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Inflatable Structures and Digital Fabrication

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ABSTRACT: The construction industry has changed drastically over the past several decades. In today's age, engineers and architects aim to build bigger and lighter whilst remaining sustainable. Inflatable structures can be utilized to achieve these aims. This study investigates how to digitally manufacture inflatable structures to be more efficient. For this reason, digital manufacturing as well as casting and moulding are studied and compared. Firstly, software modelling was explored to evaluate the behaviour of elastomeric materials. 3D printing in Tango Plus FLX930 and silicone casting was compared. It was found that Tango Plus FLX930 was inadequate due to its low elasticity compared to the considered silicones. Under pneumatic loading, indeed, Tango Plus FLX930 would delaminate. Whereas, with casting and moulding silicone, the prototype could resist the required amount of internal pressures. This shows the feasibility of moulding and casting and the limitation of 3D printing fabrication techniques.

1 INTRODUCTION

The search for new materials, technological breakthroughs and innovations are forever progressing. The construction industry is no exemption to this and is endlessly in the search for new means to advance current methods and materials in order to improve the quality of people's lives. There is always room for improvement, particularly with larger more complicated structures. These require long spanning elements with structural behaviour attained through the best use of architecture, geometry and materials. These modern structures need innovative solutions and materials that are light yet adequately strong and fit for purpose, allowing structures to be more efficiently designed and built.

Tensile membrane structures allow to span larger areas as they are extremely thin and light. Inflatable structures are a contemporary type of structure, for which their potential can still be investigated. The weight of these structures is very low, resulting in them being able to span large areas without internal supports such as stadiums and sheltered spaces.

Inflatable structures are light, transportable and easily erected, although, a lot of time and labour is required during the manufacturing process. Manufacturing a large-scale inflatable structure will require a lot of human interaction, increasing the risk of human errors. To eliminate this, digital manufacturing processes can be implemented to build these structures. Currently, additive tooling processes have become the forefront of digital fabrication. These methods can be suitably used for inflatable structures built as complete monolithic structures.

This paper aims to explore the different typologies, materials, uses of inflatable structures and discover novel methods to manufacture these through the medium of digital fabrication. In this paper digital fabrication is used for both additive manufacturing and subtractive manufacturing (i.e. CNC). This will lead to the use of modelling software's to design and produce a realistic model to reinforce the idea of digitally manufacturing an inflatable structure.

To validate this hypothesis, the final prediction of the deflected inflatable structure should match this model. This will show the successful use of digital manufacturing methods at its peak potential on a much larger scale than previously intended.

1.1 Inflatables

An Inflatable (pneumatic) or air-supported structure is a novel type of textile membrane shell structure. Oñate, 2005 gives a general description of inflatable structures and their unique set of features such as: lightweight, foldability, portability and their increase in popularity in the recent years for a wide range of applications. Inflatables are used in many fields such as civil engineering, architecture, aeronautic and airspace. Typical uses consist of permanent roofs (stadiums), shelters, temporary structures for recreational or disaster struck areas.

Since 1995, Nick Crosbie has created many different types of inflatable structures. He explains that inflatable structures are a quick and efficient way to build architecture in organic flowing forms. He goes on to explain how these can be achieved by the different types of inflatable structures available;

- Airflow – are structures which are inflated and kept to a pressure by a constant flow of air. These structures are easily erected and can span 27 meters without trussing. Air beam systems and trusses can be used to span further areas.
- Sealed air pressure – this type of structure is a heavy-duty inflatable structure. They are completely sealed and filled with high pressure allowing them to span longer distances. These are typically made from PVC coated polyester joined by heat welding and stitching. The structural performance can be controlled as these permanent installations are constantly exposed to differential weathering.
- Hybrid air structures – the two main types of inflatable structures mentioned above can be combined to create hybrid inflatable structures. Sealed air beams are used in areas more vulnerable to structural integrity in case of power failures. These structures can span like sealed inflatable structures but be more efficient. They are typically made from TPU fabrics offering higher levels of performance.
- Pressurized single skin – these structures generally work better at larger spans above 10 meters. They are better value for the area to cover such as for tennis courts or sports arenas. These structures require a pressure lock door or revolving doors as they are filled with positive pressure, like a balloon.

These structures can also be aesthetically enhanced with the aid of different textures and internal lighting. All typical inflatable structures are created with fabrics as they can resist enough tension and are strong enough to withstand external loads. The most commons structural fabrics used are polyester re-enforced PVC and PU or PVC coated Nylons. These fabrics are either stitched, HF welded, or glued. All fabrics are coated for fire protection.

