 3D printed specimens.** These materials are new and are still under studies. Few companies like CEAD are working to introduce them into the large-scale 3D printing industry, and have successfully printed different products.

Figure 19 3D printed bench made of FRP's

Figure 20 3D printed trashcan made of FRP's

The idea to introduce fibers into the polymer resins, is to boost its mechanical properties (strength) to increase the variety of functions in which the products can be used. The following table is a summary of techniques and materials used for 3D printing of fiber reinforced polymer composites and it also shows the mechanical properties improvement of resulting composites.

Technique	Materials	Fiber loading	Maximum tensile strength (MPa)	Tensile strength improvement polymer
FDM	Short glass fiber/ABS	18 wt%	58.6	140
	Short carbon fiber/ABS	40 wt%	70	115
		5 wt%	42	24
		13 wt%	70.69	194
Direct write	Short carbon fiber/Silicon carbide whisker/epoxy	35 wt%	66.2	127
FDM based co-extrusion	Continuous carbon fiber/nylon	34.5 vol%	464.4	446
	Continuous carbon fiber/PLA	6.6 vol%	185.2	335

Figure 21 Mechanical properties improved by reinforcement particles

CARBON FIBRE REINFORCEMENT

Carbon fibre has incredible strength to weight properties. It is a very stiff material that remains close to rigid until failure, in which case it often fractures or splinters. It's best used in constant loading conditions when you want to match the strength of metal at a fraction of the weight, since it behaves like aluminium. The disadvantage of using this material is only the costs. It is more expensive than other reinforcement particles, but instead, it increases more the mechanical properties of the composite. For the birdcage design carbon fiber reinforcement is an option but since the loads carried are relatively low, it is possible to use another reinforcement as fiber glass (Lee, 1993).

FIBERGLASS REINFORCEMENT

Fiberglass is a robust reinforcement option that has a bit more flex and energy return to it than carbon fibre. It's best used in intermittent loading conditions, and bends until eventual fracture (Lee, 1993). Fiberglass is a great general-use fibre for when you need sturdy parts, and it is the most cost-effective reinforcement option. Thus, these particles are ideal and will be used for the birdcage design, combined with the ASA polymer resin.

KEVLAR REINFORCEMENT

Kevlar is a very shock-resistant material ideal for impact loading or similar use cases. It is very tough, and will fail by bending until it eventually permanently deforms (Lee, 1993). Nevertheless, it can be considered for other printable alternatives but not necessarily for the birdcage.

HSHT FIBERGLASS

HSHT Fiberglass is a heat-resistant fibre reinforcement material. It has a higher heat-deflection point than the other fibbers, meaning it can hold its strength at high temperatures (Lee, 1993). It is similar to fiberglass in that it has high energy return and will bend until it fractures. But it does cost more than the common fiber glass particles.

MATERIAL TO BE USED (POLYCORE ASA 3012)

For this design the material used is PolyCore ASA 3012, but different plastics will have different properties in regards to shrinkage and viscosity. As the newer 3D printers are able to print the polymer resin with the reinforcement particles, the final chosen material for 1:1 scale should be discussed with the 3D printer provider to assure the correct functionality and printing process. Maximum percentage of reinforcement added to the resin is up to 40%, and more than that can clog the nozzle.

Due to the low variety of materials, and lack of knowledge on the materials properties, there are only a few of options available that can be used in this design. However, as the technology develops, more materials will be created allowing BAM International to consider them for future designs. The most optimal material found and the only material known to be tested in large scale printed specimens is the Polycore ASA 3012.

This material information is provided by CEAD (large scale 3D printers manufacturer). PolyCore ASA 3012 is a glass fibre reinforced (20% mass percent) ASA pellets featured with excellent printability, warping resistance and weather resistance. **Therefore, this material will be used in the birdcage design for the Tanjun Jati study case.**

ASA (plastic resin) or Acrylonitrile styrene acrylate was developed as an alternative of ABS filaments, but with improved weather resistance, and is commonly used in the automotive industry. Its UV resistance and mechanical properties also make it a perfect option for FDM techniques in 3D printing. PolyCore ASA 3012 is a fibre reinforced polymer composed by the ASA resin with 20% mass percent of glass fibre reinforcement (note that more than 40% of fibres content in the resin can cause the material to clog at the nozzle exit).

Another advantage of ASA resin is their resistance to moulding shrinkage, which happens in the cooling phase after the material is heated and extruded. In large scale 3D printing this has been one of the biggest challenges since many try outs of large structures have shown warping deformations in the cooling process.

When compared with polycarbonate thermoplastics, ASA has higher stiffness, impact resistance, heat distortion temperature, and weatherability. According to the design parameters Polycore ASA 3012 is suitable for the application of birdcages in projects with similar characteristics as the Tanjun Jati project in Indonesia.

PHYSICAL PROPERTIES OF POLYCORE ASA 3012

Property	Testing Method	Typical Value
Density (g/cm^3 at 21.5 °C)	ASTM D792 (ISO 1183, GB/T 1033)	1.2
Melt index (g/10 min)	220 °C, 10 kg	6 - 10
Glass transition temperature (°C)	DSC, 10 °C/min	98
Vicat Softening temperature (°C)	ASTM D1525 (ISO 306 GB/T 1633)	105

Figure 22 Polycore ASA 3012 Physical properties

MECHANICAL PROPERTIES OF POLYCORE ASA 3012

Property	Testing Method	Typical Value
Bending modulus (MPa) (X - Y)	ASTM D790 (ISO 178, GB/T 9341)	3320 ± 160
Bending strength (MPa) (X - Y)	ASTM D790 (ISO 178, GB/T 9341)	66.6 ± 3.5
Charpy Impact strength (kJ/m^2) (X - Y)	ASTM D256 (ISO 179, GB/T 1043)	5.0 ± 0.32
Bending modulus (MPa) (Z)	ASTM D790 (ISO 178, GB/T 9341)	1646 ± 170
Bending strength (MPa) (Z)	ASTM D790 (ISO 178, GB/T 9341)	27.2 ± 2.1
Charpy Impact strength (kJ/m^2) (Z)	ASTM D256 (ISO 179, GB/T 1043)	2.3 ± 0.2

The cross-sectional resistance of a 3D printed object is anisotropic, which it means that the physical properties have a different value when measured in different directions. Therefore, to find these values, the material needs to be tested first after being 3D printed for more accurate results. The following picture shows how the specimens were tested to find the values showed in the prior tables.

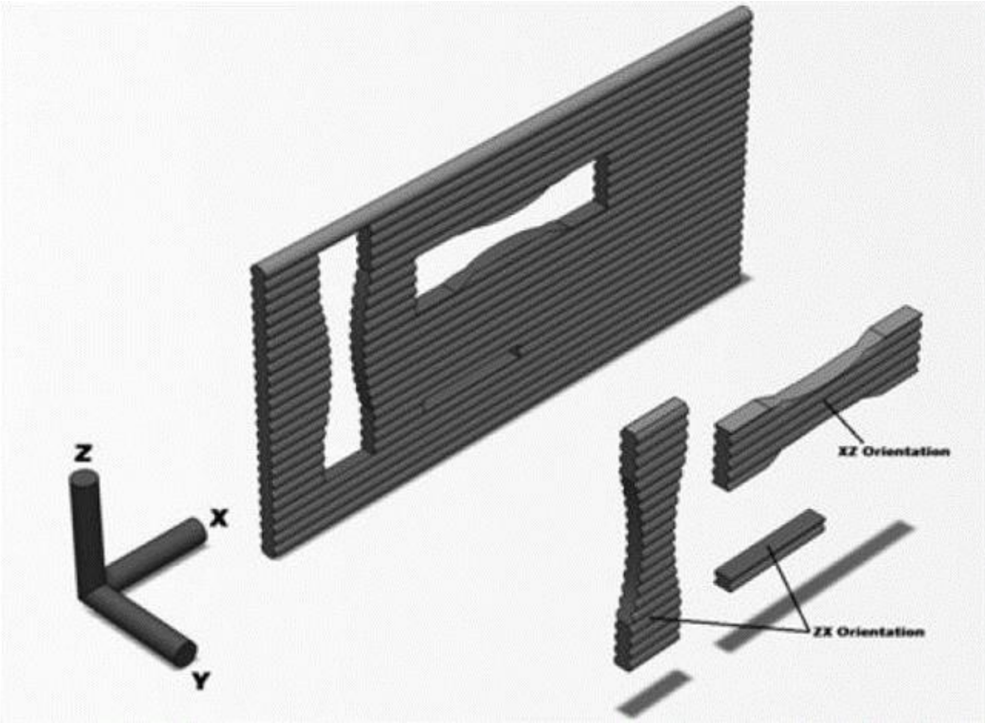


Figure 23 Polycore ASA 3012 Printed specimens for testing

LNP THERMOCOMP AM COMPOUND AC004XXAR1

Another option to be which can be suitable for the birdcage design is the LNP thermocomp AM compound AC004XXAR1, (Same as the PolyCore ASA 3012, this material information is provided by CEAD). LNP is a compound based on ABS resin containing 20% carbon fibre for large format additive manufacturing (LFAM) applications needing higher stiffness against glass fibre. ABS based compounds provide easy processing. Low warp and good print surface quality, making them good material for a broad range of applications and tooling, including thermoforming and vacuum-forming. This material is an alternative to 3D print temporary works but since it has not been tested, the mechanical properties are unknown. Hence, it cannot be considered for this design.

MECHANICAL PROPERTIES OF FRP'S

The mechanical properties of 3D printed structures by using FDM (fused deposition modelling) will vary when measured in different directions (orthotropic). This is due to the position of the layers, FDM technique deposits layer by layer on the growing work. Therefore, if the force is tensile, compressive, or shear, then the resistance stress of the material will be different. One of the disadvantages of 3D printing is to accurate calculate the strength of the material beforehand. This is because this technology has many different factors which can alter the behavior and resistance of the printed part as it is the material viscosity when being printed, the printer settings, and the cooling process. The following shows a summary of techniques and materials used for 3D printing of polymer nanocomposites and properties improvement of resulting composites.

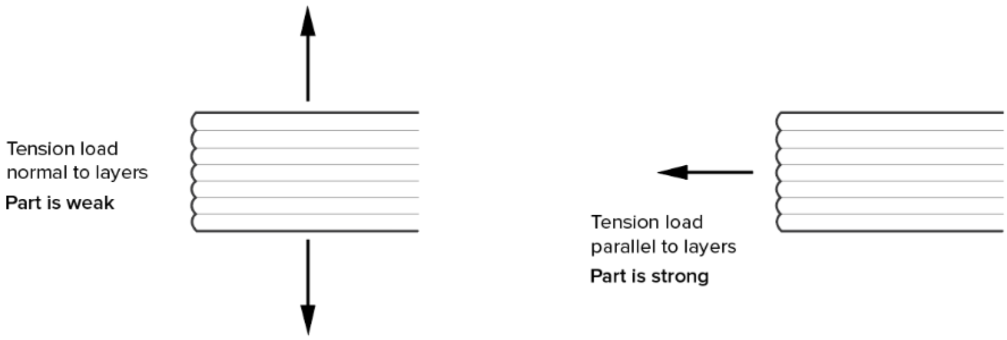
Technique	Materials	Enhancement in properties
FDM	TiO_2/ABS	Improved tensile modulus and strength, reduced elongation
	Carbon nanofiber/ABS	
	Montmorillonite/ABS	Improved tensile strength and modulus, flexural strength and modulus, and thermal stability, reduced thermal expansion coefficient
	Graphene/ABS	Improved electrical conductivity and thermal stability
	Carbon nanofiber/Graphite/ polystyrene	Better voltammetric characteristics, less capacitive background current
SLA	CNT/epoxy	Improved tensile strength, reduced elongation
	Graphene oxide/photopolymer	Improved tensile modulus, strength and elongation
	TiO_2/epoxy acrylate	Improved tensile strength and modulus, flexural strength, hardness and thermal stability
	$BaTiO_3$/PEGDA	Improved piezoelectric coefficient
	CNT/acrylic ester	Improved absorption of electromagnetic energy
	BST/epoxy	Ultralow thermal conductivity and high energy conversion efficiency
DLP	Silver/PEGDA	Improved electrical conductivity
SLS	Carbon black/nylon-12	
	Al_2O_3/polystyrene	Improved tensile strength and impact resistance
	TiO_2/nylon-12 and graphite/ nylon-12	Improved tensile modulus, reduced elongation
	Silica/Nylon-11	
Solvent-cast direct writing	CNT/PLA	Improved electrical conductivity

Figure 24 Enhancement in properties of FRP's

TENSILE

If the forces applied in the structure are tensile, then the fibbers alignment should be horizontally positioned related to the printing bed. Note that not all 3D printers can position and decide the alignment of the mentioned fibbers and thus, the material should be gathered from a specific manufacturer who has already printed and tested specimens with the specific material.

In FDM, the built parts or structures have anisotropic properties, meaning they are much stronger in the XY direction than the Z direction, due to the layer's deposition. It is important to consider the application and direction of the loads. In FDM it is more likely that the structure will fracture when placed in tension in the Z direction compared to the XY direction. It is up to 4- or 5-times difference in the tensile strength. (Redwood, n.d.).



FLEXURAL

When the structure is withstanding flexural stresses the inside or top face of the beam will carry compressive forces while the outer or bottom face will withstand the tensile forces. By putting rigid materials (no infill patterns) on the extremes of the beam, the structure will be reinforced effectively. That is why common fibre reinforced materials are called sandwich panels.

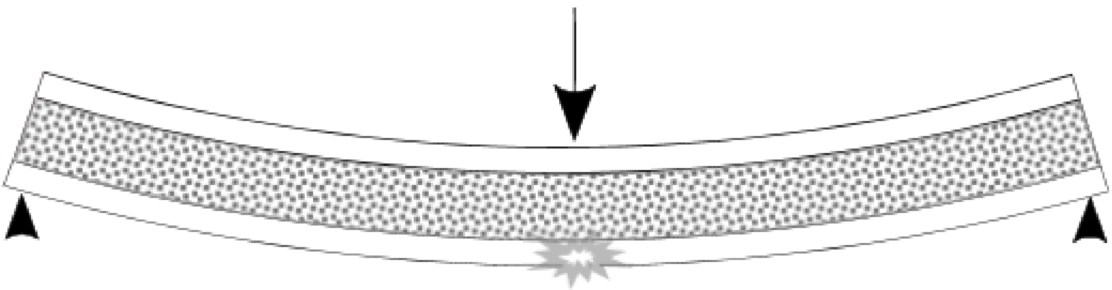


Figure 25 Bending of a fiber reinforced beam

COMPRESSIVE

When the structure has compressive loads the fibre reinforcement should serve as a scaffold, distributing the load along the fibbers path. The outer parts of the structure can be 100% infill, producing a larger resistance and re-distributing the applied forces.

Figure 26 Compression of a fiber reinforced beam

PRINTED FRP'S PROPERTIES

The result of 3D printing a part by layers is that material properties of the finished part are anisotropic. That is, the material properties are dependent upon the angle of the forces applied to the structure, in this case the alignment of the filament layers.

Therefore, when producing 3D printed temporary works not only will the selected material properties have to be designed for, but also the alignment of the extruded filament. Foremost and perhaps intuitively, the tensile properties of a printed part are strongest when the force is aligned parallel to the filament layers and weakest when vice versa. As the figures below show the greater the printing angle the greater the tensile strength.

