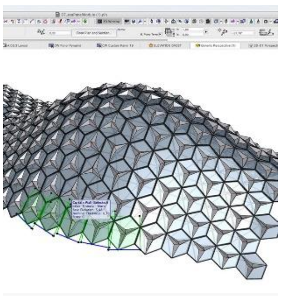
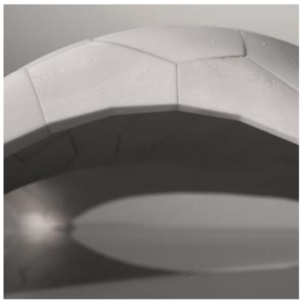
CIVE3750 – Individual Research Project

Aims and Objectives

Designing with digital fabrication – Free Form Shells



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Civil and Structural Engineering

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3.Introduction

Structures can be categorized in many ways according to their shape, geometry, function, behaviour and the material they are made of. (Adriaenssens, et al., 2014). The simplest way to describe a structural element is by its shape. A beam that has one dimension much larger than the other two dimensions can be defined by a straight line. A slab that has two dimensions much larger than the third can be described as a plane. An arch by a curved line and a shell by a curved surface.

Shells can be curved in one direction like a tower, or in two directions like a dome. And it is always thin in the direction perpendicular to the surface. The ideal shape for a shell structure is the shape that allows the structure to carry the loads by membrane action only without any bending moment. The mode of deformation in this case is called in-extensional mode of deformation, and the shell structure is called a funicular shell.

The word “funicular” comes from a Latin origin that translates into “slender rope”. A hanging slender rope adjusts its shape to carry its own weight without bending moments. Only tension internal forces exist (Figure 1). If the rope is to be reversed, the load will be carried entirely through compression internal forces and the shape would be called a catenary arch (Broughton & Ndumbaro, 1994). A concept that has been used by Antoni Gaudí for Sagrada Família basilica in Barcelona (Figure 2).

Figure 1: Hanging ropes by Antonio Gaudí

Figure 2: La Sagrada Familia, Barcelona

The catenary arches and uniform stress shells (in-extensional mode of deformation) are an optimal case that only applies in some cases especially where the self-weight of the structure is dominant.

However, this is not always the case in practice. In the real world there might be different constraints on the shape of the or different loading scenarios where the self- weight is not dominant. These constraints might arise from functional or aesthetic reasons and from the fact that forces like wind and snow might be significant depending on the structure material (Tang, 2015).

There are multiple methods used to obtain a shape for shell structures. Historically, some methods have been more common. Physical methods have been used to acquire a shape that resembles a physical object. The aforementioned “La Sagrada Familia” in Barcelona is an example of resembling a physical object, in this case a hanging rope.

Mathematical methods that require imagination and are only limited by the mathematical knowledge of the individual (Williams, 2000). However, mathematical methods produce differential equations that are very difficult to solve unless the structure is simple (Zingoni, 1997).

Modern shell structures generally have high strength to weight ratio due to the use of more advanced materials than materials available historically. The advancements in building materials field allowed for materials like concrete to be used in shells. Thin concrete shells and timber shells are much more common than masonry shells and arches (Zingoni, 1997). The use of such materials with high strength to weight ratio raises the need for new design methods that take into account out of plane deformation and bending moments.

The previous methods are called form-finding techniques. Form finding is the process of obtaining a structural geometry for a mechanism to carry a certain load (Williams, 2000). However, the constraints and loading cases of the structure might render the previous methods inefficient or simply not feasible. The solution is to use a free form shell, a structure that is formed by manipulating materials either physically or by computer. Computer software can be used to generate free form shells starting with a predefined shape (Figure 3). The shape provides a “constrain” for the software to follow and by manipulating the parameters, a shell structure can be obtained that resembles the initial shape (Harris, 2011).