These structures are easily and quickly erected on site as they are completely manufactured off-site. They can be packed to a fraction of their inflated size and transported used as temporary shelters/buildings, although, they are engineered as permanent buildings. Structures which have over 100m^2 internal space require structural engineering expertise. Apart from the inflatable itself, the structures to foundation connections are as important, and when anchorage to the ground is not available ballast is used within the walls of the inflatable (Crosbie, 2016).

1.2 Fabrication

Current fabrication methods for inflatable structures have been explained by (Oñate, 2005), which include the use of a FEM (Finite Element Method) to model the 3D shape. This is sometimes followed by an aerodynamic and/or thermal analysis depending on the condition of the structure. The most crucial part is a mapping of the patterned design to ensure the correct shape of the structure is achieved. By using relevant software's, finite element patches are defined and by using isoparametric mapping, the pattern geometry can be represented as 2D shapes.

Mosadegh et al., (2014) have utilized the casting process to create soft robotic actuators for bending. The 3D printing is used to create the moulds for the different elements of this actuator. This pneumatic network (PneuNets) are made from an elastomer with a set of internal channels and chambers. The geometry enhances the effect of bending and can be controlled by wall thickness or material properties. It is built up of different layers with different mechanical properties to further help the bending of the actuator.

These actuators can be further controlled by adding materials with varying elastic properties. This causes the “stretchy” material to expand more than the “rigid” one which ultimately causes the inflatable to bend. The thickness of the layer also influences how stretchy or rigid the actuator is, known as a differential strain effect.

The use of 3D printers is increasing as the discovery of new technology and materials are being made. Currently, 3D printers can almost print anything that can be melted. The most common material used is TPU (Thermoplastic Polyurethane) which has characteristics closest to rubber. Researchers at Cornell University have 3D printed soft robotic actuators to imitate muscles using digital mask projection stereolithography. They successfully fabricated and tested an antagonistic paired actuator which possessed tentacle-like motion. This process differs from typical stereolithography as it projects a whole layer of UV light through a masking layer that works like a virtual photomask (Peele et al., 2015).

2 PROTOTYPING AN INFLATABLE SMALL SCALE STRUCTURE

This worked aimed to investigate the feasibility to prototype a small scale object of size 10 x5 cm, that is capable of bending when inflated. The intention is to explore the possibility to adopt either 3D printing or more recent techniques developed in soft robotics and known as soft pneumatic actuator (Kow et al. 2018). The following subsections show the type of investigated materials, and the investigated fabrication processes, and the achieved prototypes.

2.1 Design Optimisations

For the design process the independent, controlled and dependent variables need to be identified. This was important for design optimisation of the aspired prototype as it will help to narrow and emphasize the main factors that affect inflatable structures. The material and fabrication choice has a great influence on the design regarding what was physically achievable, therefore, these were kept as the controlled variables. The final inflated shape was dependent on the geometry (independent variable) of the design. Although the whole geometry was very broad to optimise, therefore, only precise adjustments were made to taper the possible outcomes to the final design.

2.2 Materials

The use of 3 rubber-like materials were investigated for the prototype, i.e. Dragon Skin 20A, Smooth-Sil 935 and Tango Plus FLX930. As the shore hardness of the silicones increase, the elongation at break reduces showing they are becoming stiffer and less elastic. Tango Plus FLX930 is specifically used with 3D printers, but it also simulates thermoplastic elastomers with rubber-like qualities like silicone. Dragon Skin and Smooth-Sil are silicone rubbers, which are used for casting. They possess high elongation at break percentages and low shore hardness’s, which make them highly suitable for modelling such an inflatable structure that requires flexibility and durability. The material properties and Ogdens 3rd order mathematical material coefficients are shown in Table 1 and Table 2.

Table 1. Material properties (Stratasys.com. 2018, Smooth-On, 2018a, b)

Material	Tensile Strength	Elongation at Break	Shore Hardness
Tango Plus FLX930	0.8 – 1.5 MPa	170 – 220 %	26 – 28A
Dragon Skin 20A	3.79 MPa	630 %	20A
Smooth-Sil 935	4.48 MPa	300 %	35A

Table 2. 3rd order Ogden material coefficients (Agarwal, 2016)

Ogden (3rd Order)	μ (N/mm2)	α	D(mm²/N)
1	0.001887	– 3.848	2.93
2	0.02225	0.663	0
3	0.003574	4.225	0

2.3 Fabrication

Choosing the most effective and efficient digital fabrication process was based on cost, time, accuracy, availability and achievability. This choice was made with careful consideration of fabrication at a larger scale in real life. The factor of human error was also of high importance because the larger the structure is the higher the chance of errors to occur.