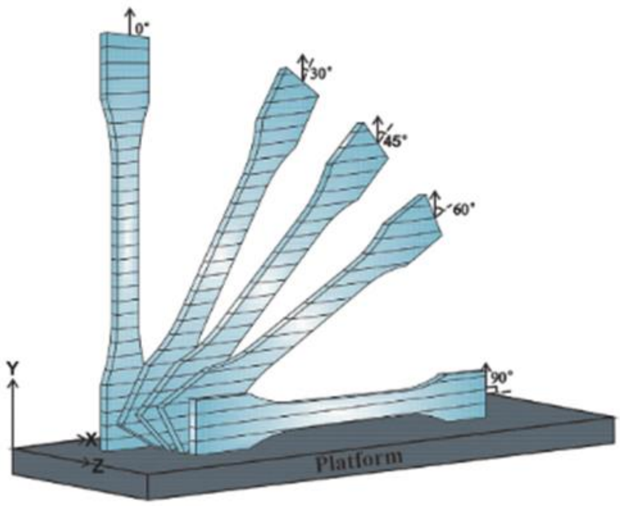


Figure 27 Print orientation variants

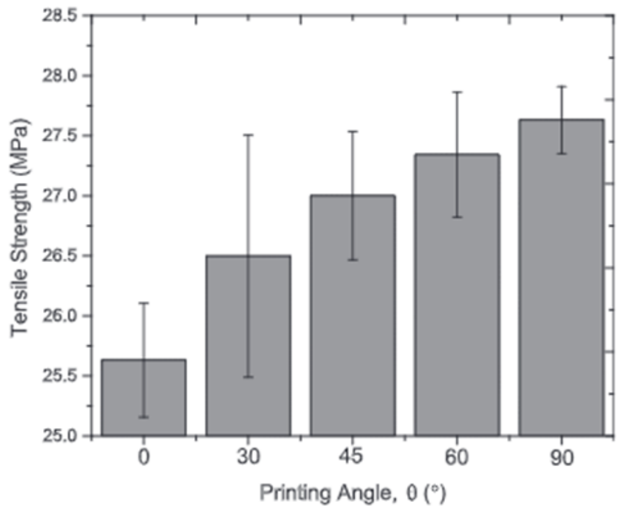


Figure 28 Print orientation results

MATERIAL BEHAVIOUR DURING THE PRINTING PROCESS

After installing the filament material and the printer is in place to start the printing process, the filament starts being extruded in a heated nozzle head which softens the material to then be laid on the printing bed layer by layer. This occurs in fused deposition modeling which involves the processing of material by thermal cycles which can create distortions (warpage for example) in the built parts (Armillota , Bellotti, & Cavallaro, 2018).

WARPING OR SHRINKAGE

Warping or shrinkage is the deformation of the structure caused by different cooling rates of the plastic as shown in the picture below. The further a layer is from the print bed, the faster it will cool and thus shrink. Larger heights produce greater vertical deformation. Therefore, the design should minimize the height when possible. The latest updates in large scale 3D printing are trying to tackle this problem by creating a constant room temperature and by including fans around the nozzle to control the cooling rate of the material (Kamran & Saxena, 2016).

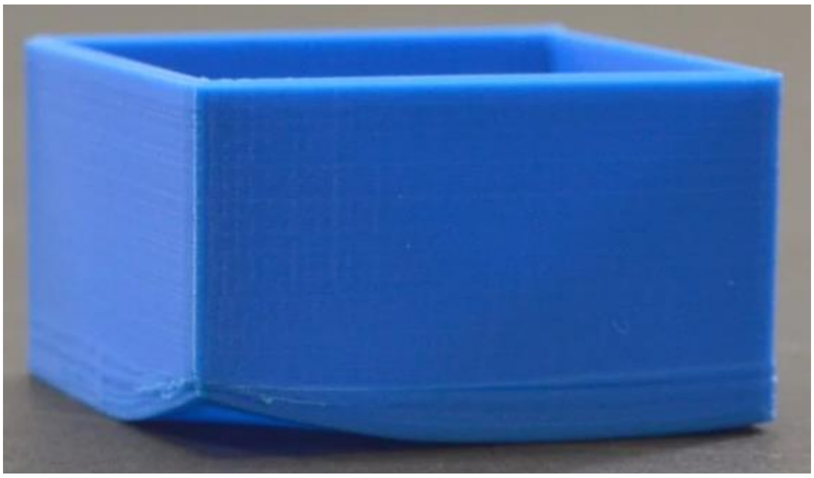


Figure 29 Warping example

CANTILEVERING AND BRIDGING

Cantilevering and bridging happen when one-layer placed overhangs the previous layer. Too large an overhang (>45 degrees) will result deformation due to the filaments sagging from gravity. Therefore, the design should be able to allow the printer nozzle to prevent this and thus it should be designed so the material doesn't overlay the layers below as shown in the picture below (N.goc, Cristopher, & Naskar, 2018).

Figure 30 Bridging example

RECICLABILITY OF 3D PRINTED PARTS

Materials for 3D printing and specially in FDM technique, have the advantage to be fully recyclable since these materials belong to the thermoplastics class of polymers, which as different to thermosets, thermoplastics have the advantage to be melted and hardened again. As an example, a research done by Isabelle Anderson called 'Mechanical Properties of Specimens 3D Printed with Virgin and Recycled Polylactic Acid' and published in the article '3D Printing and Additive Manufacturing Vol. 4, No. 2' pure materials and recycled materials were analyzed to define the mechanical and physical properties of both showing promising results for the 3D printing industry. The testing was done on 3D printed specimens evaluating tensile and shear as shown below.

The following values are only intended to show the material properties after being recycled to understand the possibility to recycle the birdcages once the project is done.

TENSILE TEST RESULTS ON RECYCLED SPECIMENS

In the tensile test results, it can be seen that the recycled material has slightly lower yield strength. A possible technique to increase again its properties when recycled, would be to add 20% of virgin material to produce new birdcages for future projects.

	Virgin	*Recycled*	*T Test*
Number of specimens (*n*)	25	25	
Average tensile yield strength (Mpa)	40.43	35.85	*p* = 0.000003
Standard deviation	1.849	3.348	
Average tensile modulus of elasticity (Mpa)	4258	4032	*p* = 0.053546
Standard deviation	260	498	

Figure 31 Tensile test results of recycled 3d printed specimens

SHEAR TEST RESULTS ON RECYCLED SPECIMENS

The test results indeed show that recycled plastic has lower mechanical properties for the tensile test, but surprisingly the recycled average shear strength was 6.8% higher than the virgin material. The research has not a clear reason for this, but it is assumed that the 3D printed specimens appeared to expand differently, therefore is possible that the materials (virgin and recycled) has a different poison ratio as the specimens were being compressed and is possible that expanded different.

	Virgin	*Recycled*	*T Test*
Number of specimens (*n*)	31	31	
Average shear yield strength (Mpa)	33.00	35.25	*p* = 0.000024
Standard deviation	0.80	2.40	

Figure 32 Shear test results of recycled 3d printed specimens

Since the intended material to be used in the design of a birdcage is a composite material made of a thermoplastic (ASA) and fiberglass particles reinforcement, then it is possible to recycle the material once the project is done due to the advantage that thermoplastics have being able to be melted and hardened again. Nevertheless, in this report the focus is the design and therefore, it is recommendable to do a further study in the recycling process and the material behavior after it has been recycled.

STRUCTURAL ANALYSIS OF 3D PRINTED FRP'S

The structural analysis of a structure made of fibre reinforced polymers by means of 3D printing has certain conditions which needs to be taken into account in the design process. When analysing the internal forces and stresses, it is important to note that the structure will be produced layer by layer. Therefore, the structure will be anisotropic and the physical properties will vary depending in the direction of the force applied. Industrial additive manufacturing by using 3D printing as a manufacturing process is rarely a new method with undergoing researches about the different components that could influence the stability of the final 3D printed products. However, a design code for fiber reinforced polymers produced by different techniques than 3d printing, will be used as a supportive standard.

The CEN Technical Committee 250 (CEN/TC250) has taken the initiative to prepare a document addressing the purpose and justification for new European technical rules and associated standards for the design and verification of composite structures made of FRP's (Fibber reinforced polymer) (Ascione, et al., 2016). This design guide will be used in this study case as a supportive tool to analyse and design the birdcage.

The needs of such standards are due to the steadily increasing market volume and the wide range selection of materials for FRP structures. At the same time the increasing number of structural FRP applications has led to a growing interest of researches and governmental institutions to release an appropriate design code to be applied in infrastructure and civil engineering works. Yet, new standards must be drawn to analyze FRP's structures produced by means of 3D printing.

The proposed design standard follows a step-by-step approach:

1. Preparation and publication of "Science and Policy Report''
2. After agreement of CEN/TC250, preparation and publication of CEN technical specifications.
3. After a period for trial use, CEN/TC250 will decide whether the CEN Technical Specifications should be converted into Eurocode parts.

Since the materials (FRP) and technology used in large scale industrial 3D printing has just started in the last five years, the idea of the CEN code guide is to standardized the methods of designing with these materials.

Note: The CEN technical specifications ONLY studies the design of fiber reinforced polymers structures fabricated my other means but NOT via 3D Printing. Thus, this guide will only be used as a supportive tool to understand the material behavior but further tests on the structure needs to be done before use to find the real strength of the structure.

BIRDCAGE ANALYSIS

In order to analyze the internal forces of the birdcage, the structure is divided into sections to represent the different schemes and to find the resultant stresses of each part according to how the force is acting on it. The structural analysis for the birdcage will be done using the finite element analysis of Autodesk Inventor software. Nevertheless, the calculations in this report show indicative values which must be compared with the results of tests done in a 1:1 scale prototype.

ANALYSIS CRITERIA

The analysis of the structural design should be carried out taking into account the linear elastic behavior up to failure and, if necessary, the anisotropic nature of the materials. No redistribution of stresses due to plasticity can be assumed. The anisotropic elastic modulus of composite materials, laminates or sandwich structures, as well as their strength properties, may be obtained by experimental testing (Ascione, et al., 2016). The use of classical theoretical models for composite materials only allows this report to obtain indicative values. Therefore, the values provided in this design must be followed by testing a 1:1 scale 3D printed birdcage.

In order to calculate the forces in the structure, the birdcage design will be broken down into sections. These sections are based around the 'buttresses' which support the structure. Each part is then treated like a cantilever beam attached to a fixed support. With the fixed support being where the inner birdcage meets the outer wedge. This allows for the forces in each support to be calculated.

For the material spanning between the supports the forces will be calculated by treating it as a beam between two fixed supports. And for the loading requirement phase the designed birdcage will assumed to be 50% infill despite other infill percentages used at later stages.

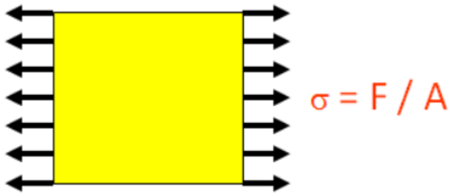
FINITE ELEMENT ANALYSIS

According to Autodesk Finite element analysis (FEA) is a computerized method for predicting how a product reacts to forces, vibration, heat, fluid flow, and other physical effects. Finite element analysis shows whether a product will break or work the way it was designed. It is called analysis, but in the product development process, it is used to predict what is going to happen when the product is used. FEA works by breaking down a real object into a large number (thousands to hundreds of thousands) of finite elements, such as little cubes. Mathematical equations help predict the behaviour of each element. A computer then adds up all the individual behaviours to predict the behaviour of the actual object (Autodesk.help, 2019).

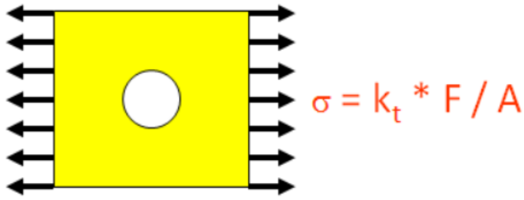
FEA adds considerable value to the product design process. It provides significant understanding and design guidance that helps to create better products. Some of the specific benefits and outcomes of using FEA include the following:

- Predict performance for planned use.
- Predict potential failure with predictable abuse.
- Evaluate and correct observed failure.
- Improve performance and safety of a known design.
- Improve cost/weight of a known design.
- Develop new and innovative concepts.
- Gain insight into design concepts or directions.
- Modelling decisions should be driven by goals.

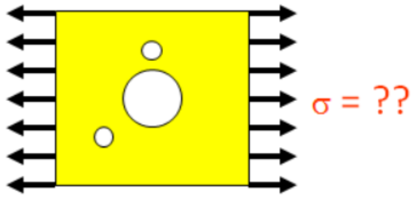
As an example of why FEA is important in the product design, in the following case simple equations describes the maximum stress:



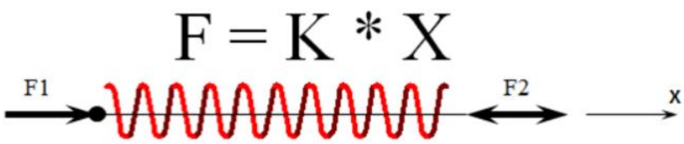
Then if the structure is not as simple, a more complex equation can be used:

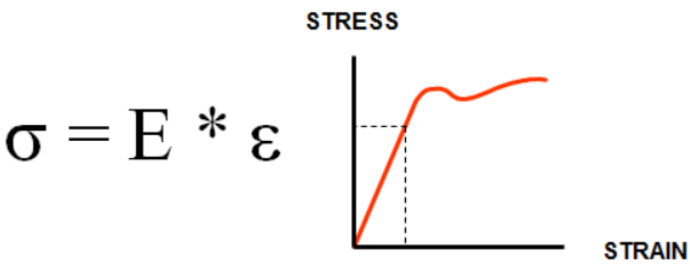


However, if the structure is more complex the normal equations can no longer be used:

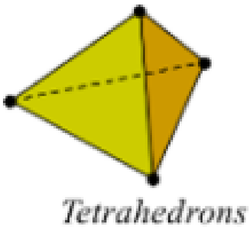
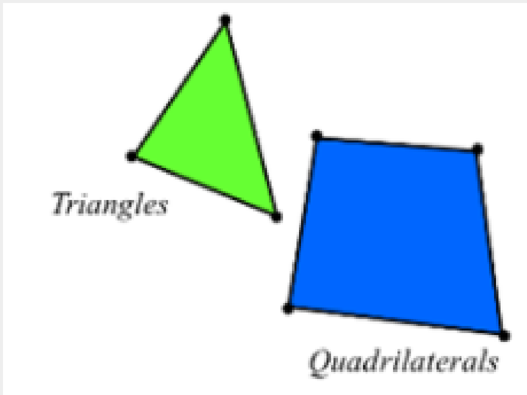
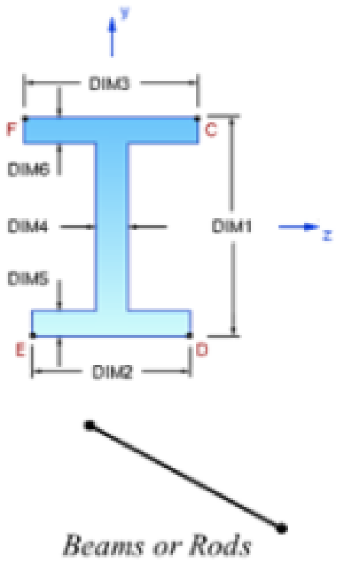


In FEA the force and the stress are determined from measured displacements:

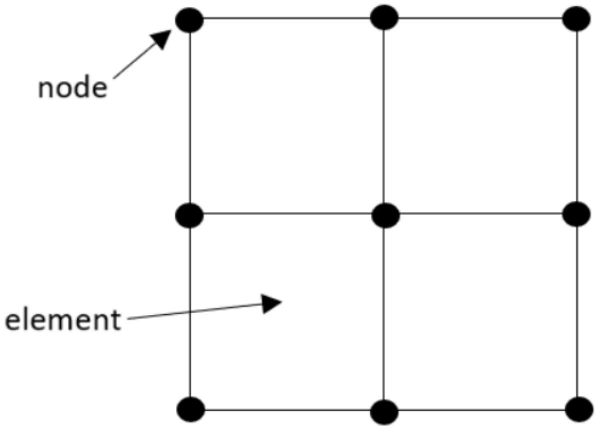




The nodes are points in 3D space which connect the elements, and elements are areas or volumes defined by nodes (Autodesk.help, 2019):

Element Type	Example Elements
Solid Elements No element properties are required.	
Shell Elements Element thickness is required.	
Line Elements Cross section and orientation are required.	

In FEM the mesh is created to split the domain into a discrete number of elements for which the solution can be calculated. The data is then interpolated across the whole domain (Allison, 2020).



BOUNDARY CONDITIONS: LOADS AND CONSTRAINTS

The 3D model design will need to define the parts which will be subjected to loads and the faces which will be connected or attached to something else (constraints). These constraints can be fully fixed or partially fixed in different directions.