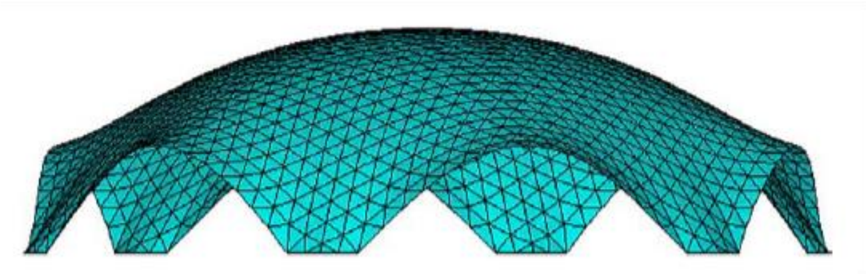


Figure 3: Hexagonal Free-Form shell supported on 6 corners (Vizotto, 2010)

Free-form shells is the term used to describe shells that have no geometric or mathematical representation. The ideal stress condition for these shells is pure compression (Vizotto, 2010). Providing the correct boundary conditions, it is possible to simulate the deformation of an isotropic material. This is the first step to produce a shell with the capacity to be planarized to combine 3D CAD design with form-finding techniques.

An advantage of a planarized surface for shells is that the shell can be broken down into small planarized pieces. These planar elements can be built from planar pieces of material or constructed using formwork with linear sides (Rippmann & Block, 2011). In addition to the recent growth in the additive and subtractive manufacturing techniques that open the possibilities for new designs of free-form shells (Tamplin & Iuorio, 2018).

Starting at a simple initial shape, using computer software to generate a free-form shell that follows the initial constraints of the shape provided after tuning some parameters. The process of planarization produces 2-dimensional panels that can be easily manufactured. This process of design is unique for each project. But in general, design is an iterative process where the findings of the last step can be fed into the parameters to optimize the design and produce a more efficient and sustainable shell structure (Figure 4).

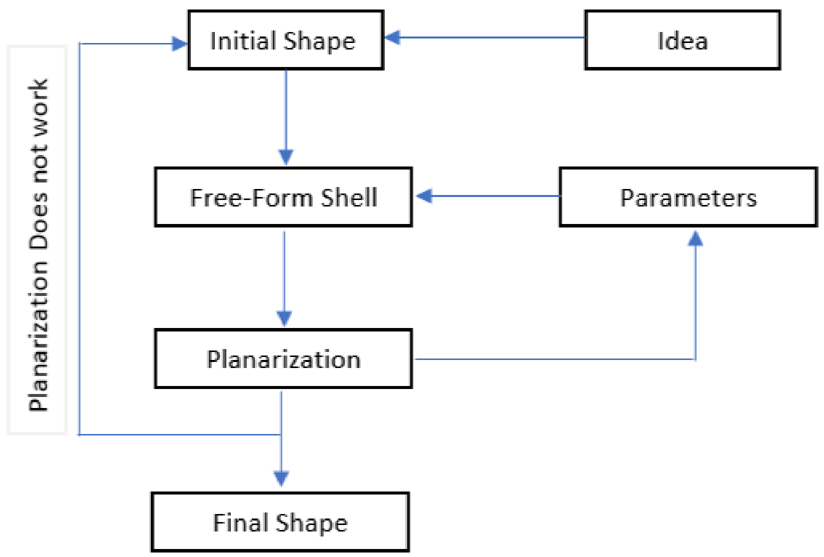


Figure 4: Simple design process

4.Aim

The aim of this project is to design a model of a free form shell using Rhinoceros® software and the plugin Grasshopper®. A tessellation and planarization process will be carried out using Kangaroo® plugin to investigate the possibility of generating a shell structure by using only planar panels made of 3-6mm plywood and 3D printed connections between the panels, made of ABS plastic or other material depending on the availability and capability of University of Leeds equipment.

Such a shell structure can be assembled and disassembled. And the possibility of scaling the structure will be investigated in order to meet the requirements for a competition held by the International Association for Shell and Spatial Structures (IASS-Structures) in Barcelona in October 2019.

The structure is made predominantly of 3-6mm plywood that will form a free form shell accompanied by 5 arches as shown in (Figure 5). The arches and the shell form a structure that has been submitted to IASS competition under the name ECHO.