3D printing

3D printing of plastic material was explored to fabricate the element. The printer used was a PolyJet Object1000 Plus printer by Stratasys. It can print larger parts with a combination of up to 14 different materials with ranging hardness all in one single job. Almost no post-processing is required, as support material is removed with a water jet. These advantages are combined with accuracy up to 600 microns, layers as thin as 16 microns with resolutions; x-axis: 300dpi; y-axis: 300dpi; z-axis: 1600 dpi. (Stratasysdirect.com, 2018). This printer has a built-in UV light which cures the material as it builds, although, further curing is required after completion of a part. This fabrication method is completely manufactured without human interaction making it more accurate, quicker and easier to produce many iterations rather than the casting method. 3D printing models allowed for many iterations, which were produced quickly and easily. Critical analysis of the different geometries were carried out to determine failure prone areas of the models. The initial model was inspired by Mosadegh et al., (2014)'s soft actuators, but was adapted to a larger surface area. The 3D printed prototype was made all of Tango Plus FLX930 (Table 1). It is worth noticing, that to allow the object to bend when inflated, it was necessary to work on the geometry, that needed to allow to have stiffer surface at bottom and a less stiff surface at the top. To achieve this a series of different geometry were analysed. Initial models, when inflated, failed as they were too intricate and had very thin walls, which were prone to delamination. This model was optimised with thicker walls so that the internal geometry of the inflatables could resist the pressure applied. This improved model had failed in delamination of the layers rather than the walls. Figure 1 shows the delamination of the internal walls, which carried on to the external wall. It can be seen how the air could not evenly spread throughout the inflatable, which lead to excessive pressure splitting the top layer from the bottom. The failure modes clearly demonstrate that a very careful designed is necessary to allow the 3D printed prototype to perform as required, and, indeed further studies are necessary to achieve this.

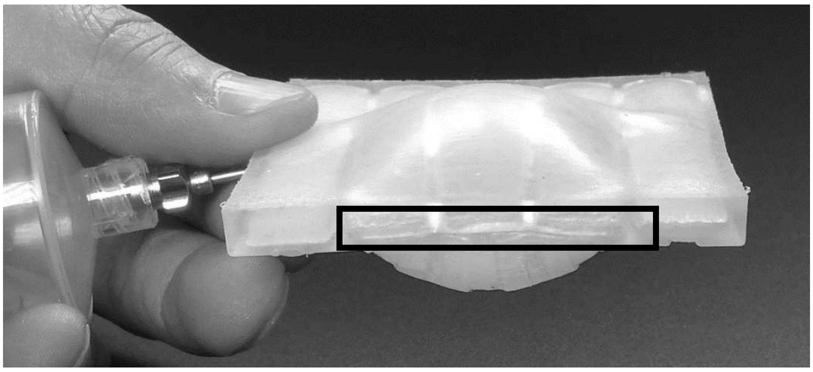
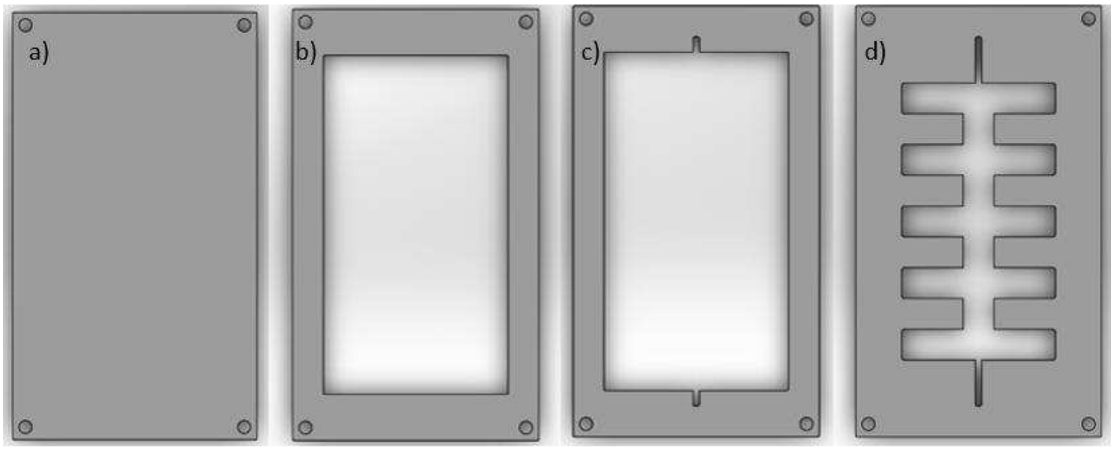


