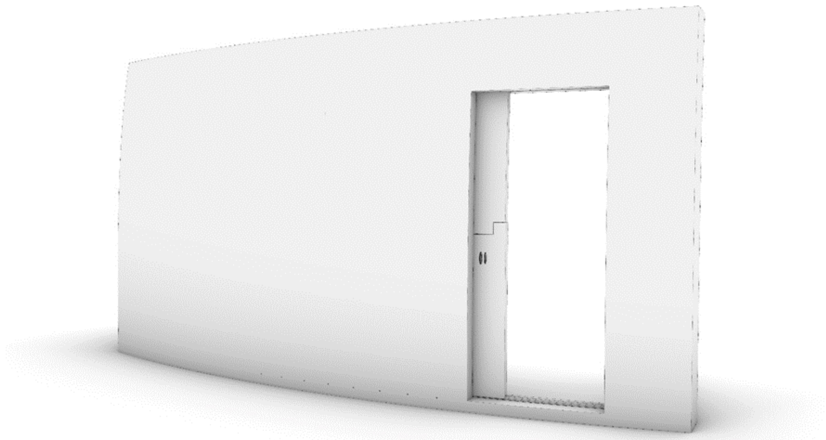
Opening the bottle:
designing openable surfaces
in a mono material construction of recycled PET



Master Thesis TU Delft

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Preface

This research on mono material construction took place under highly exceptional circumstances. In the midst of the covid-19 global pandemic. Following Delft University's policy I was given the choice at the start of lockdown to shift this design research using PET materials into a purely theoretical research making use of simulation models only. My decision was to continue the original plan, while changing the intended tests of the full scale prototypes into several tests of smaller units of the prototype. Since the lab with printing facilities and robotic arms was no longer available, I was given the opportunity to temporarily take one of the printers with me to my student home, providing me with a noisy and stubborn roommate for several months.

Nevertheless, looking back I do not regret this choice to stick with the physical testing route, for two reasons in particular. Firstly, the opportunity to work with and test large scale prototypes was what motivated me to join this graduation track in the first place. Making and testing real things instead of just simulations is something I believe to be essential to the design process, notably for the type of architectural engineer I want to become. Secondly, since mono material construction is such a new field of research, I had my doubts whether a 100% theoretical research would bring representative results. And indeed, when looking into structural simulations in the later phase of my project, I repeatedly ran into the limitations of available simulation programs. The fact that I had to work within the limits of student licenses, forced me to translate intended simulations into an approximation of an approximation, making it really difficult to confidently corroborate the claims following from my design research. This reminded me that simulation is indeed just that: simulation. Finishing this report would not have been possible without the expertise of my mentors Fred Veer and Paul de Ruiter, with special thanks for the continuous emotional support from Paul during the writing process under these difficult conditions.

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1. Introduction

This report embodies the research done for the sustainable graduation studio for the faculty of architecture and the built environment at TU Delft. The chosen graduation studio ‘Living in a bottle’ tackles the current non-sustainable material usage in the building sector. Nowadays building materials are extracted from nature and either thrown onto landfills or down cycled after use. The studio investigates possibilities of mono material construction using waste stream materials, in order to create a closed material chain for the building sector. The general research question for this studio was: “How will a mono material (PET) design of a small building define the goals, variables and constraints in the computational design process, also taken into account the high volume additive manufacturing process?”. The specific task for this research project has been to design a printable openable surface for the mono material tiny house envisioned in the studio.

Chapter 2 describes the context for the general studio assignment and states the research question for this particular project. Chapter 3 summarizes the preliminary research on types of movement for openable surfaces and gives the results on material-tests for recycled PET. Chapter 4 states the design-criteria which followed from the preliminary research. Chapter 5 describes the design process using FEM simulation. Chapter 6 focuses on the fabrication by means of additive manufacturing: after describing the calibration process, small scale physical tests have been conducted on the printed products. Chapter 7 takes a step back and analyses the structural capabilities of the entire design using simulation software (finite element method in ANSYS). Chapter 8 and 9 contain conclusions and reflections.