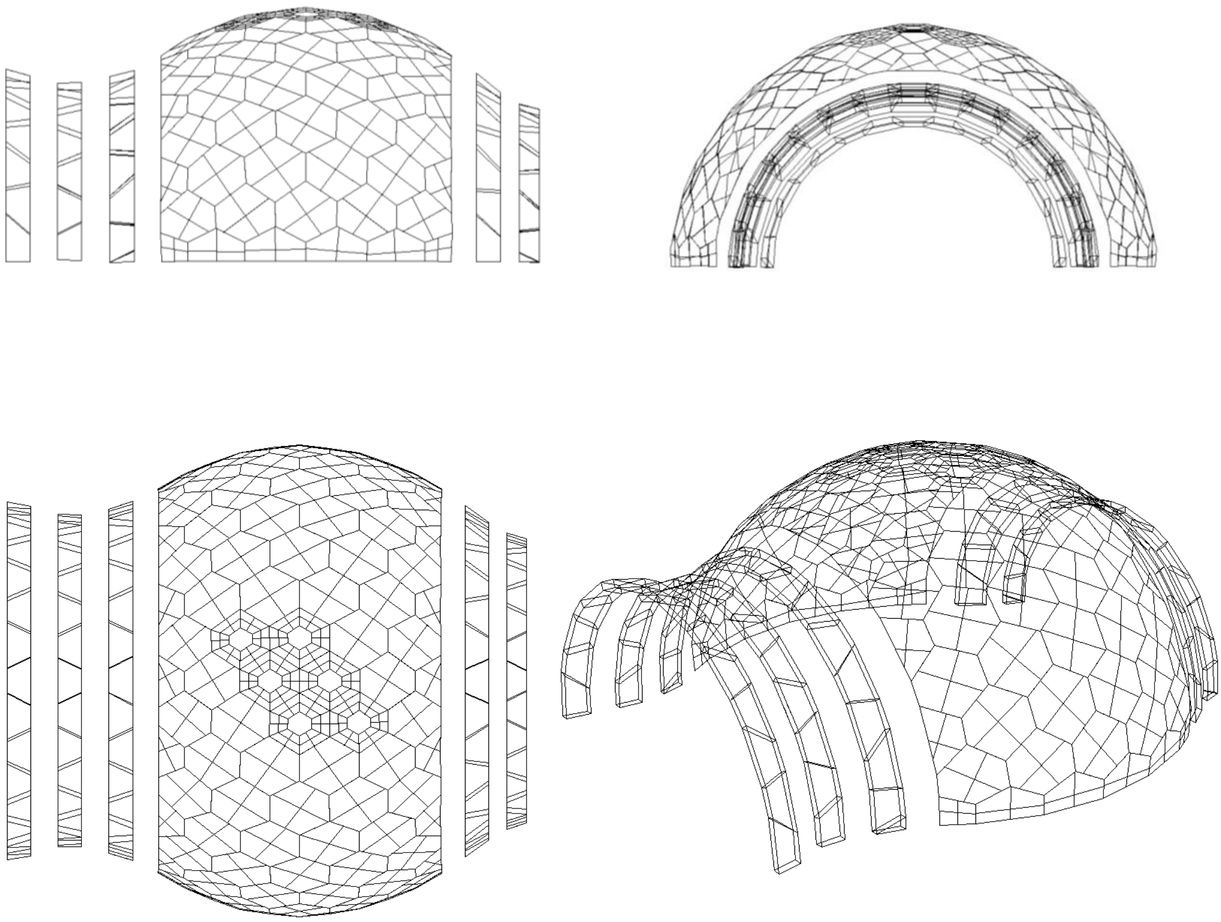


Figure 5: ECHO free-form shell

All individual panels are shaped as hexagons (Figure 6). The hexagons are not similar and should be numbered. It is possible to check the symmetry of the shell and the possibility of having one or two symmetry axes to make the process of manufacturing and assembly easier.