LINEAR MATERIAL ANALYSIS

If a member goes beyond its capacity (elastic limit or yield point), it will experience some sort of strain hardening or cracking and it will start losing its stiffness which also means that the total stiffness of the structure is also changing (Jinal Doshi, 2018). During this design, only linear elastic analysis will be used:

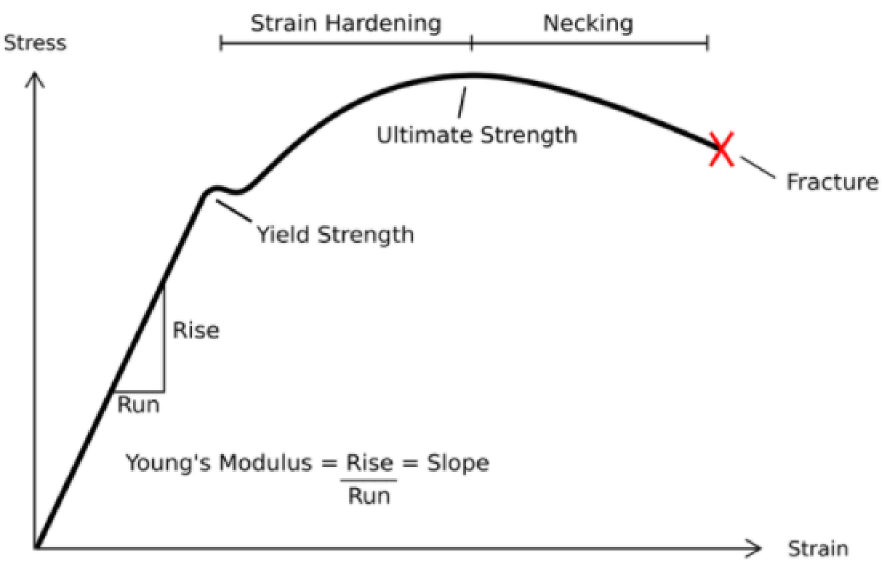


Figure 33 Hooke's law (Jinal Doshi, 2018)

When the materials move into the zone beyond its yield strength, it no longer behaves in a linear way and permanent deformations can occur.

SUMMARY OF DECISIONS

Based on the desk research done, it is concluded that the following decisions are the most optimal for the design of the 3D printed birdcage. The material is provided by CEAD group who is also manufacturing the large-scale industrial 3D printers (CFAM Prime). These printers work with FDM technique which is the desired method to be used in this design. The material is a fiber reinforced polymer composed by the ASA resin mixed with 20% of fiber glass, providing the required mechanical and physical properties. The material is a thermoplastic; thus, it is 100% recyclable and can be re used to produce other temporary works.

Material Name	*PolyCore ASA 3012*
Resin	*ASA (acrylonitrile styrene acrylate)*
Fibers	*20% fiber glass*
Recyclability	*yes*
Printing Technique	*FDM*
Printing Equipment	*CFAM Prime (CEAD)*
Print Orientation	*90°*
Structural Analysis	*Finite element method*
Infill percentage	*50%*
Infill pattern	*Rectilinear*

METHODOLOGY

This chapter will introduce the general approach to design the birdcage. The study case used is based in a real project (Tanjun Jati) in Indonesia. Birdcages were used in the construction of a Jetty for the works needed in each pile. The current birdcages used are made of steel and are commonly manufactured by an external company. The idea of 3D printing the different temporary works will reduce the time and costs of the overall project, and for this the following design methodology approach is used to acquire the main goal of this research.

Figure 34 Steel birdcage

DATA COLLECTION

The data is collected by interviews with the project managers of BAM who has extensively information about the use of the birdcages and its requirements. The project managers can provide the information needed for the structural design of the structure and the minimum technical requirements.

For the design it is important to understand the manufacturing process, and since this technology is rarely new, interviews with the 3D printers' providers are needed. Two companies have been contacted: CEAD based in DELFT provide large scale 3D printers and robotic arms which are also used in the automotive industry, and Colossus S.A based in Belgium provides a portable containerized 3D printer that can be placed at the project location. The information provided by both companies is used in the modelling process, to allow the 3D file to be printed by their current printers.

Since these two companies have experience with fiber reinforced polymers materials, they will also provide the information on the material properties. As stated before, the fused deposition modeling technique creates the object layer by layer affecting the cross-sectional resistance. Thus, the material chosen for this design is provided by CEAD.

This study is based on codes and standards derived from the American Society of Engineers (ASCE) and the normative references mentioned in the scientific and technical report created by the CEN Technical Committee 250 (CEN/TC250), who has taken the initiative to prepare a document addressing the purpose and justification for the new European technical rules and associated standards for the design and verification of composite structures made of FRPs (Fiber Reinforced Polymer or Plastic). This standard proposed that new European technical rules for such structures are related to the principles and fundamental requirements of the EN Eurocodes. Thus, the document will be converted into Eurocode parts (Ascione, et al., 2016). The starting point for the design is to understand what is the existing system and how it works.

CURRENT DESIGN USED BY BAM

The first step in this research is to understand the current design which this research aims to replace by introducing 3D printing technology and composite materials. BAM International is currently using a platform (birdcage) to support the personnel and equipment when doing the required works in the piles of the jetty. The material used is steel and uses a clamp system to attach itself to the pile, securing it from falling or sliding. To withstand the uplift forces of the waves, the surface of the upper plate is open (grating shape) and to provide safety for the workers, it has a handrail system around the edges. (This report's objective is to replace the birdcage shown above, by a 3D printed structure made of fiber reinforce polymer's).

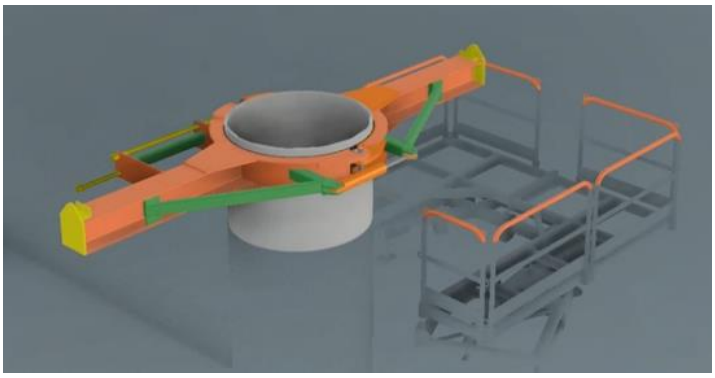


Figure 35 Clamp system of the steel birdcage used by BAM International

Figure 36 Steel birdcage platform

The birdcages stability is mainly from the clamp system. Therefore, the new design should replace the clamp by a new method which still satisfies the stability requirements. Clamps rely on friction (including high friction rubber contact surfaces) to convert normal forces into horizontal frictional forces. Thus, in part the platform stability is dependent on its weight. If the frictional forces are not large enough, hooks on wires are attached from the platform onto the top of the sheet pile for additional support.

FUNCTIONAL REQUIREMENTS

The design optimization of the birdcage will require a different design approach since the manufacturing technology and material (3D printing techniques and composite materials) are different to the most common ones (concrete or steel) affecting the material and cross-sectional behaviour. The initial prototype of a specific design will need to be tested to assure the quality and structural stability of the 3D printed object/structure.

This research will replace the current clamp system by securing the platform using its own weight to attach the birdcage to the pile with wedges which will avoid the structure to slide down. To achieve this, it is important to take into account the printing parameters because this has a major influence in the birdcage functionality.

3D PRINTING DESIGN PROPOSAL

The birdcage design proposed in this research will serve the same working and technical requirements as the currently used birdcage, but it is designed to be produced onsite and with fiber reinforced polymer materials. To achieve this, the design must fulfill the printing and structural parameters. The design process will consist of a first sketch and a 2D drawing to define the final dimensions. Then, the initial sketch will be 3D modeled and by using the stress analysis tool of Autodesk Inventor a finite element analysis will be done to the 3D model. Once the structure stability is check, then the model will be sent to the slicing software to define the printing process, infill density, and infill patterns; to finally, be sent to the 3D printer.

2D DRAWING

The 2D drawing shown in the next picture was done on AutoCAD software. The dimensions were defined according to the printing and technical parameters which are explained prior in this report. This drawing includes a top and bottom view, two cross sectional views, and the wedge dimensions. The following top view dimensions are used for the hand calculations. The full CAD drawings can be found in the appendix “birdcage 2D drawings” section. Since the printer capacity is up to 4x2 meters, the surface of half the platform is 3.8 x 1.7 meters. This allows the birdcage to be 3D printed at 90° and still meet the working requirements of minimum of 1 meter from the pile to the outer edge of the birdcage.

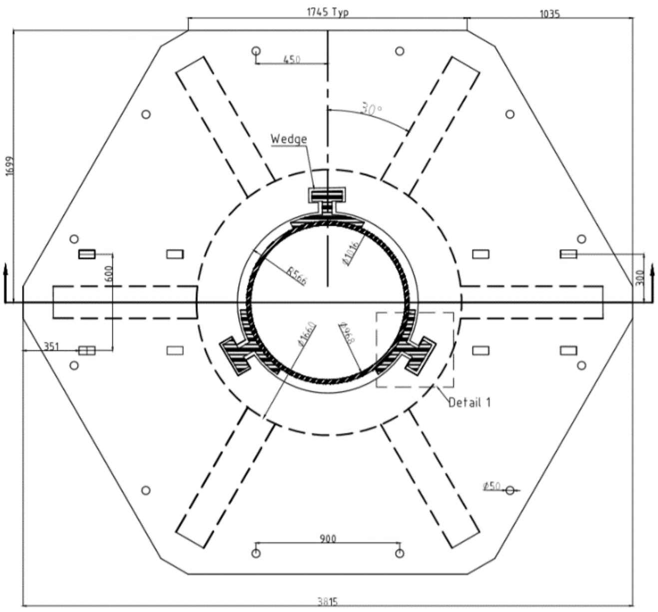


Figure 37 Birdcage 2D drawing - top view

3D MODEL

The 3D model shown the figures below was done on Autodesk Fusion 360. This is a cloud-based CAD/CAM tool for product development, widely used for the 3D printing community. The software creates a file which can be sent directly to the slicing software to then be 3D printed. Fusion 360 has a simulation feature (static stress simulation) that can do a finite element analysis on the structure but in this case, since the structure has a orthotropic behavior, the stress analysis will be done in Autodesk Inventor software since this program takes into consideration the material mechanical properties of each of the different axis (x, y, and z). This feature defines the mesh, contacts, constrains, and loads on the structure; thus, the most critical parts of the birdcage can be studied.

PART A

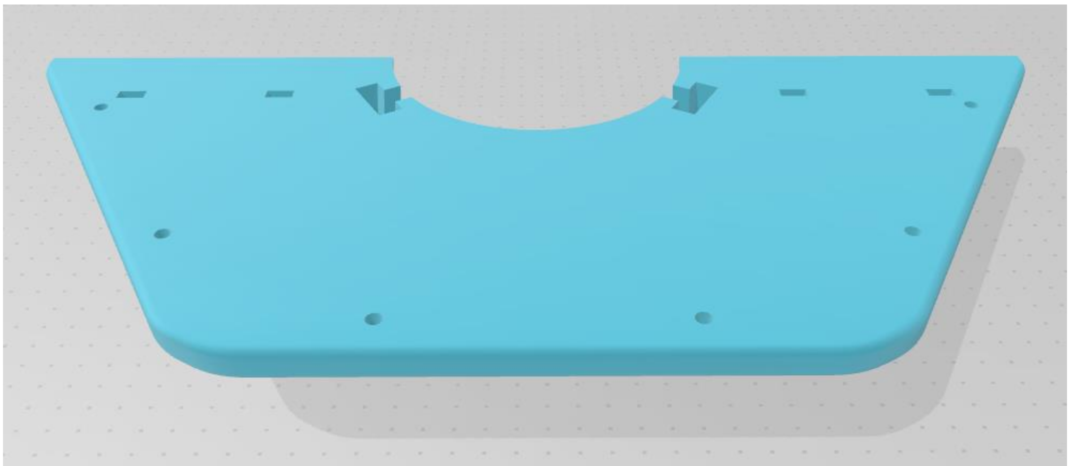


Figure 38 Part A 3D model - top view

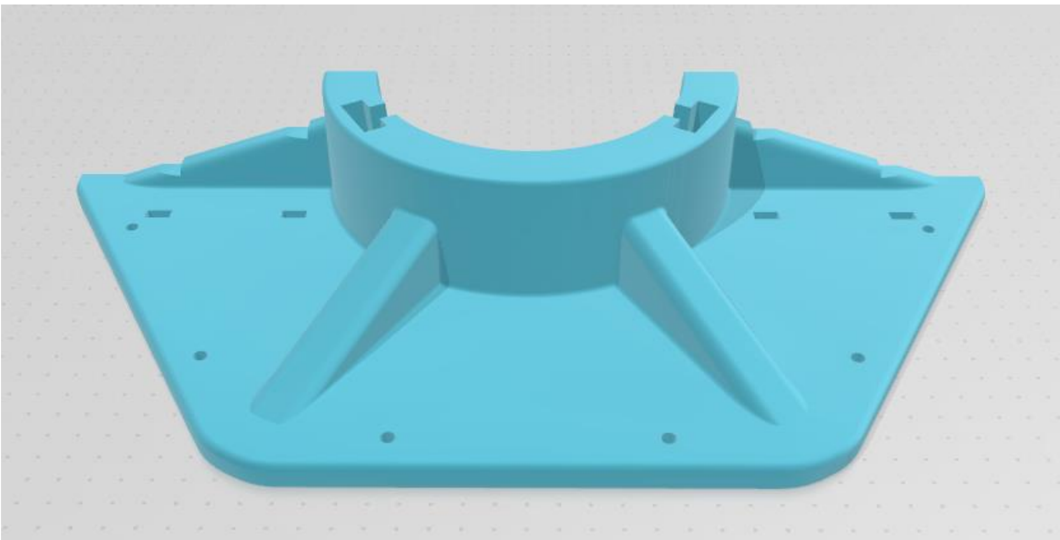


Figure 39 Part A 3D model - bottom view

PART B

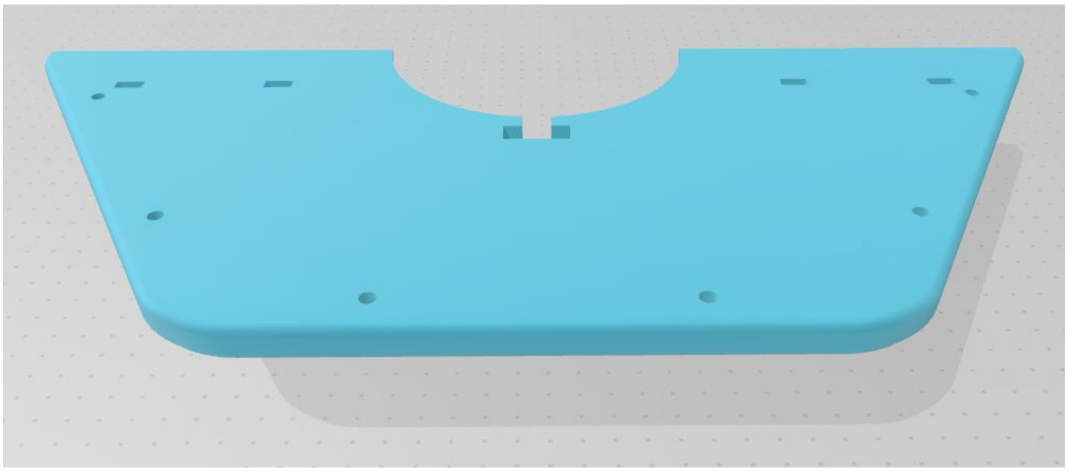


Figure 40 Part B 3D model - top view

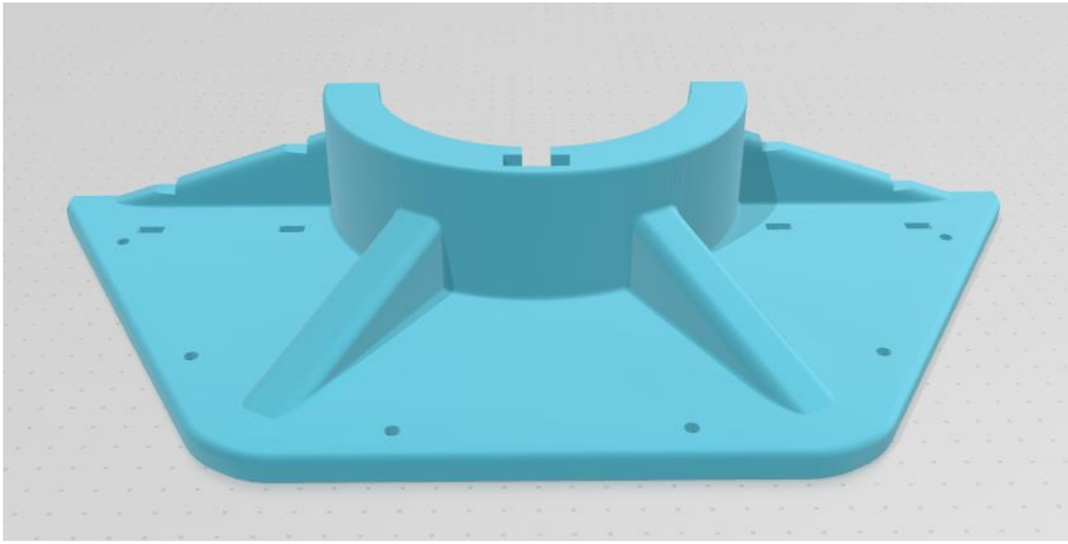


Figure 41 Part B 3D model - bottom view

WEDGE

The prior birdcage design done at BAM international had a total of 4 wedges system. In this design it has been decided to have 3 wedges instead of 4. If the wedges are not placed at the exact same position, by using 3 wedges the structure will have more stability. The wedge design consists of two flanges and one web. The outer flange will be place in the spacing of the birdcage and the inner flange will be against the pile. The web will transfer the compression forces to the pile, pressing against it to secure the structure at a desired distance from the top of the pile. The wedge thickness will be gradually increasing from the top to the bottom, this will provide a bigger diameter than the allowed for the birdcage, and thus, it will prevent the structure from sliding down.