2. Research framework

In 2008 the European Union created Directive 2008/98/EC also known as the Waste Framework Directive, in this directive it is stated that by 2050 more than 50% of all household waste and 70% of construction waste should be reused or recycled (European commission, 2008). In the Netherlands it is estimated that 40% of all waste is generated in the build industry through either construction, renovation or demolition. Making it the sector that produces the most waste (Koutamanis et al., 2018). Up to 90% of the building sector waste consists of stone, brick and asphalt, the other 10% contains plastics wood and metal. Due to the relative ease of extraction, value, regulations and social involvement, metals appear to be in a closed-loop waste system. For example: 95% of the stone, brick and asphalt construction and demolition waste is getting crushed and reused as road base material (Bodzay & Bánhegyi, 2016). This is a method of down cycling which does not reduce the need of high-quality stony materials for future constructions. And the end-of-life use for the road base material is non- existent as it will end up as waste. Hence down-cycling extracted materials from the building sector is not an efficient way of recycling. The goal would be a closed cycle construction sector (Bodzay & Bánhegyi, 2016), in which the materials are either recycled or up-cycled, thus having the same properties as before their use or be useable for products of better quality and environmental value. In this way high-graded materials will be recovered and reused, the need for new extracted materials will be reduced, and waste production will end. Transitioning to mono-material construction would potentially be a great way to approach such a closed cycle, as will be elaborated below.

2.1 Problem statement

The building sector is currently exhausting natural resources and it burdens the environment with waste. Material usage in the building sector is unsustainable. Although means have been taken to extend the lifespan of the materials through down-cycling, more effort has to be put into closing the material cycle. Innovation is needed since the current way of construction does not allow for materials to be properly recycled: different types materials are joined together in such a way that separating them is too time intensive and/or expensive. Roughly three innovative ideas are currently being researched worldwide:

1. The use of a material passport to create more value for the used materials and thus making it a worthwhile investment to properly extract them. The idea behind the material passport is to view buildings as material banks. By describing defined characteristics of materials in the building, these materials are given more value for recovery, recycling and re-use. (Heinrich & Lang, 2019).
2. Design for disassembly. When buildings are designed for disassembly, rather than demolition, larger portion of building materials could be reused. In such a scenario, the embodied energy would be recovered along with the materials, reducing the total energy requirements of the built environment.(Crowther, 1999, p. 98)
3. In the graduation track 'Living in a bottle' of which this research project is a part, we explore potentials for a third innovative idea: mono-material construction using waste-stream materials.

The problem statement for projects in this graduation track has been set as follows: explore for a pre-given waste stream material (PET), the uses for mono-material construction of a tiny house, using additive manufacturing techniques. The reasons for choosing a tiny house are briefly that this allows all research projects once finished, to be executed in combination in a full scale model, leading to a physical showcase illustrating the potentials of mono material construction and additive manufacturing to the building sector. Note that currently there is no nation-wide definition of 'tiny house' in the Netherlands; for this graduation track we assumed a residence with 28 m^2 interior space.

2.2 Research Objective

In the problem statement a number of elements for the design process have already been indicated; these elements will be elaborated here as research objective by answering four questions:

- Why mono material?
- What is required to replace multiple materials with different forms with a single material?
- Why chose PET as mono-material?
- Why chose additive manufacturing (AM) as production technique?

Why Mono material?

As stated above, multiple innovative ideas are being researched which could help to create closed material cycles. The idea behind mono material construction is to tackle the phenomenon that nowadays, every function of a building-envelop is being fulfilled by a different material. For example, in a typical wall constructed for housing today, separate materials are used for structure, thermal insulation, water vapour barriers and aesthetic façade. This multitude of materials becomes an issue when the building is demolished: separating the materials then becomes too time consuming and costly to be economical, minimizing chances of recycling. Here the most radical solution for this issue is explored: to reduce all materials back to one.

This principal of mono material has found its way into the consumer industry already, from mono material clothing to packaging, making the products easier to be recycled. For the building industry however this is a difficult approach because of all the functions and criteria that we have for our living environment. The main reason that so many different materials are used in the construction of a house is that these materials perform different functions. In the case of a mono material construction all these functions need to be performed using one and the same material. This brings with it a lot of design challenges that will lead away from conventional building methods.

- What is required to replace multiple materials with different forms with a single material?

Due to the chosen limitation of a single material, there are no specialised materials chosen per function. However, as designers we are able to shape the selected material to the desired function. This means that the functionality needs to be generated through geometry. A common example of this practice is corrugated cardboard which gets it strength form the corrugated sheet in between the two linerboards. In the field of construction, at the TU Delft research has recently been initiated into how geometry can facilitate function, by means of the 'Sponge 3D' project.