Figure 6: Overall ECHO shell after tessellation and planarization (3D visualization)

5.Objectives

I. Develop a free-form shell structure.

- Modelling of the shell structure in Rhinoceros®
- Tessellation and planarization of the shell and the arches using Grasshopper® and Kangaroo® plugins.
- Optimize the shell and tessellation process to improve constructability.
- Improve the design of the shell by assessing the possible symmetries.
- Produce a sample set of three adjacent panels to check the fit, angle and possible connection systems.

II. Develop a joining system for the panels

- Develop multiple joining systems using Autodesk Fusion360®
- Produce a G-Code and 3D print multiple sample connection.
- Determine the best joining mechanism and improve the design of the joints.

III. Scale the prototype to meet the requirements of IASS-Structures competition.

- The entire shell should be suitable for assembly and disassembly.
- The entire shell should weigh no more than 192 KG, has dimensions of no more than 4X4 m.
- The shell should fit in six boxes, each box weighs no more than 32 KG.

6.Methodology

I. Develop a free-form shell structure

The structure will be manufactured using plywood planar panels that are cut to shape using a laser cutter. The panels are hexagons with interlocking grooves to improve stability. There are slots at the point where three panels meet. The shape, size and direction of these slots will be determined by the final joint type. (Figure 7)

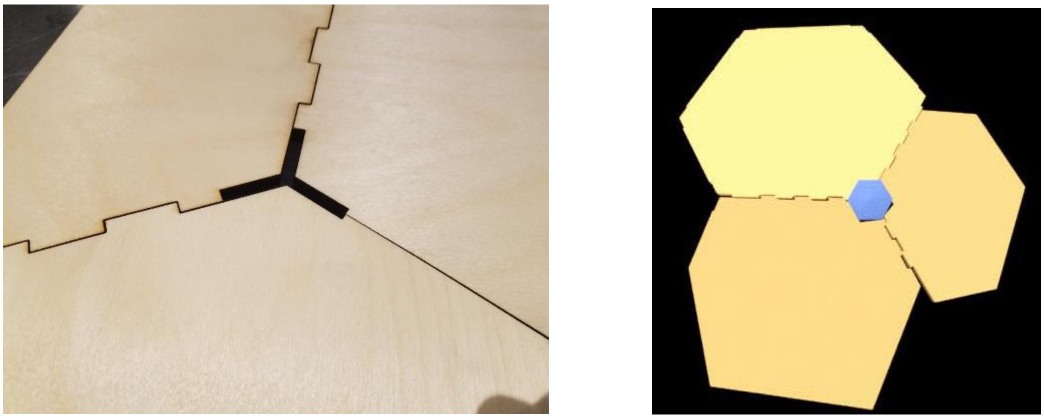


Figure 7: Laser cut panels

II. Develop a joining system for the panels

Multiple joining systems are being developed using Autodesk Fusion360 ®. The most efficient joint will be produced using 3D printing. The material choice for the joints will be determined based on the samples. ABS plastic or a more flexible material can be used to accommodate small errors that are bound to occur in the manufacturing step. (Figure 8) shows two of the connection types that are being investigated. There is a possibility of further changes to the design.