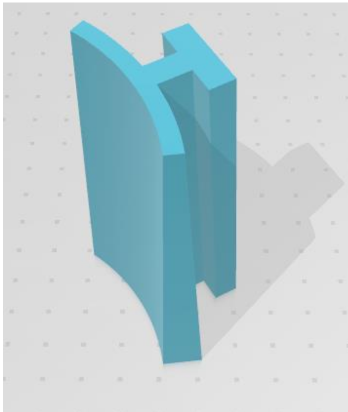


Figure 42 Wedge 3D model

STRESS ANALYSIS

To analyze the birdcage, is possible to simplify the structure and divide it in three different parts since it is a fully symmetrical structure. The following pictures show the part of the birdcage which will be structurally analyzed:

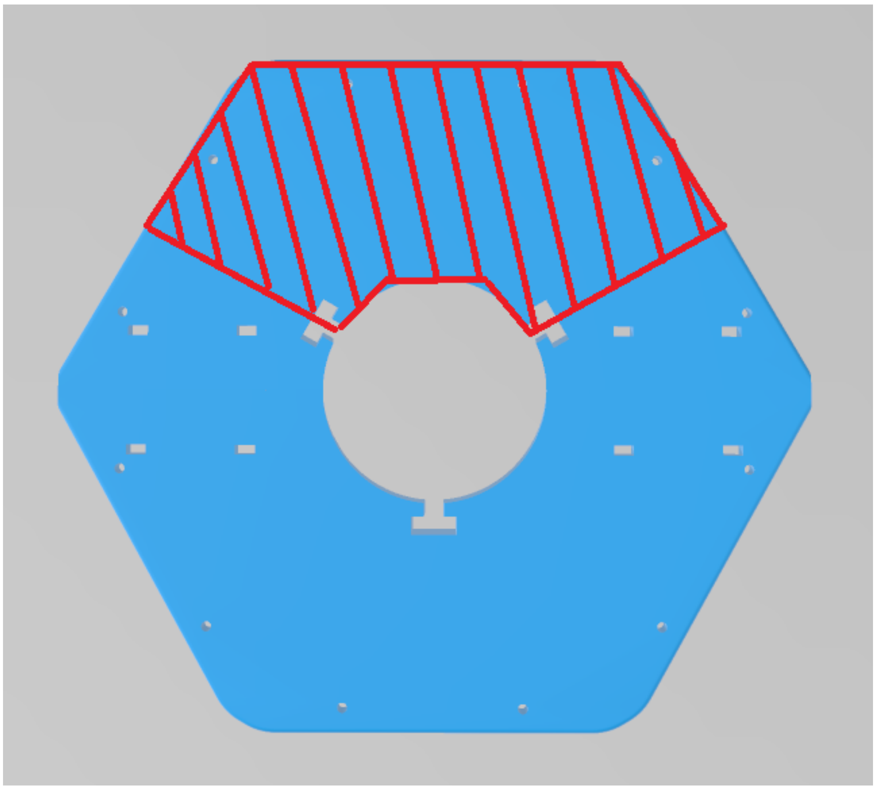


Figure 43 3D model simplification for analysis - top view

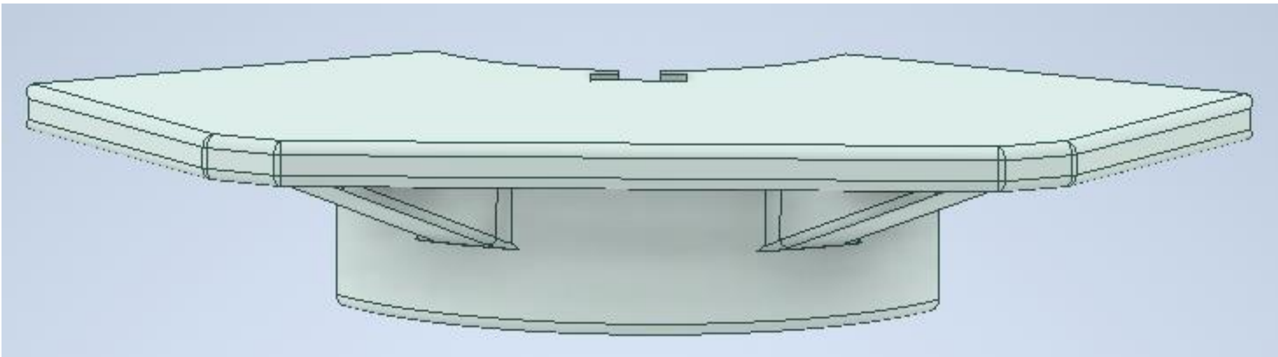


Figure 44 3D model simplification for analysis - front view

When dividing the structure in three, each part will still have the corresponding boundaries and constraints to have a more realistic simulation. The analysis will be done with Autodesk Inventor software. Inventor has a stress analysis tool which will apply a finite element method to the structure to verify the stability under determined loads.

MECHANICAL PROPERTIES FOR LINEAR STATIC ANALYSIS

The initial mechanical properties given by the material provider were found in testing of different 3D printed specimens. The mechanical properties are as follows:

Density	*1.2 g/cm³*
Bending modulus (X-Y)	*3320 Mpa*
Bending modulus (Z)	*1646 Mpa*
Bending strength (X-Y)	*66.6 Mpa*
Bending strength (Z)	*27.2 Mpa*
Poisson Ratio	*0.38*

In order to do a finite element analysis, the Young's modulus and Shear modulus needs to be derived from the prior mechanical properties. According to the flexural testing done on the 3D printed specimens, the bending modulus represents the Young's modulus. As for the shear modulus, the following modulus will be:

$$G = \frac{E}{1 + v}$$

G = Shear modulus

E = Young's modulus

v = Poissons ratio

Therefore, the shear modulus measured in X and Y direction is:

$$G = \frac{3320}{1 + 0.38}$$

G (x-y) = 2405 Mpa

And the shear modulus measured in Z direction is:

$$G = \frac{1646}{1 + 0.38}$$

G (z) = 1192 Mpa

APPLYING THE INFILL RATE FOR THE MECHANICAL PROPERTIES

The infill rate which will be used in this design will be 50 %. But since the software simulator stress analysis does not include the infill rate in the calculation, the mechanical properties need to be modified to have more realistic results. The following formula will be used:

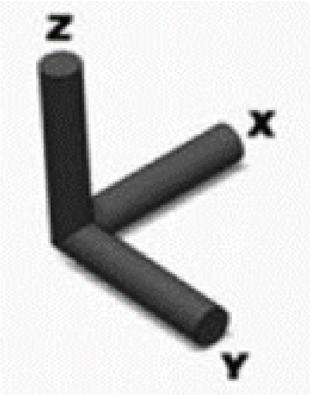
E adjusted = (1– Infill rate %) E apparent

E = Young's modulus

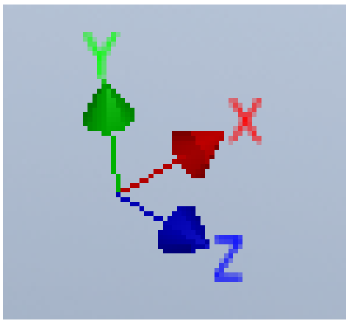
Consequently, the adjusted mechanical properties for the finite element analysis will be:

Density	*1.2 g/cm³*
Young's modulus modulus (X-Y)	*1660 Mpa*
Young's modulus (Z)	*823 Mpa*
Bending strength (X-Y)	*66.6 Mpa*
Bending strength (Z)	*27.2 Mpa*
Shear modulus (X-Y)	*2405 Mpa*
Shear modulus (Z)	*1192 Mpa*
Poisson Ratio	*0.38*

The axes orientation for the 3D printed specimens was:



The axes orientation in Autodesk Inventor simulation is:

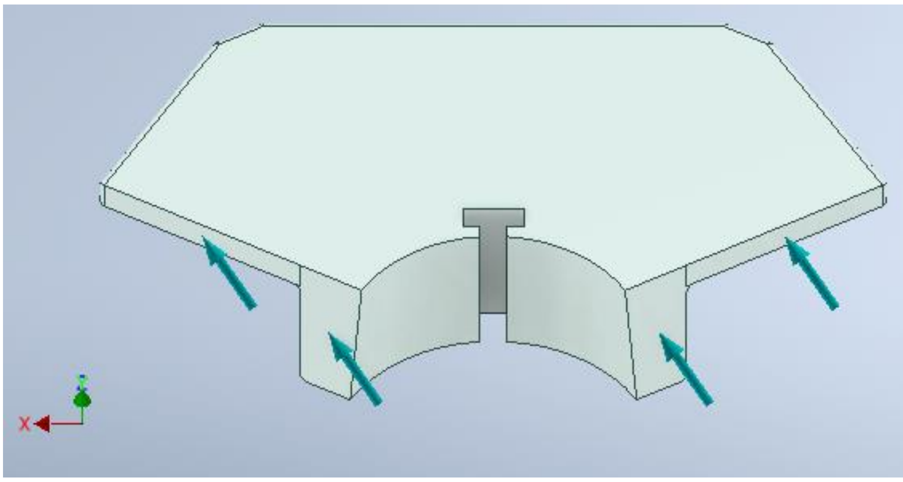


Therefore, the values of the directions Z and Y should be exchanged:

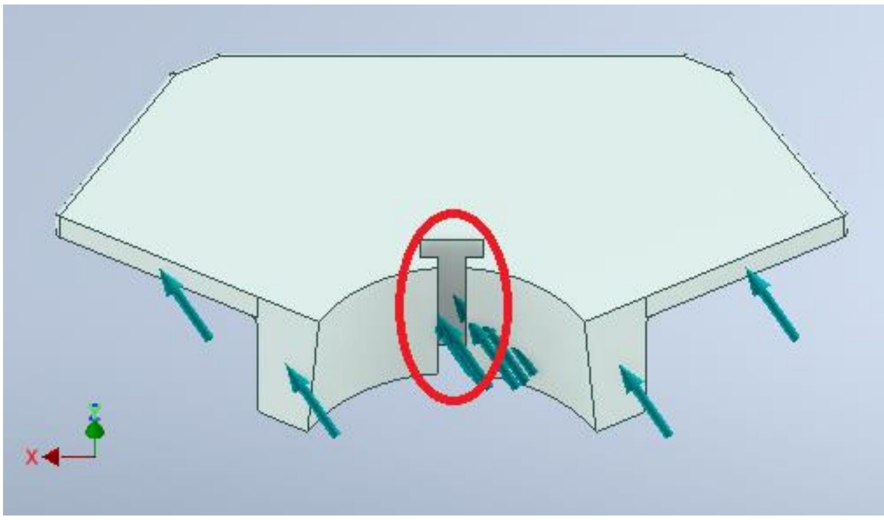
Density	*1.2 g/cm³*
Young's modulus modulus (X-Z)	*1660 Mpa*
Young's modulus (Y)	*823 Mpa*
Bending strength (X-Z)	*66.6 Mpa*
Bending strength (Y)	*27.2 Mpa*
Shear modulus (X-Z)	*2405 Mpa*
Shear modulus (Y)	*1192 Mpa*
Poisson Ratio	*0.38*

CONSTRAINTS

To simplify the simulation, the birdcage was cut in three. The area where the split is made, will only be fixed in the Z direction as the following:



The inner part where the wedge will be located and where all the forces will be transferred to the pile, will be fully fixed as the following:



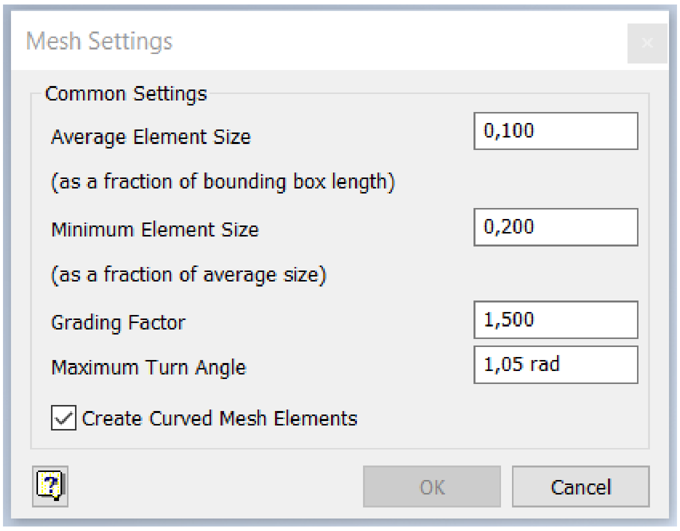
LOADS

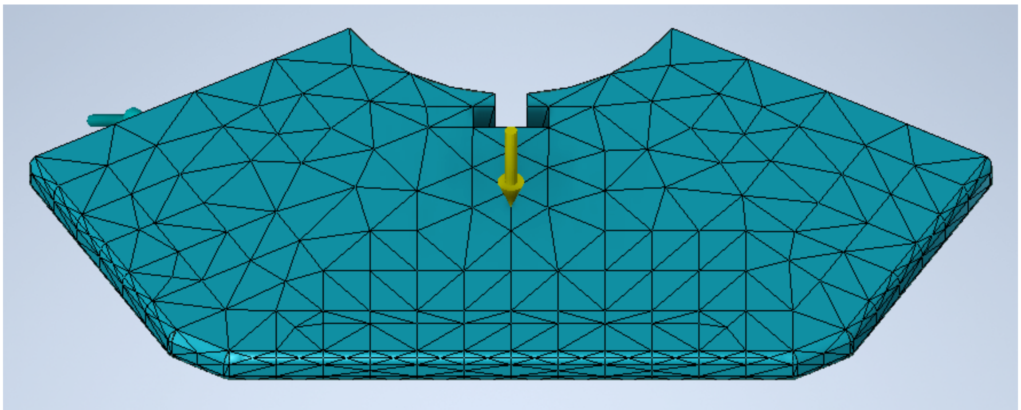
The load case applied in this finite element analysis:

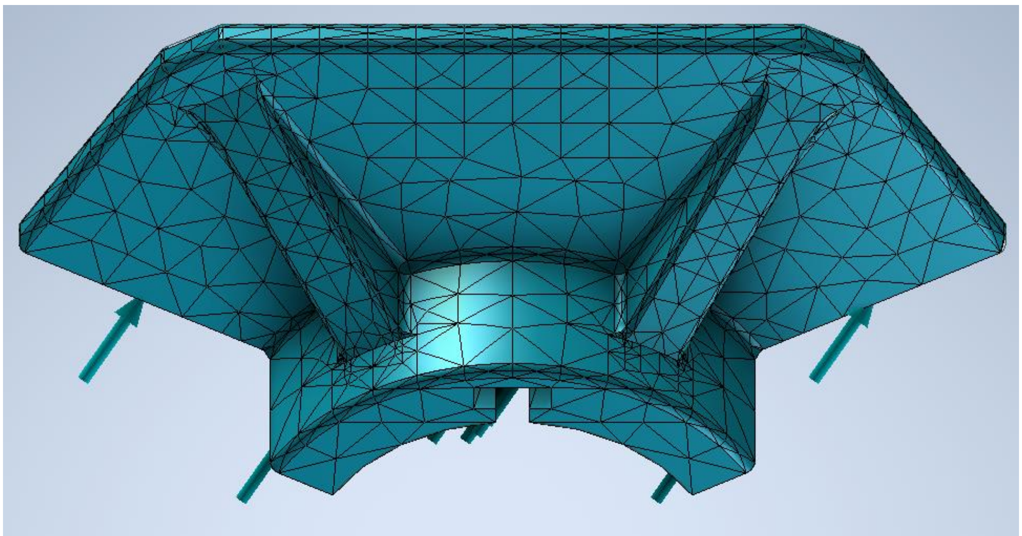
- Evenly distributed load of 5 kN/m.