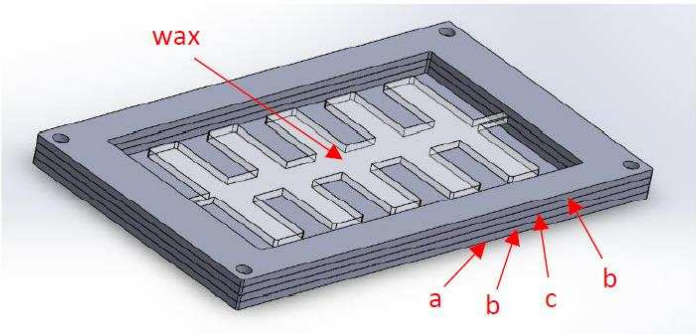
Figure 1. Side elevation at maximum inflation (Model 3).

This design was optimised independently two more times and the same outcome occurred. This was an issue with the bonding of the layers when 3D printing rather than the geometry. The bonding was not sufficient enough to hold together and evenly dissipate the pressure around the model. This is an issue with the material chosen and its properties. As shown in Table 1, it has an elongation at break a lot lower than the silicones. Therefore, the fourth optimised design was then fabricated using silicones to investigate if this problem was solely due to the material used.

2.4 Silicone Mould and Cast Prototype

The second investigated method was a moulding and casting process. This process is used for casting silicones. For the mould, four layers of acrylics where designed, cut and assembled. Each layer was laser cut out into 2 or 1 mm thick acrylic and built up as shown in Figure 2. Layer a) represents the support layer on which the base layer material was casted. Then Layer b) and c) were used for casting the Dragon Skin, and layer c) also presents the inlet for the air. Layer d) was used to create a wax mould replicating the air cavity and was set inside the silicone. The wax acted as a sacrificial support material since it is a lot simpler and easier to remove, either by air pressure or melting. Each layer of silicone had to be set separately as there were changes in the geometry within the model. Figure 2 e) shows a 3D image of the final mould.





e)

Figure 2. Mould layers for casting: a) Base layer; b) Main core layer; c) Wax core layer; d) Wax mould, e) 3D view of the assemblage.

The base layer was cast in Smooth-Sil 935 as it is a stiffer material which will allow for the bending effect. The rest of the inflatable was cast in Dragon Skin 20A (material properties shown in Table 1). The casted prototype was inflated using a pressure gun, as a syringe would not provide adequate constant high pressure to keep its shape.