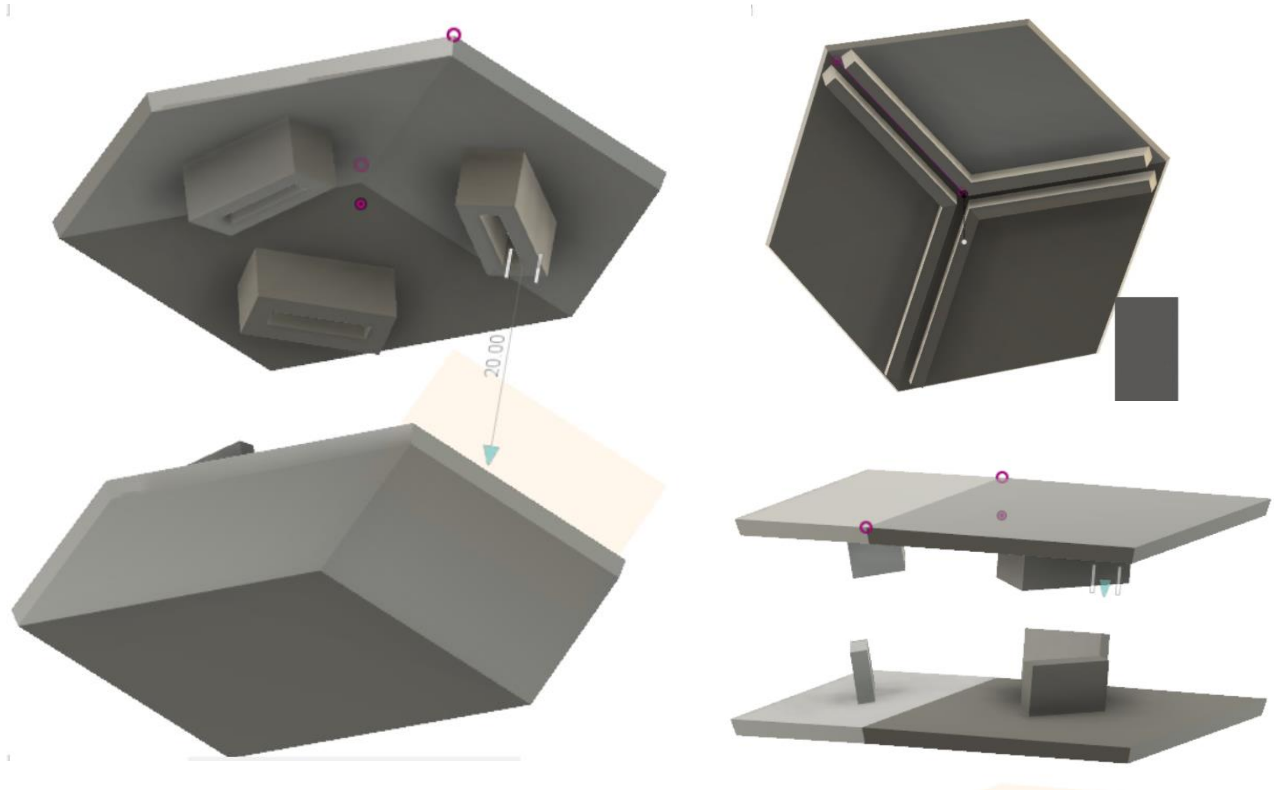
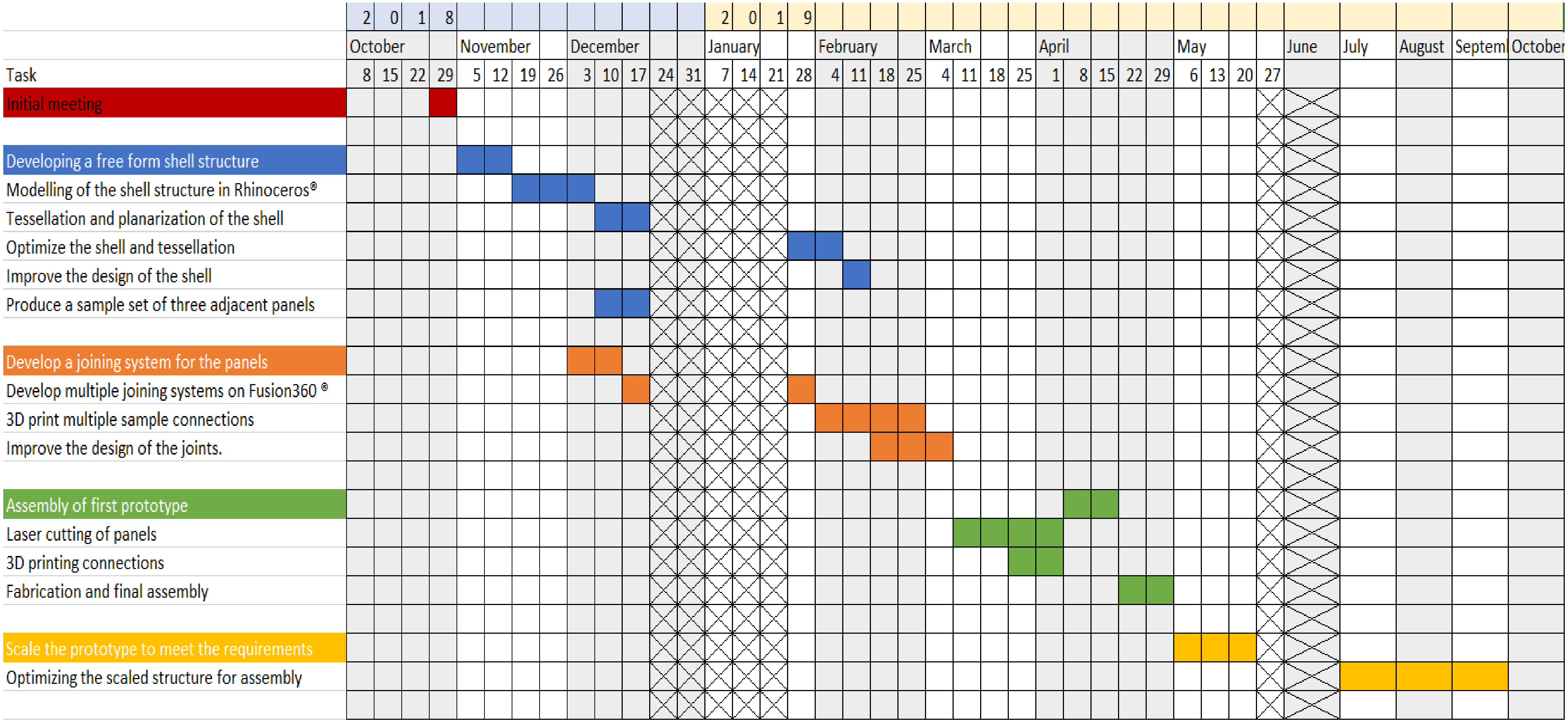