MESH SETTINGS

The mesh in this solid model uses tetrahedrons and the mesh settings are as follows:







STRESS ANALYSIS RESULTS

The values attained from the stress analysis done in Autodesk Inventor can be seen in the appendix "FEA results". This analysis includes different values which analyzes the maximum displacement and stresses in the different elements of the birdcage mesh. The safety of the structure is also represented in the maximum safety factor and maximum Von mises stress which is used to determined if the birdcage will yield or fracture. The following table shows the results summary for each aspect:

Name	Minimum	Maximum
Volume	534744000 mm^3	
Mass	1414,69 lbmass	
Von Mises Stress	0 MPa	1,51693 MPa
1st Principal Stress	-0,614133 MPa	0,42242 MPa
3rd Principal Stress	-1,59746 MPa	0,0879623 MPa
Displacement	0 mm	0,30292 mm
Safety Factor	15 ul	15 ul
Stress XX	-0,694462 MPa	0,208849 MPa
Stress XY	-0,292222 MPa	0,371327 MPa
Stress XZ	-0,420413 MPa	0,253597 MPa
Stress YY	-1,34711 MPa	0,122087 MPa
Stress YZ	-0,269701 MPa	0,45025 MPa
Stress ZZ	-0,719141 MPa	0,248257 MPa
X Displacement	-0,0248771 mm	0,0248832 mm
Y Displacement	-0,302562 mm	0,00000169784 mm
Z Displacement	-0,023975 mm	0,0253635 mm

The decisive aspects are:

- Maximum Von Mises Stress: 1,51693 MPa, lower than the yield limit of the material which is 27.2 MPa.
- Maximum displacement: 0.30292 mm, which according to the safety factor value (15 UL) means that the structure will not fracture when carrying the designed load. When comparing maximum deflection of this model to a concrete beam of similar dimensions it can be seen that the maximum deflection allowed is around 16 mm. Yet, since the technology and material are rarely new and still under studies, the displacement shown in this report is a first indicative value which needs to be tested in 1:1 scale prototype to be able to confirm the stability of the birdcage.
- Safety factor: 15 UL, since when the stress in the model remains much inferior to the strength of the material, the safety factor stays superior to 1 and therefore the model is safe.

According to the results summary it can be deduced that the structure is over engineered and the dimensions can still be reduced in different parts of the model. Nevertheless, to assure the safety and the stability of the structure, and taking into account that this technology and material is still unpredictable due to the lack of research, the dimensions will stay as it is designed. Yet, this initial model must be tested in a 1:1 scale prototype before used.

SLICING PROCESS

3D slicers define how a model is built and instruct the 3D printer how it is printed. A slicer is a program that converts digital 3D models into printing instructions for a given 3D printer to build an object or structure. In addition to the model, the instructions contain 3D printing parameters, such as layer height, speed, and support structure settings.

The slicer software to be used in this project is Slic3r. This has the features to decide which infill rate and pattern to apply in the structure, reducing the material needed and therefore the printing time. The following picture illustrates an example of the print setting which Slic3r software provides:

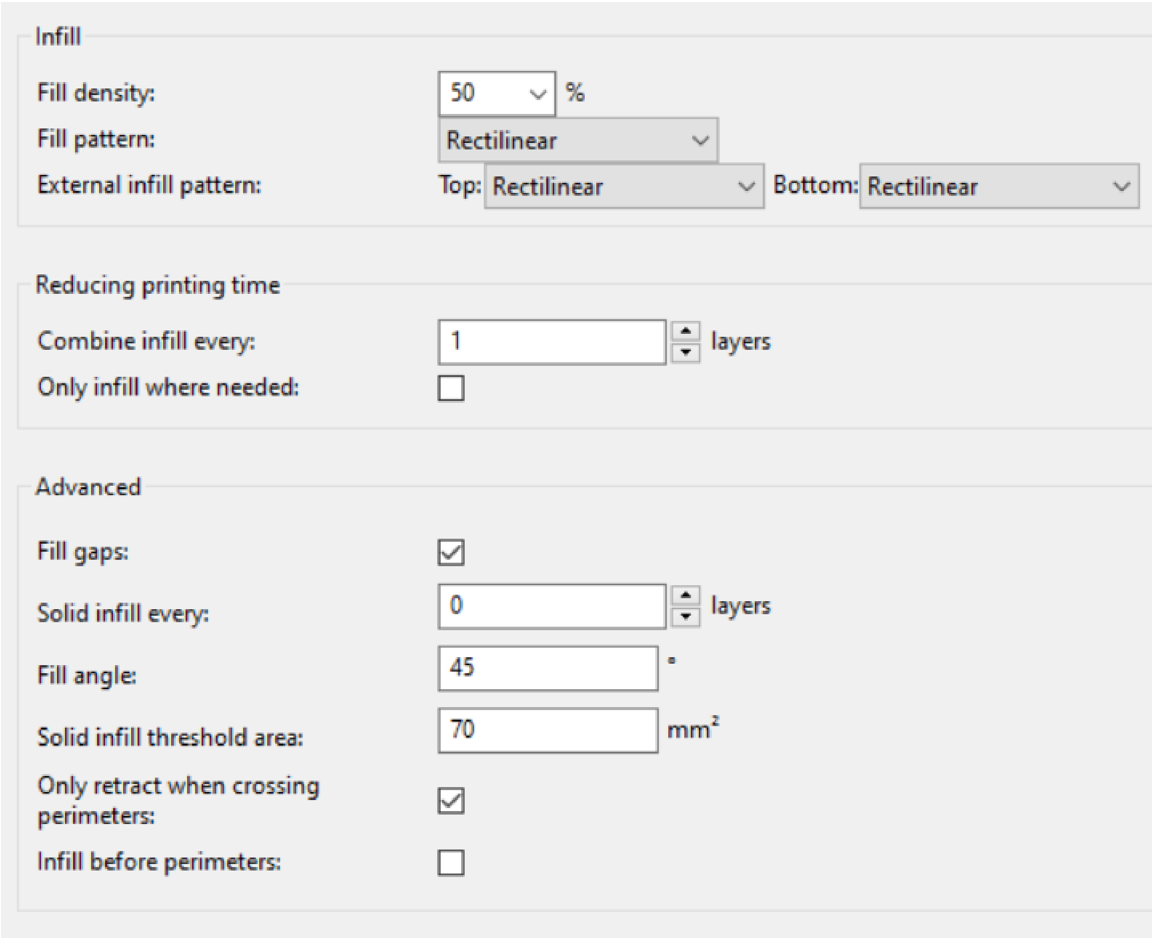


Figure 45 Slicing software settings

DESIGN REQUIREMENTS

The following are design requirements to take into account for the correct functionality of the 3D printed birdcage:

Parameters	
Distributed Material Dead load	This loading will always be constant for the structure since is the self-weight of the structure.
Distributed live loads	Loads spread over parts of the platform by the workers using it and their equipment.

bam international

Point Loads	Loads at a fixed point in a structure, pressing heavily on one point and inducing moments in the structure.
Impact Loads	Loads from a sudden impact force which is greater than the weight of the object alone due to its moment. Has the potential to seriously damage brittle materials.
Combustion	Combustion could cause the platform to light ablaze, endangering those on it if it does so quickly. Additionally, the fire will weaken the material and decrease its resistive strength, possibly critically.
Frictional Loads	Between outer wedge and pile: As the 3D printed birdcage will use a wedge-shaped system, the frictional load will be induced directly from the vertical loading, and any vertical increase in loading will result in a horizonal load of proportional magnitude. However there still needs to be enough friction between the pile and the outer wedge for this load to be converted.
Life expectancy	The life expectancy of the birdcage/material, if recycled plastic, would be 20 years or more.
Weather and chemical conditions	In prototype stage: It should be suitable for application in hot and wet climates (ME, AP) and cold and marine climates (Canada). It should be chemical resistance against oil spills.
Printer capacity	According to the maximum printing space, the maximum length of the structure should be no more than 4 m * 2 m, and the height is 0.6 m.

MULTICRITERIA ANALYSIS (MCA)

Once the design is done, an MCA is needed to study the different alternatives and to analyze the most optimal design to be used in the construction of Jetties. The MCA will define the most appropriate design out of the proposed options. This method allows us to compare and evaluate the different alternatives based on the stated criteria. The selection of the most suitable option is depended on how much the final sub criteria weighs. The alternative with the highest score will be chosen as the best option.

ALTERNATIVES

Three different design alternatives are studied:

- Option 1: Steel birdcage which is currently used by BAM in the construction of Jetties.

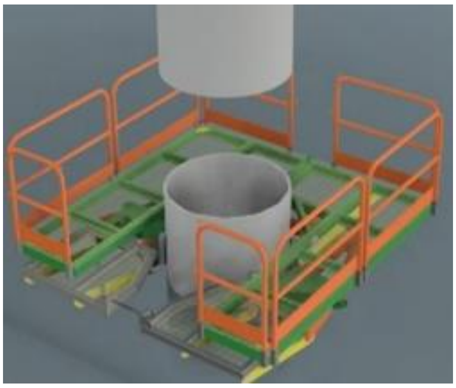


Figure 46 Option 1: steel birdcage

- Option 2: The first 3D printed design made of polymer filaments.

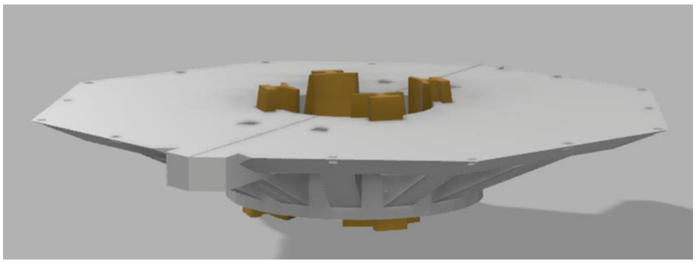


Figure 47 Option 2: First 3D printed birdcage design

- Option 3: The optimized 3D printed design made of fiber reinforced polymer filaments.

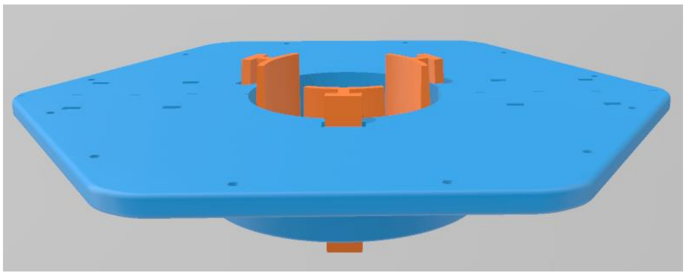


Figure 48 New 3D printed birdcage design

CRITERIA

Flexibility: This criterion will define the flexibility of each alternative when being manufactured. It is measured on how flexible for producing (location) and shaping/customization of the design. The more flexible the most score each alternative receives. Weight criteria: 25%.

Costs: As an economical factor, this criterion has a major impact in the decision making of which temporary work to use since it directly affects the overall costs of the project, but not including the printing equipment costs. The less costs the higher the score. Weight criteria: 25%

Time of fabrication: Along with the costs, it is important to take into account the time of fabrication since it directly affects the overall duration of the project, and therefore affects the total costs. The less time the higher the score. Weight criteria: 25%.

Environmental Impact: It is important nowadays that all the projects have the less possible negative impact in the environment, therefore each of the alternatives will be weighted according to their possible impact in the environment according to its recyclability. The less impact the higher the score. Weight criteria: 25%.

CRITERIA ANALYSIS

The four criteria contribute to the decisive characteristic which is the costs. Thus, the option with the lowest costs has the most possibilities to be used in a project. Each criterion maximum score is 25 and the total score will be taken from the addition of all four criterion. Therefore, the overall maximum score is 100.

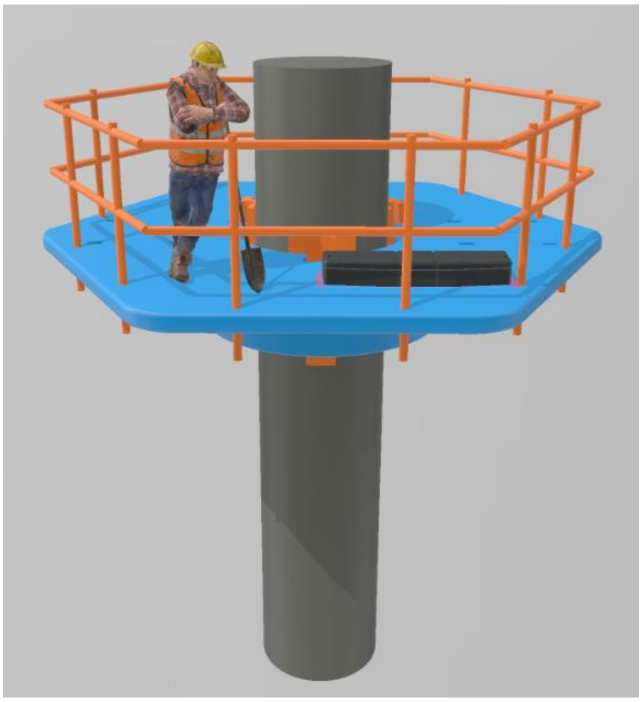
Variant	Criteria	Score	Total
Option 1	Flexibility	10	55
	Costs	20	
	Production time	10	
	Environmental Impact	15	
Option 2	Flexibility	20	75
	Costs	15	
	Production time	15	
	Environmental Impact	25	
Option 3	Flexibility	25	100
	Costs	25	
	Production time	25	
	Environmental Impact	25	

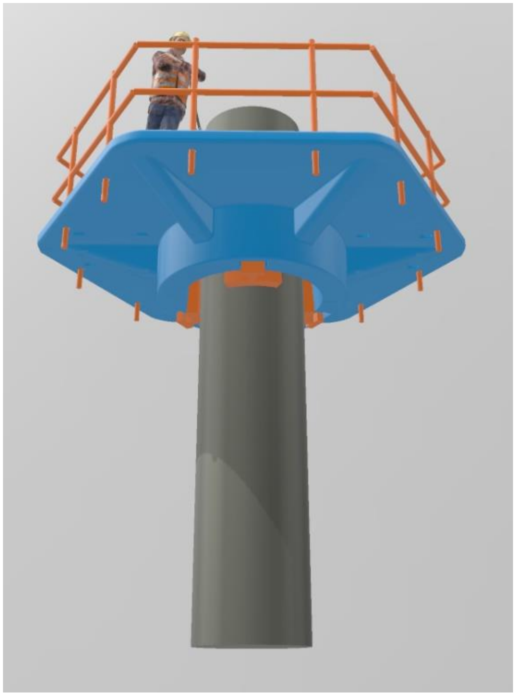
After analyzing the four different criteria, the option which has the better outcome is option 3. As for flexibility, the birdcage design proposal is better over the other options since the manufacturing process is FDM and it can be produced at the working site. For the cost, option 3 is the cheaper compared to the other options since it requires less material and less investment in logistics. Yet for this criterion the cost of the manufacturing equipment (3D printer) needs to be taken into account, but still over time will be a cheaper option. Option 3 has less material than option 2 and smaller dimensions. Therefore, for the production time is also better compared to both of the other options, being produced as fast as in day and a half per birdcage. The last criteria, environmental impact, is directly according to the variant recyclability. Therefore, option 3 the material is a thermoplastic, and the fibers chosen are glass fiber, option 3 is fully recyclable to produce the same or other type of structures produced with the same technology.

RESULTS

BIRDCAGE DESIGN

The birdcage designed in this research is for the Tanjun Jati project where the piles to be installed have a constant diameter of 1016 mm. The initial design starts from a 2D sketch and the dimensions are symmetrical in both axes (X, Y) to facilitate the printing process. In order to achieve the desired printing and technical parameters, the birdcage needs to be 3D printed in two parts. Each part will be printed upside down to facilitate the nozzle movement and to avoid the bridging and warping effects during the cooling process. The birdcage has a total of six buttresses (supports) and a total of three wedges. Part A will have two openings for wedges while part B will have one opening. Thus, a total of three wedges has to be 3D printed. The two parts of the birdcage also have four openings for the ratchet straps which will secure the birdcage horizontally, and two openings in each span for the handrailing legs. As shown in the picture below, the workers will have enough space to do the required tasks on the piles. The outer wholes on the surface are intended for the handrailing, evading the workers to fall out of the surface. The wedges are secured thanks to the compression force caused by the own weight of the whole structure. Therefore, the compressive force will prevent the surface to slide down to the water.





DIMENSIONS

The following top view dimensions are used for the hand calculations. The full CAD drawings can be found in the appendix section. Since the printer capacity is up to 4x2 meters, the surface of half the platform is 3.8 x 1.7 meters. This allows the birdcage to be 3D printed at 90° and still meet the working requirements of minimum of 1 meter from the pile to the outer edge of the birdcage.