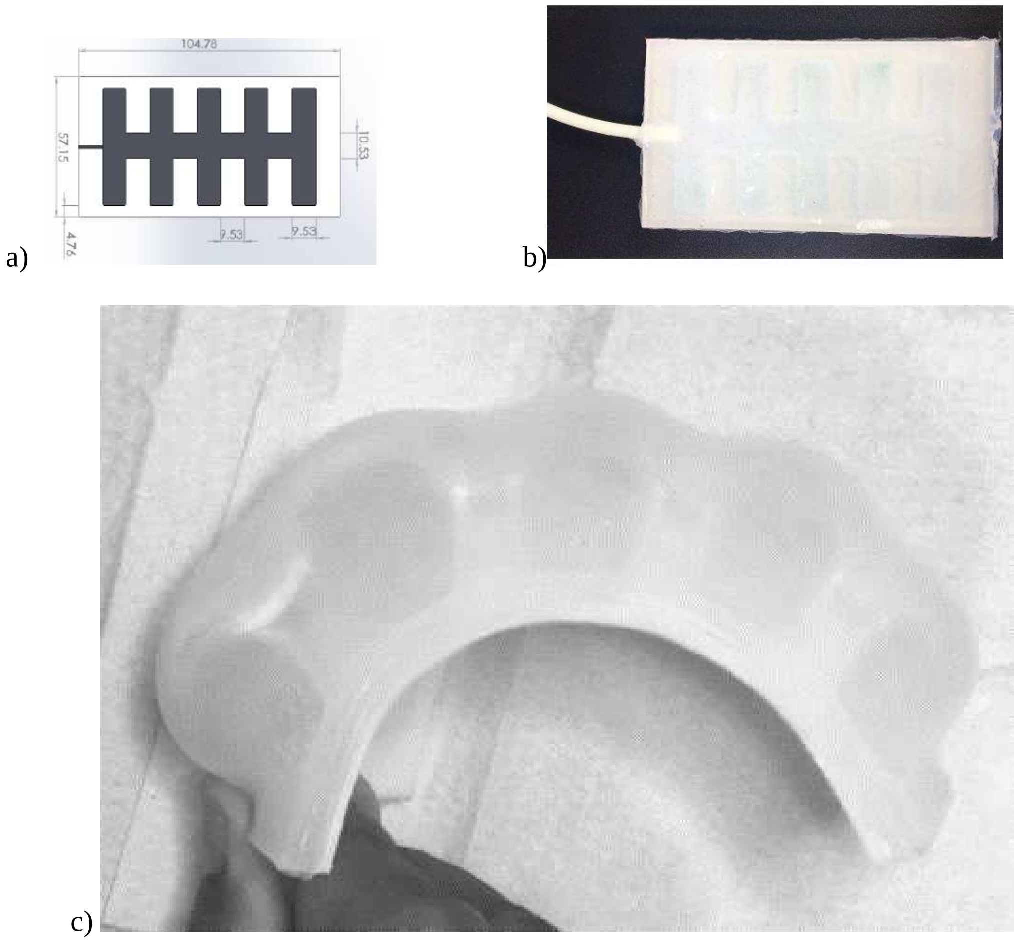


Figure 3. Casted Prototype: a) geometry (dimensions in mm), b) plan view of the realized prototype, c) Final deflected shape during inflation.

Figure 3 shows the final bended shape. This shows that silicones were essential as they can withstand high pressures and deformations, unlike Tango Plus FLX930. This is due to the chemical bonds within the silicone, which gives it such a high elongation at break %. The deflected shape Figure 3 shows an almost perfect arch at the strain limiting layer. The top of the structure has deflected a large amount to produce this curve. The excessive inflation at the top and the curvature could be in the future controlled by adding an extra strain limiting layer at the top such as stiffer silicones or fabrics.

3 CONCLUSION

In conclusion, this paper has shown that there is a large market for inflatable structures in many different fields and their uses and capabilities have not been totally exploited. As mentioned by Oñate (2005), developments in manufacturing can be made in terms of using a knowledge-based industrial process with the latest IT tools, and studies in new lighter and cheaper materials are needed to allow better optimisation processes. It shows there have not been many attempts to FDM 3D print inflatables. Although all current digitally fabricated inflatables objects are very small, new innovations and developments are constantly happening to print new materials at bigger scales.

The main determinant is the ability to print in the required material at a large scale. Currently, there are many large 3D printers, which print buildings and aeroplane parts, cars and even buildings (ORNL, 2018; Post et al., 2017). Holshouser et al., (2013) says that “the size 3D printers can print is unrestricted". Although size must be paired with the correct material. ACEO, (2018) have successfully been able to 3D print in silicone. After testing the viability of 3D printing an inflatable structure from silicone, it can be amplified to a larger scale. Kow et al., (2018) have designed a novel fabrication technique that stacks thin layers of silicone, which is cut into pre-designed actuators. With advances in machinery and technology, such techniques can be adopted at larger scales.

Another very important aspect of a large 3D printed inflatable structures is its feasibility. This should consider the structure, safety and workability of the inflatable. Larger structures would require stronger materials or supports integrated within the design. Mindfulness of collapse mechanisms, fire protection, natural disasters and aesthetics need to be considered when designing and digitally fabricating these structures.

The aim of the work presented in this paper was to design and digitally fabricate an inflatable structure to assess its feasibility for being utilized at large scale in real life. This paper has optimised a design for inflatable structures and assessed two materials which were fabricated in different ways. Multiple attempts of modelling show that Tango Plus FLX 930, used through a PolyJet 3D printer, was not an adequate material to use for inflatable structures. Although, this does not mean an inflatable structure cannot be 3D printed already shown by (Clarkson, 2014; Peele et al., 2015; Patel et al., 2017). Silicones were successful where Tango Plus FLX 930 failed, showing a range of material that can be used for further optimisation. It also proves that new innovations can be integrated to successfully digitally manufacture inflatable structure and their application in the real world.

3.1 Further Research

Further research should be done on how to utilize elastomeric materials like silicone with digital manufacturing processes. Yirmibesoglu et al., (2018) have successfully created a 3D printer which mixes and heats silicone before being extruded in three-dimensions.

Tibbits (2016) shows the research done by The Self-Assembly Lab, which was established at MIT. The researchers there were successfully able to create programmable textiles in four dimensions. Programmable fabrics can be used to strain structures to achieve any required shapes. Examine and explore how fabrics within inflatables can enhance its structural and aesthetic properties. Embedded 3D printers can play a huge role in inflatable structures. Truby et al., (2018) has embedded sensors into soft robotics, which goes to say restraining materials can be embedded into inflatables to control their morphology.

Although, investigation is needed in the feasibility of how large 3D printed inflatable structures in the real world would exist and if they will be structurally sound.

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