Figure 8: Connection types. Type A (Upper right corner), Type B (Left and lower right corner)

III. Scale the prototype to meet the requirements of IASS-Structures competition

Scaling the prototype involves checking the rigidity of the structure and the sufficiency of the connections to keep the structure safe and stable. The structure will not take additional loads but should be able to stand under its own weight.

7.Work Plan


2018
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Task
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Initial meeting
Developing a free form shell structure
Modelling of the shell structure in Rhinoceros®
Tessellation and planarization of the shell
Optimize the shell and tessellation
Improve the design of the shell
Produce a sample set of three adjacent panels
Develop a joining system for the panels
Develop multiple joining systems on Fusion360 ®
3D print multiple sample connections
Improve the design of the joints.
Assembly of first prototype
Laser cutting of panels
3D printing connections
Fabrication and final assembly
Scale the prototype to meet the requirements
Optimizing the scaled structure for assembly

8.References

Adriaenssens, S., Block, P., Veenendaal, D. & Williams, C., 2014. *Shell Structures for Architecture: Form Finding and Optimization.* London: Routledge.

Broughton, P. & Ndumbaro, P., 1994. *The analysis of cable and catenary structures.* London: Thomas Telford Services Ltd.

Harris, R., 2011. Design of timber gridded shell structures. *Structures and Buildings,* 164(2), pp. 105-116.

Rippmann, M. & Block, P., 2011. New Design and Fabrication Methods for Freeform Stone Vaults Based on Ruled Surfaces. *Computational Design Modelling,* pp. 181-189.

Tamplin, R. & Iuorio, O., 2018. *Challenges in designing and fabrication of a thin concrete shell.* Boston, International Association for Shell and Spatial Structures (IASS).

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Vizotto, I., 2010. Computational generation of free-form shells in architectural design and civil engineering. *Automation in Construction,* 19(8), pp. 1087-1105.