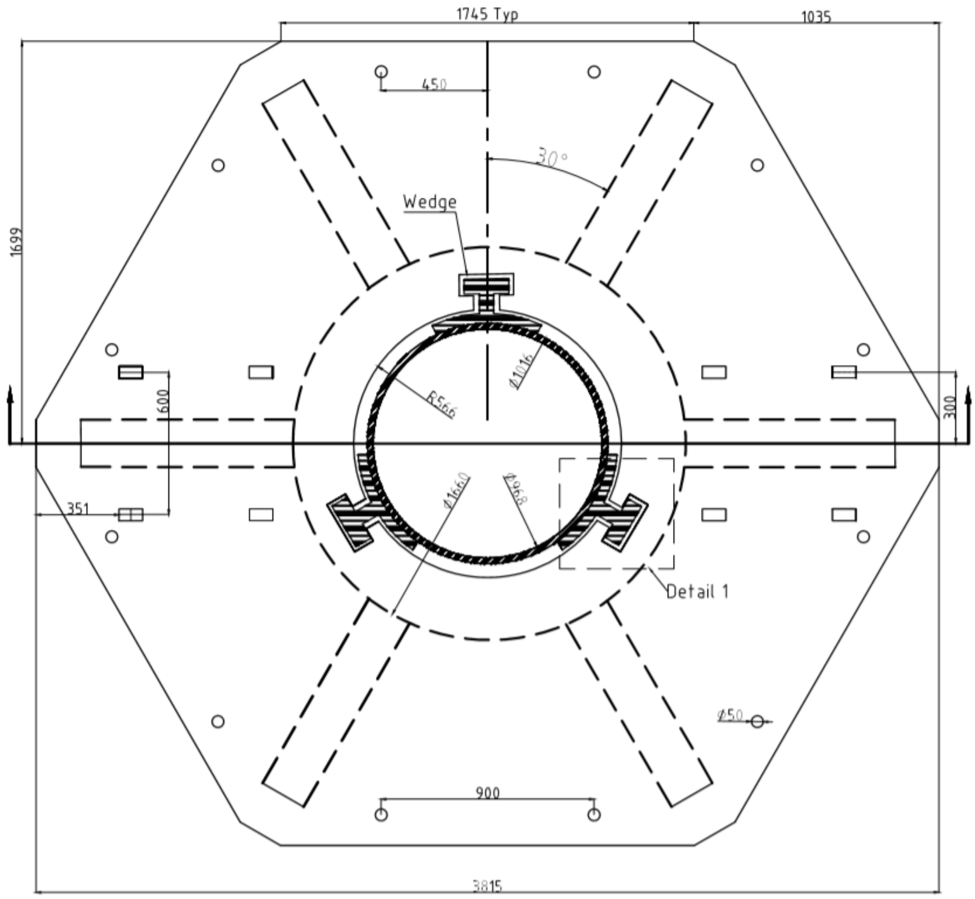


Figure 49 Birdcage drawings - top view

CORE FUNCTION

The design will need to provide stability and therefore, the core of the structure needs to be secured from falling. For this design the core will have a wedge system. The forces and moments transferred by the buttresses will be taken by the core of the structure. The 3D printed birdcage will use a wedge system to withstand the frictional load, and any increase in the vertical forces will be converted into axial compressive force towards the pile, contributing to the stability of the structure. The core has a T-shape opening where the wedges can be secured due to gravity force and self-weight of the birdcage.

Figure 50 Wedge proposal

The wedges will be secured at a specific distance from the top of the pile with a hook system. Due to the frictional force and compressive force induced by the loads, the hooks can be taken off once the birdcage is positioned and secured. The initial design for a 3D printed birdcage had four wedges, but in later stages in the design this was reduced to three wedges. This will assure that the inner part of the wedges is always in contact with the pile and the compressive forces will be transfer trough the web to the wider flange of each wedge.

PRINTING PROCESS

The birdcage platform is intended to be printed upside down to avoid any bridging effects on the material when cooling down. The vertical shells will have a perimeter of 3 layers minimum and no horizontal layers will be added to allow the upper platform to be open. The initial infill density is 50% and infill patter will be rectilinear to allow an even distribution of the forces.

PLATFORM LAYERS

The first layer to be printed will be in opposite direction of the second one as shown in the figure below, and it will go on for 110 mm:

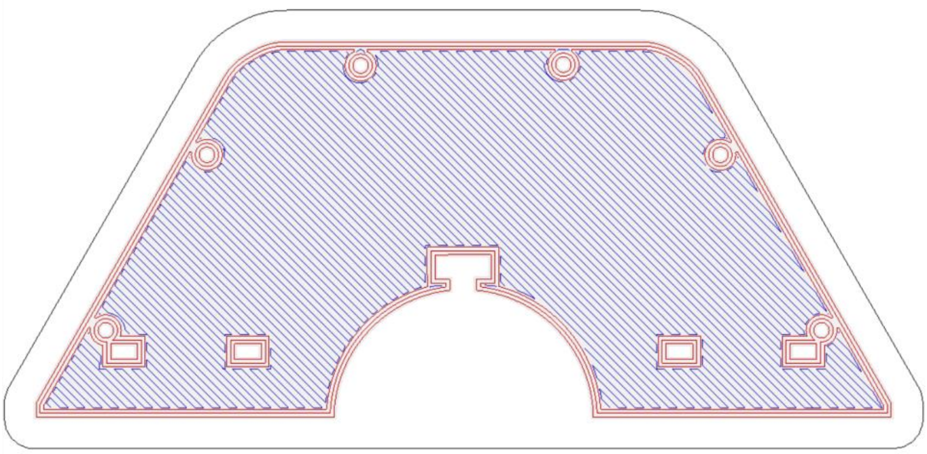


Figure 51 Plate first layer

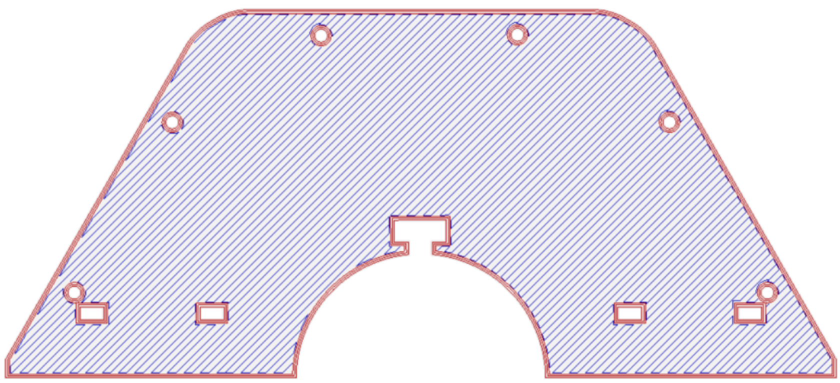


Figure 52 Plate second layer

SUPPORTS LAYERS

The same procedure will happen when printing the supports and the core of the structure:

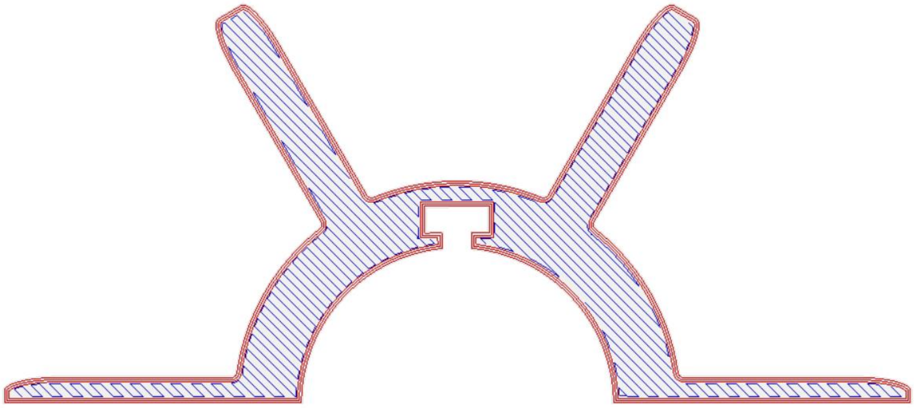


Figure 53 Supports first layer

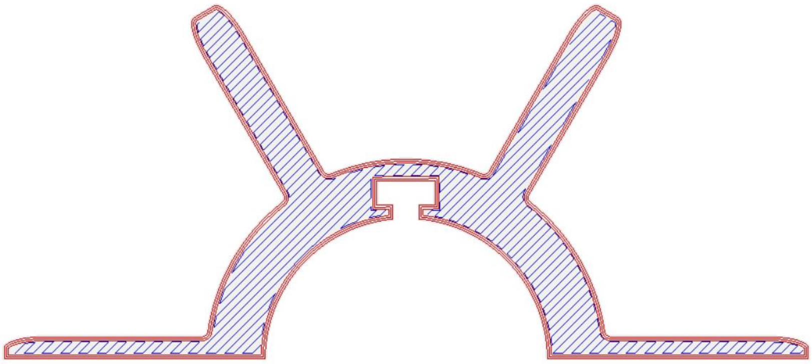


Figure 54 Supports second layer

G-CODES

As a result of the slicing process, the STL file is then converted into the G-codes file which will give the printing instructions to the 3D printer. The final model preview can be seen in the following picture:

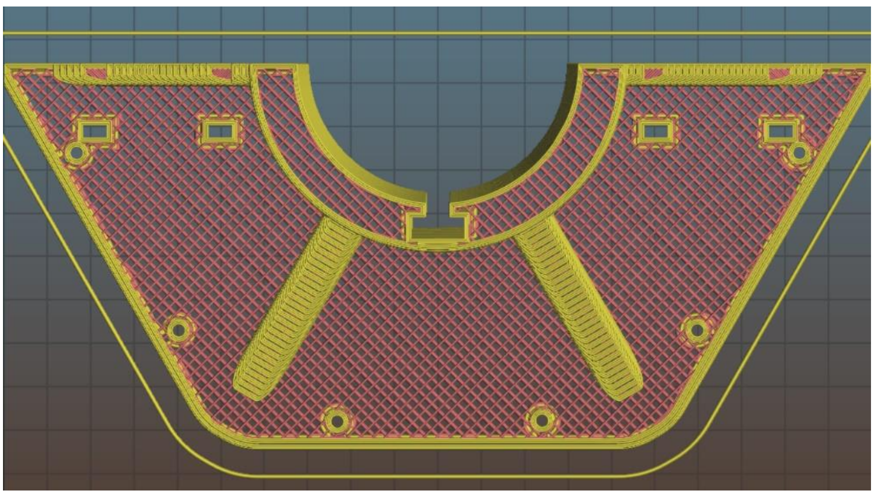


Figure 55 Final model preview

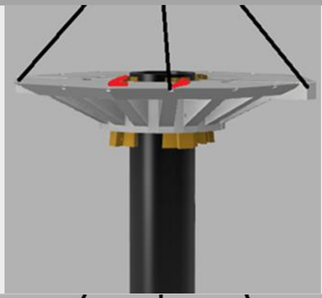
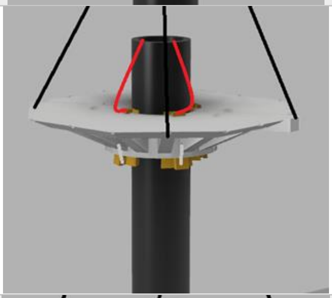
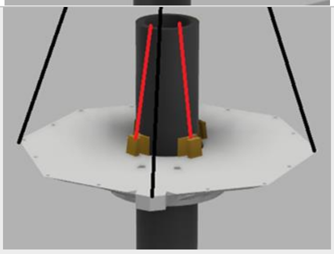
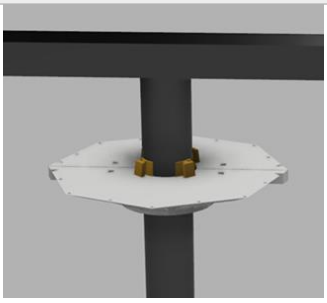
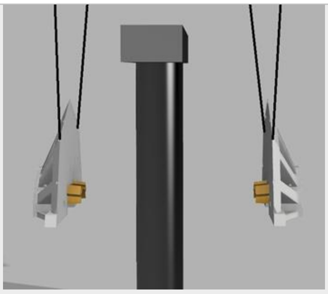
PROTOTYPE

The final birdcage design has been successfully 3D printed in scale 1:25. This is the first example to demonstrate the feasibility of fused deposition modeling and using plastic materials. For the prototype it was used ABS material which is one of the most used in small scale 3D printing, and because as the first prototype it will not be a load bearing structure. Since the handrailing is not yet decided whether it will be 3D printed or in steel material, it was not included in this first prototype.

Figure 56 Birdcage prototype

APPLICATION

The following is the step-by-step procedure to assemble the birdcage onsite:

Steps	Figure
Platform is assembled on the ground and lifted by crane, to then be placed on the pile	
Steel wires attached to the wedges hook onto the top of the pile and then the platform is lowered	
Once the platform is at the position the hooks can be taken off and the platform will be secured by its self-weight	
The needed works on the pile are done by the workers, and the concrete beam can be place on top of the pile	
Once the works are done, the ratchet straps are loosened so each half of the platform can be taken apart and lifted with a crane.	

CONCLUSION

The optimal design of 3D printed temporary works platforms (birdcages) made of composite materials (fiber reinforced polymer) which meet the structural requirements and is economically feasible for BAM international for being used in near shore marine projects (Tanjung Jati study case) is presented in this report. The design meets the structurally and economical requirements stated by BAM international. Even though the technology and materials to be used are rarely new, the future in the construction industry is pointing towards a more digitalize approach of producing all kind of structures, reducing the costs and time invested in each project. The design presented in this report intends to offer a first insight of how this technology can be applied and the benefits/advantages of working with fused deposition modeling manufacturing technique. The first prototype was 3D printed in 1:25 scale and it shows feasibility of the design. Yet, the 1:1 scale prototype should be tested and further studied before being implemented on the job sites.

RECOMMENDATIONS

Fused deposition modeling technique is mostly being used for prototyping in small scale. Therefore, further studies need to be done to fully understand the structural behavior of the parts produced by this technique. Since FDM uses a different manufacturing method, the 3D printed parts have different mechanical properties measured in different axes directions, and yet, there is not a software simulator with a finite element analysis which completely takes into account these parameters. For this reason, is important to further research about the use of 3D printing of functional structures.

The same is happening with the fiber reinforced polymers used in FDM. Since the technology is rarely new, also the materials implemented need more testing to assure their mechanical properties. Currently there are studies happening which are looking to stablish certain standards additional for this technology and materials. In the meantime, it is recommendable to use FDM and fiber reinforced polymers only for testing prototypes.