Williams, C. J. K., 2000. The definition of curved geometry for widespan structures. *Widespan Roof Structures,* pp. 41-49.

Zingoni, A., 1997. *Shell structures in civil and mechanical engineering.* London: Thomas Telford Publishing.

Ethics Approval Form - Students

This form should be completed by the student and passed to the supervisor prior to a review of the possible ethical implications of the proposed dissertation or project.

No primary data collection can be undertaken before the supervisor has approved the plan.

If, following review of this form, amendments to the proposals are agreed to be necessary, the student should provide the supervisor with an amended version for endorsement.

The final signed and dated version of this form must be handed in with the dissertation. Failure to provide a signed and dated form on hand-in will be treated as if the dissertation itself was not submitted.

1. What are the objectives of the dissertation / research project?

The aim of this project is to design a model of a free form shell using Rhinoceros® software and the plugin Grasshopper® and to participate in IASS competition in Barcelona in August 2019.

2. Does the research involve *NHS patients, resources or staff*? YES / NO (please circle).

   If YES, it is likely that full ethical review must be obtained from the NHS process before the research can start.

3. Do you intend to collect *primary data* from human subjects or data that are identifiable with individuals? (This includes, for example, questionnaires and interviews.) YES / NO (please circle)

   If you do not intend to collect such primary data then please go to question 14.

   If you do intend to collect such primary data then please respond to ALL the questions 4 through 13. If you feel a question does not apply then please respond with n/a (for not applicable).

4. What is the *purpose* of the primary data in the dissertation / research project?

5. What is/are the *survey population(s)*?

6. How big is the *sample* for each of the survey populations and how was this sample arrived at?

7. How will respondents be *selected and recruited*?

8. What steps are proposed to ensure that the requirements of *informed consent* will be met for those taking part in the research? If an Information Sheet for participants is to be used, please attach it to this form. If not, please explain how you will be able to demonstrate that informed consent has been gained from participants.

9. How will *data* be *collected* from each of the sample groups?

10. How will *data* be *stored* and what will happen to the data at the end of the research?

11. How will *confidentiality* be assured for respondents?

12. What steps are proposed to safeguard the *anonymity* of the respondents?

13. Are there any *risks* (physical or other, including reputational) *to respondents* that may result from taking part in this research? YES / NO (please circle).

    If YES, please specify and state what measures are proposed to deal with these risks.

14. Are there any *risks* (physical or other, including reputational) *to the researcher or to the University* that may result from conducting this research? YES / NO (please circle).

    If YES, please specify and state what measures are proposed to manage these risks.

There is a laser cutting process involved. The risk involved is damage to the laser cutting machine itself and possibly any personnel operating the machine.

To prevent any harm to property or person, trained staff will be present at all times during the machine's operation. In addition, all students who use the machine is are put through an induction to be made aware of all the precautions to take before cutting any materials.

15. Will any *data* be *obtained from a company or* other *organisation*. YES / NO (please circle) For example, information provided by an employer or its employees.

If NO, then please go to question 18.

16. What steps are proposed to ensure that the requirements of *informed consent* will be met for that organisation? How will *confidentiality* be assured for the organisation?

17. Does the organisation have its own ethics procedure relating to the research you intend to carry out? YES / NO (please circle).

If YES, the University will require written evidence from the organisation that they have approved the research.

18. Will the proposed research involve any of the following (please put a √ next to 'yes' or 'no'; consult your supervisor if you are unsure):

• Vulnerable groups (e.g. children) ?	YES		NO	√
• Particularly sensitive topics ?	YES		NO	√
• Access to respondents via 'gatekeepers' ?	YES		NO	√
• Use of deception ?	YES		NO	√
• Access to confidential personal data ?	YES		NO	√
• Psychological stress, anxiety etc ?	YES		NO	√
• Intrusive interventions ?	YES		NO	√

19. Are there any other ethical issues that may arise from the proposed research?

None

Please print the name of:

I/We grant Ethical Approval

student [redacted] supervisor ____________________

(supervisor) [redacted]

Date [redacted]