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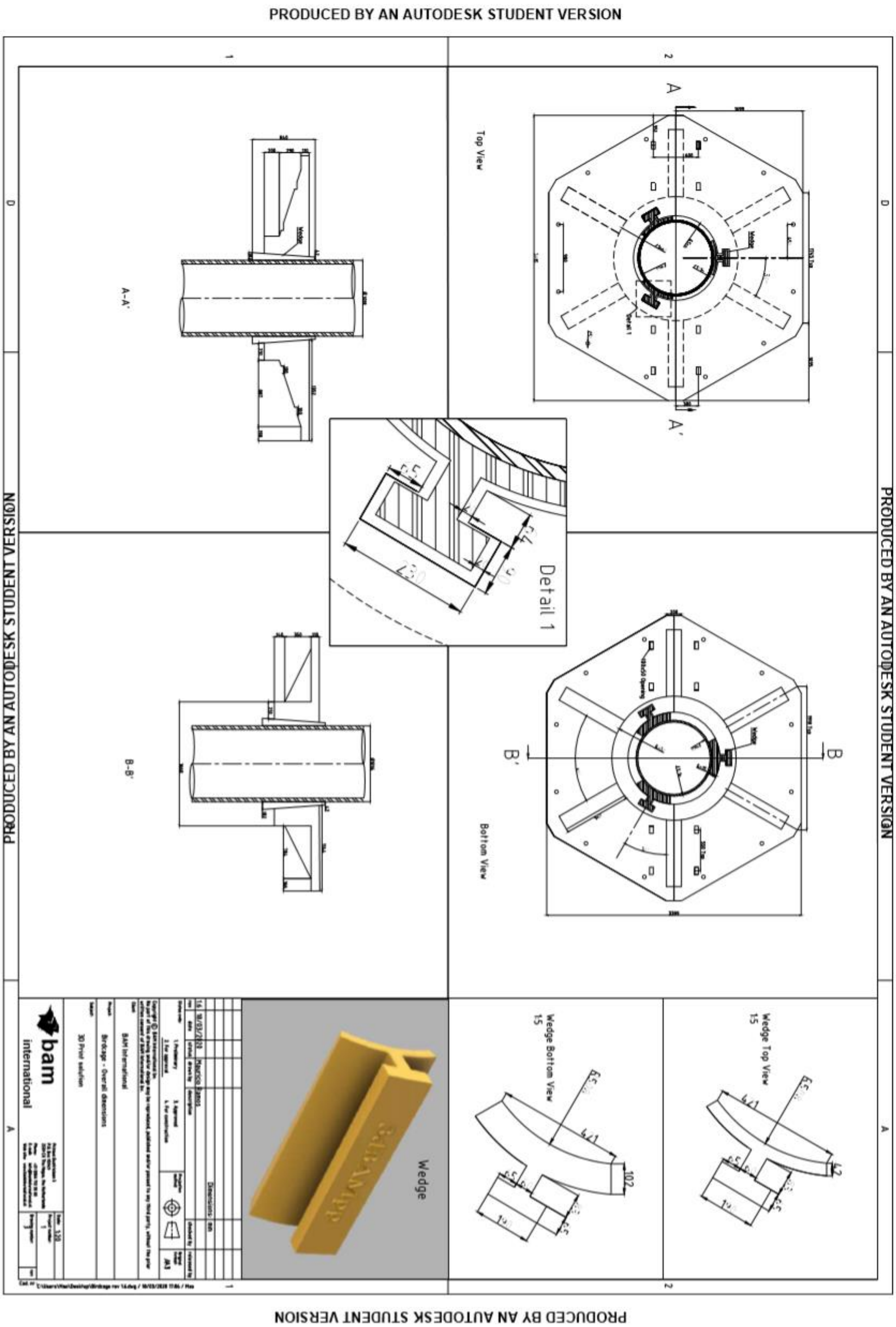
APPENDIX

BIRDCAGE 2D DRAWINGS



FEA RESULTS

INFORMATION AND PROPERTIES

⊟ Physical

Material	ASA Polycore 3012
Density	0,0433527 lbmass/in^3
Mass	1414,69 lbmass
Area	8895520 mm^2
Volume	534744000 mm^3
Center of Gravity	x=-5848,39 mm y=443,405 mm z=-2482,16 mm

Note: Physical values could be different from Physical values used by FEA reported below.

⊟ Static Analysis:2

General objective and settings:

Design Objective	Single Point
Study Type	Static Analysis
Last Modification Date	16/12/2020, 05:01
Detect and Eliminate Rigid Body Modes	No

Mesh settings:

Avg. Element Size (fraction of model diameter)	0,1
Min. Element Size (fraction of avg. size)	0,2
Grading Factor	1,5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	Yes

⊟ Material(s)

Name	ASA Polycore 3012	
General	Mass Density	0,0433527 lbmass/in^3
	Yield Strength	3945,03 psi
	Ultimate Tensile Strength	3945,03 psi
Stress	Young's Modulus	429,312 ksi
	Poisson's Ratio	0,37 ul
	Shear Modulus	156,683 ksi
Part Name(s)	Part1.ipt	

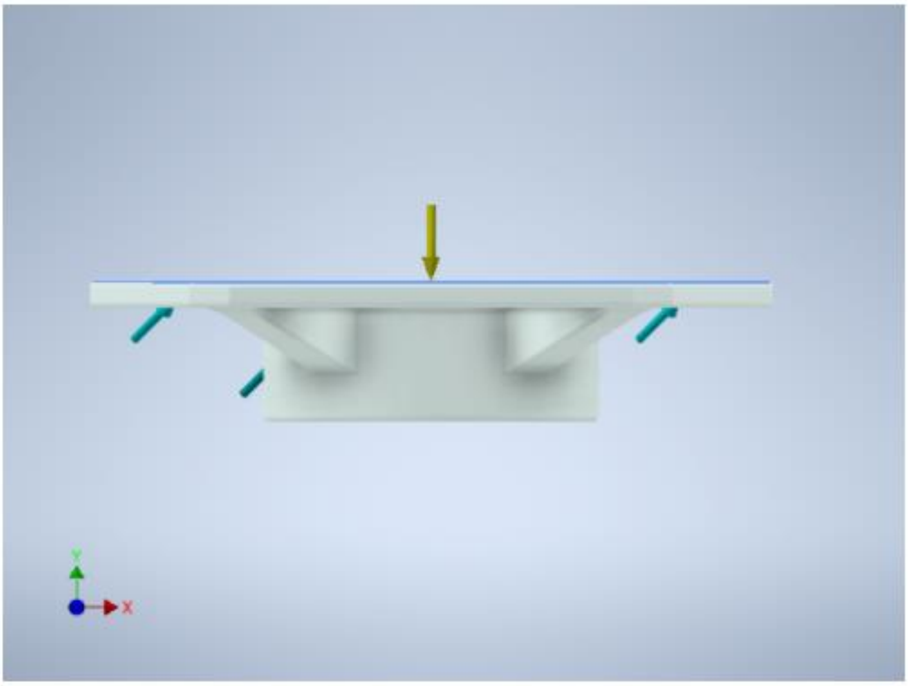
LOAD

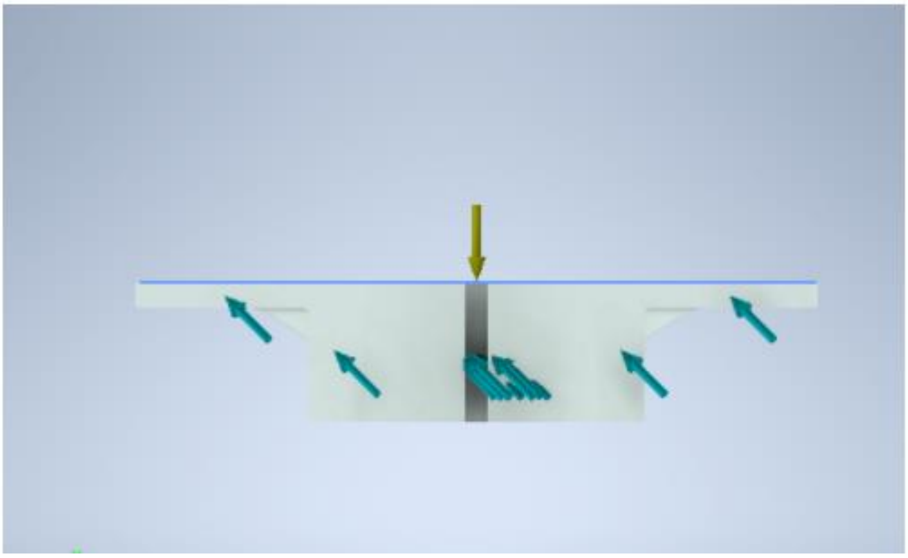
⊟ Operating conditions

⊟ Force:1

Load Type	Force
Magnitude	1124,045 lbforce
Vector X	-0,000 lbforce
Vector Y	-1124,045 lbforce
Vector Z	0,000 lbforce

⊟ Selected Face(s)



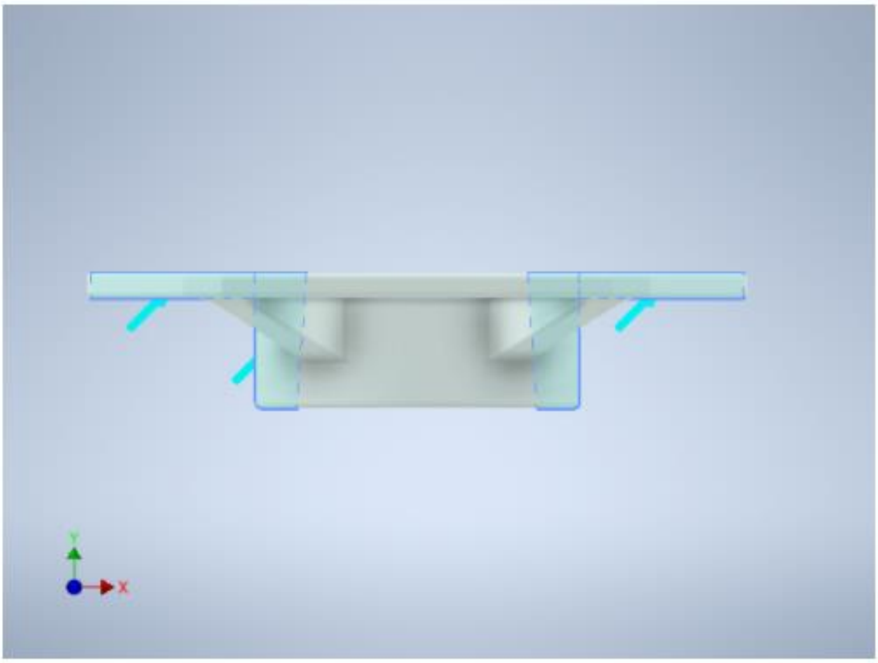


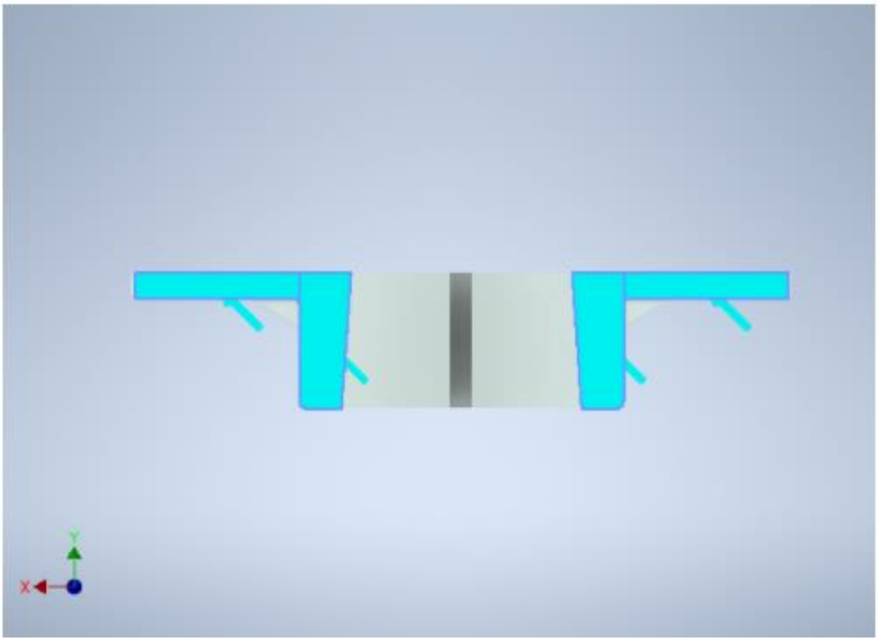
FIRST CONSTRAINT

⊟ Fixed Constraint:1

Constraint Type	Fixed Constraint
Vector Z	0,000 mm

⊟ Selected Face(s)



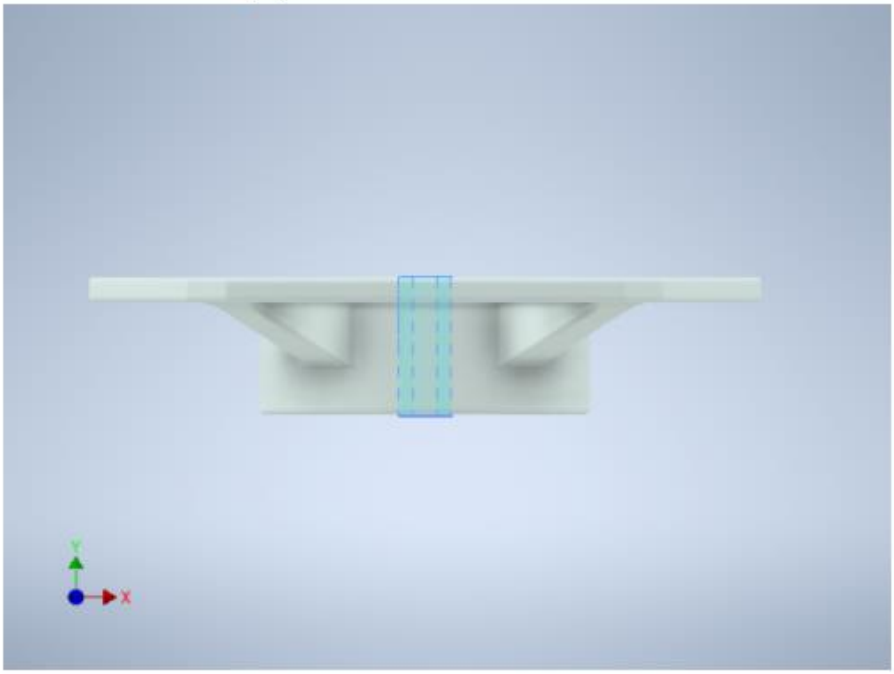


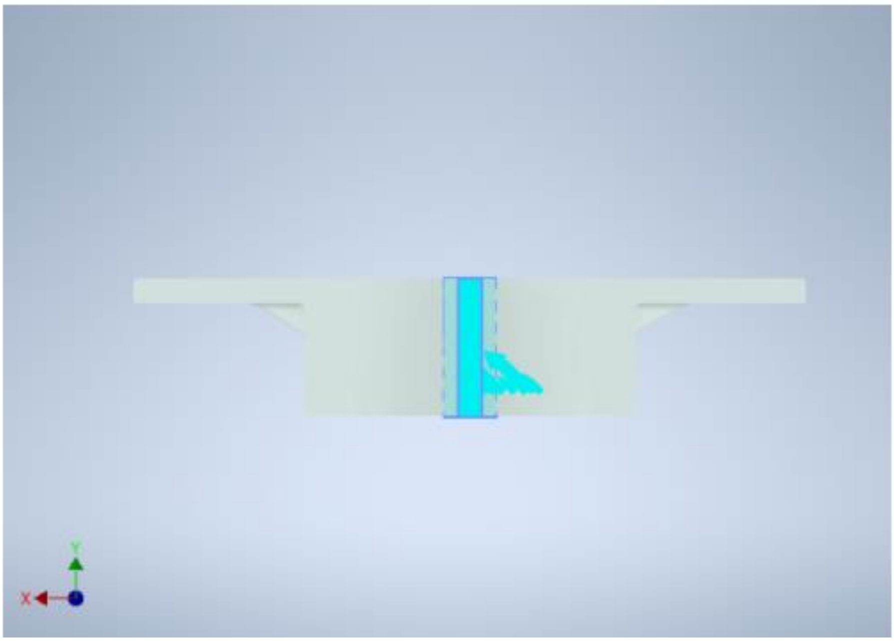
SECOND CONSTRAINT

⊟ Fixed Constraint:2

Constraint Type	Fixed Constraint
Vector X	0,000 mm
Vector Y	0,000 mm
Vector Z	0,000 mm

⊟ Selected Face(s)





RESULT VALUES

⊟ Reaction Force and Moment on Constraints

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X,Y,Z)	Magnitude	Component (X,Y,Z)
Fixed Constraint:1	192,654 lbforce	0 lbforce	1893,79 lbforce ft	-1893,76 lbforce ft
		0 lbforce		-9,65567 lbforce ft
		-192,654 lbforce		0 lbforce ft
Fixed Constraint:2	2256,62 lbforce	0 lbforce	759,321 lbforce ft	-759,259 lbforce ft
		2248,31 lbforce		9,01562 lbforce ft
		193,478 lbforce		3,6756 lbforce ft

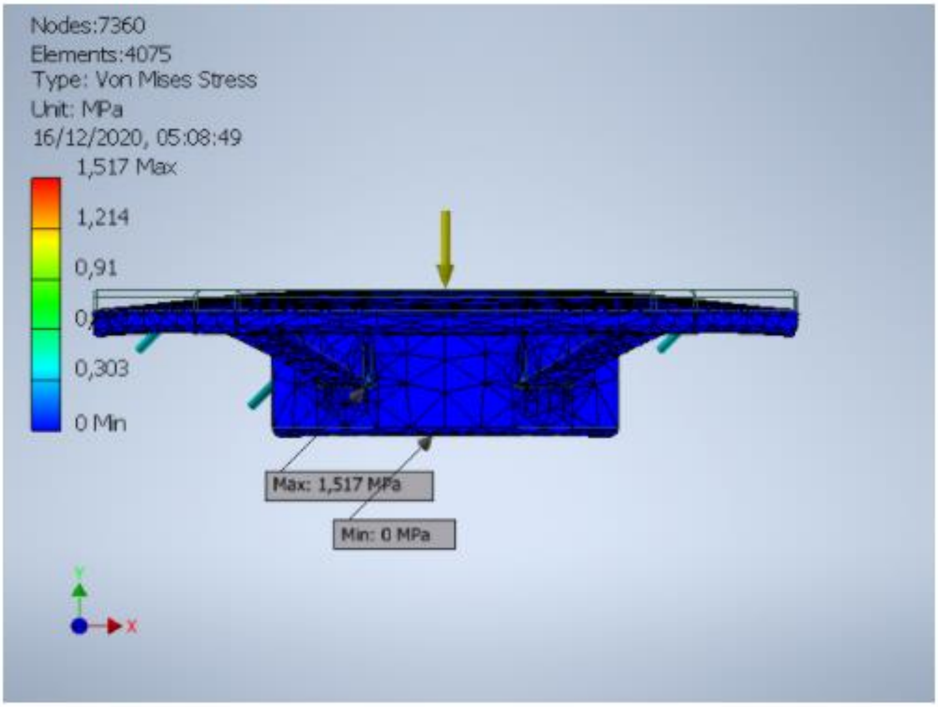
⊟ Result Summary

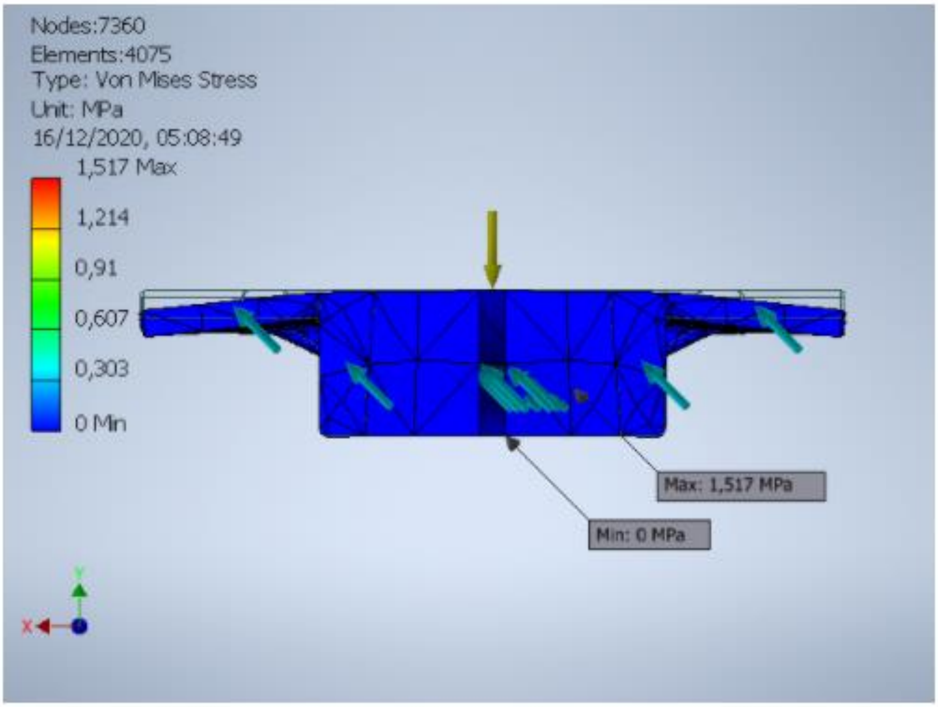
Name	Minimum	Maximum
Volume	534744000 mm^3	
Mass	1414,69 lbmass	
Von Mises Stress	0 MPa	1,51693 MPa
1st Principal Stress	-0,614133 MPa	0,42242 MPa
3rd Principal Stress	-1,59746 MPa	0,0879623 MPa
Displacement	0 mm	0,30292 mm
Safety Factor	15 ul	15 ul
Stress XX	-0,694462 MPa	0,208849 MPa
Stress XY	-0,292222 MPa	0,371327 MPa
Stress XZ	-0,420413 MPa	0,253597 MPa
Stress YY	-1,34711 MPa	0,122087 MPa
Stress YZ	-0,269701 MPa	0,45025 MPa
Stress ZZ	-0,719141 MPa	0,248257 MPa
X Displacement	-0,0248771 mm	0,0248832 mm
Y Displacement	-0,302562 mm	0,00000169784 mm
Z Displacement	-0,023975 mm	0,0253635 mm
Equivalent Strain	0 ul	0,000474293 ul
1st Principal Strain	-0,00000313609 ul	0,000303345 ul
3rd Principal Strain	-0,000495651 ul	0,000000943589 ul
Strain XX	-0,000121253 ul	0,000133243 ul
Strain XY	-0,000135251 ul	0,000171864 ul
Strain XZ	-0,000194583 ul	0,000117374 ul
Strain YY	-0,000397043 ul	0,0000666377 ul
Strain YZ	-0,000124828 ul	0,000208393 ul
Strain ZZ	-0,000126136 ul	0,000110149 ul

VON MISES STRESS FIGURE

⊟ Figures

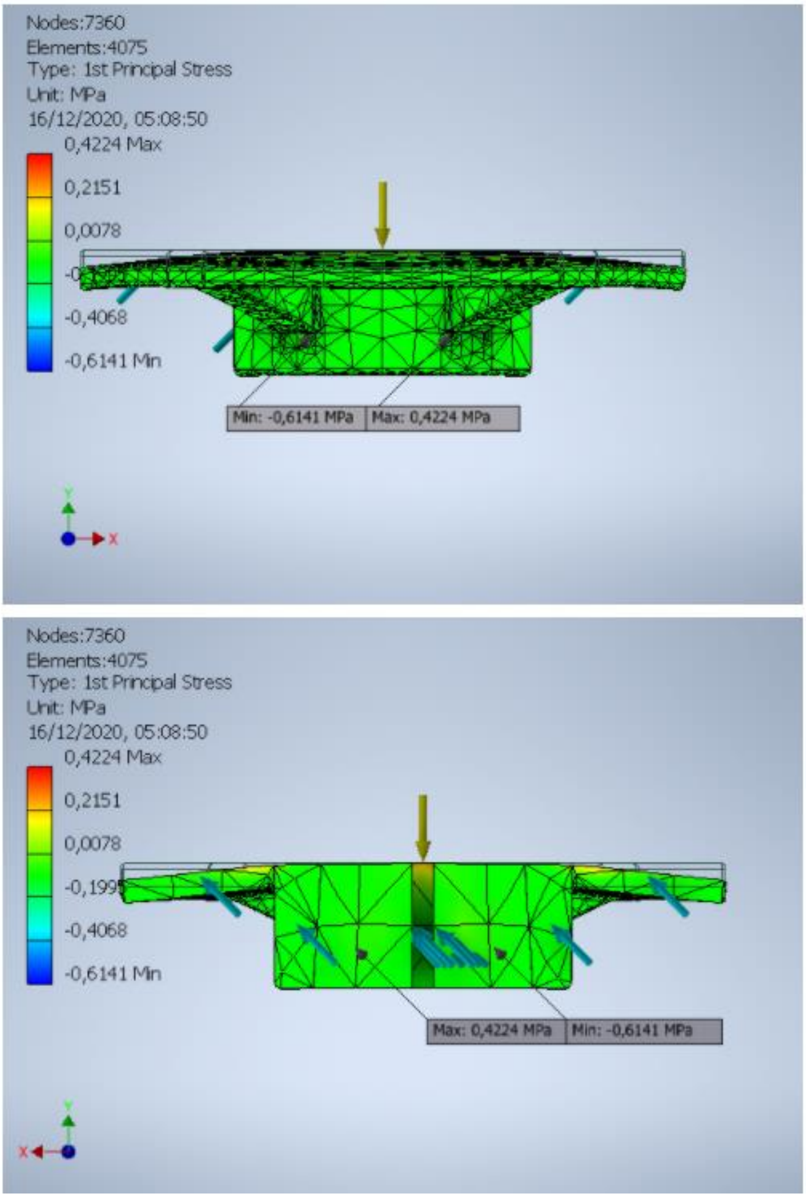
⊟ Von Mises Stress





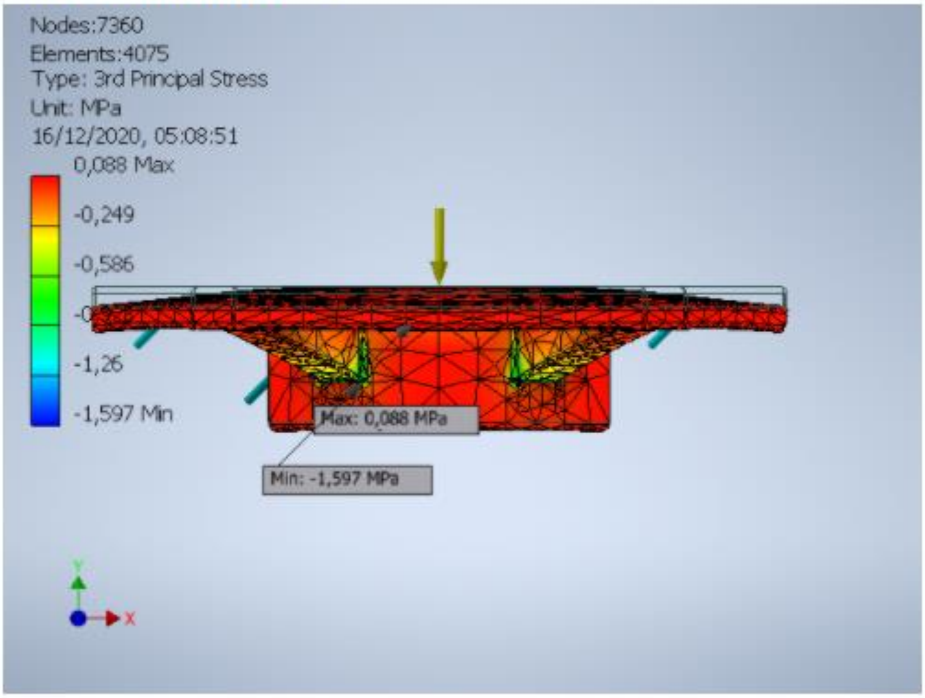
1ST PRINCIPAL STRESS FIGURE

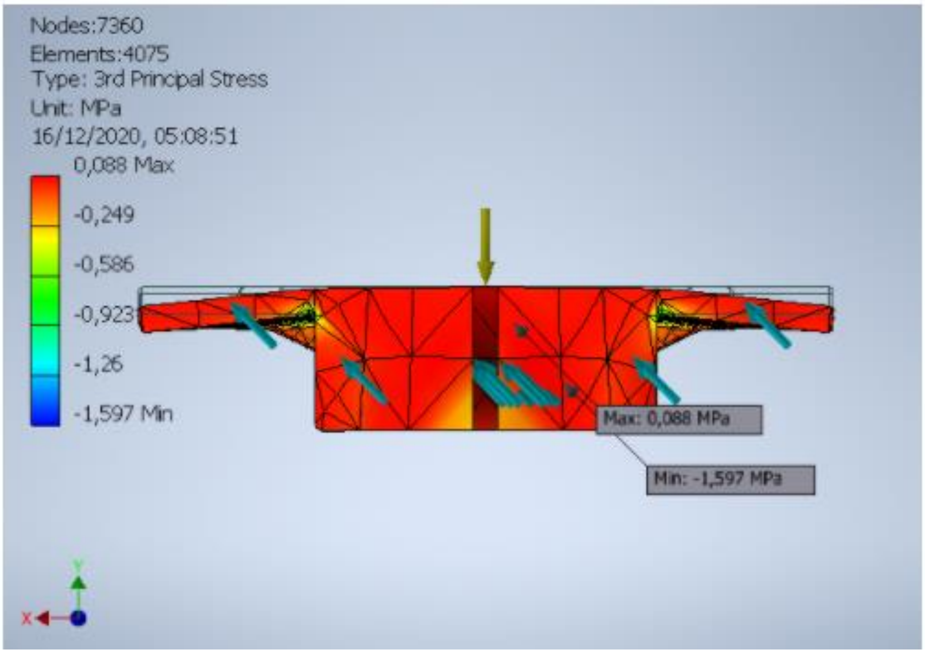
⊟ 1st Principal Stress



3RD PRINCIPAL STRESS FIGURE

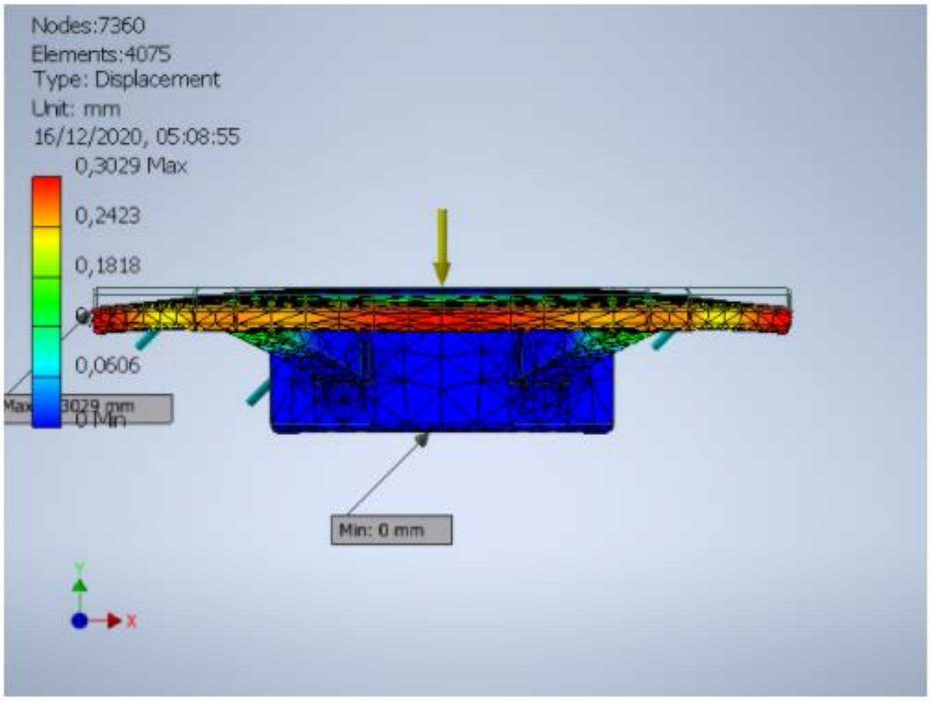
⊟ **3rd Principal Stress**

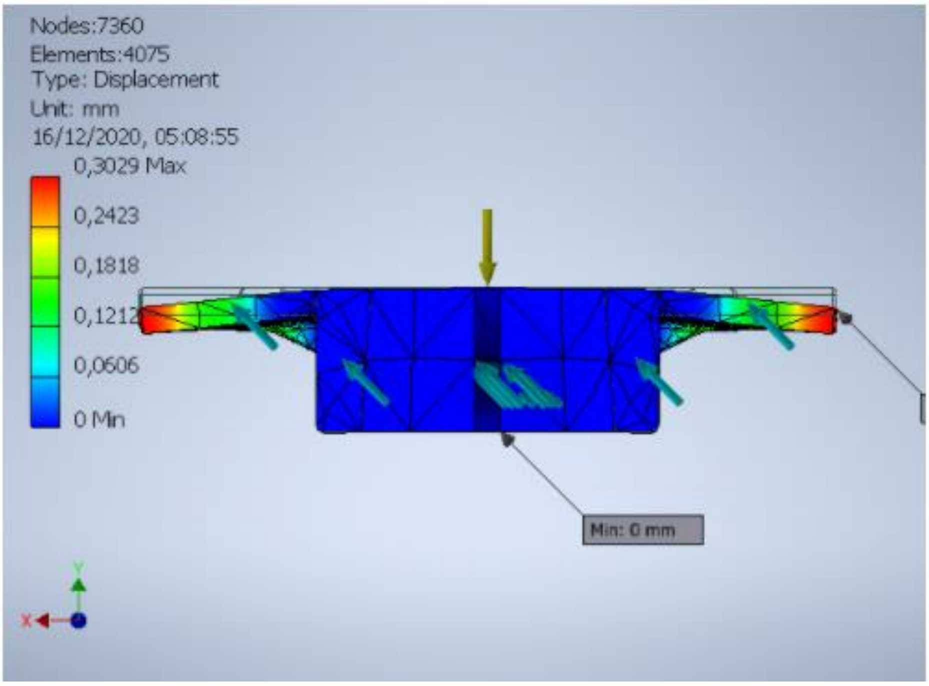




DISPLACEMENT FIGURE

⊟ Displacement





SAFETY FACTOR FIGURE

⊟ Safety Factor