Spong3D is an adaptive 3D printed facade system using PET. It consists of an outer and an inner system that are both optimised for FDM 3D-printing. It integrates multiple functions through its geometry to optimize thermal performances in response to different environmental conditions throughout the year. The outer part allowed liquid to be pumped around for active heat storage when needed, while the inner part consists out of a series of air cavities that provide thermal insulation (Sarakinioti et al. 2017).

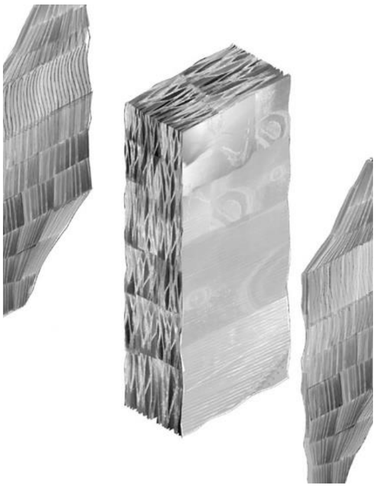


Figure 1 Sponge 3D, image sourced from Sarakinioti et al, 2017

However, Sponge 3D offers much more than an informative example: for this research the inner part of the sponge 3D has been chosen as the standard for creating thermal insulating properties of closed surfaces. Hence it will be assumed from here on that all the walls of the tiny house will consist of PET with an internal geometry similar to Sponge 3D. using the available 1 to 1 scale prototype as a guide, a wall thickness of at least 330mm was measured and also applied for this project, in order to assure sufficient thermal insulation.

Another function which can be achieved through geometry concerns structural capabilities. When considering the mono material approach and AM production methods for constructing both walls and ceilings, several options come available to increase the structural capabilities of the tiny house. This is all the more important given the choice of PET rather than steel or brick. The assumption has been made that the wall containing the openable surfaces will be a multi curved surface. The reason for making this assumption is that the shape stiffness of walls increase when one applies curved geometry.

- Why PET as choice of mono-material?

The studio assignment proposed the use of PET as mono material. A number of reasons are available for choosing this material, even though it is currently not widely used in construction.

First and foremost, PET can be acquired from current consumer waste streams. In a research done in December 2011 it was found that out of all the waste polymers 13% was PET (Jetten, Merkx, Krebbekx, & Duivenvoorde, 2011). That same research found that over 65% of the plastic waste in the Netherlands was burned instead of being reused. By using PET as the material for the mono material construction we can not only make a closed material loop but at the same time reduce a current waste stream, up-cycling the material that is mostly known for its use in single use consumer packaging.

Secondly, PET can easily be used in time-efficient and mass production techniques: in can be applied in additive manufacturing by means of fused deposition modelling (FDM)

It must be taken into account that there are also known weaknesses for using PET as building material. Notably a PET building will not be able to meet fire safety standards. And in general, PET does not perform well under high temperatures. Currently there is no solution for this problem. However, this issue was left out from the research conditions at the start of the studio-assignment. Another known weakness of all polymers is their relatively low UV resistance. Degradation by ultraviolet radiation from sunlight, is imminent. However, after this type of damage has occurred, this can be restored for PET through chemical processes.

- Why use AM as production technique?

In the building industry, automated, cost efficient production techniques for mass volumes are generally preferred, for example in pre fab building methods. Compared to this method, additive manufacturing (AM) offers extra advantages which are also relevant for this particular research project. Firstly, AM allows high freedom of form. It enables production of complex geometry. Secondly, unlike prefab, AM allows mass costumisation: tailor-made adaptations are easily applied.

A third advantage, highy practical for the industry, is that fabrication on location is possible with AM, for certain printing materials. However, this does not apply to PET since this material needs constant environmental temperature during the printing process.

2.3 Research question

The main research question of this particular project is as follows: “How can an openable surface be included in a mono material 3D printed tiny house, using FDM 3D printing?”

As stated before this research will be looking into one of the challenges that a mono material construction has to face, namely the openable surfaces. The openable surfaces are the components of the house that give us access to the indoor and outdoor and or the separated interior spaces. The openable surfaces need to be capable of serving a similar function as the wall they are a part of to a certain extent while allowing passage for people as well as for outside air when the user of the house requires it.

With the sub questions being:

- How can geometry allow for a surface to be moved?
- What are the criteria for an openable surfaces?
- What are the physical and structural properties of recycled PET?
- How can one optimize geometry for large scale 3D printing?
- How does a 3D-printed openable surfaces hold up under use?
- How does the openable surfaces connect to the structure of the 3D printed tiny house?

2.4 Methodology

The methodology of this research project will focus on prototyping and mechanical testing. By the following steps:

- Literature research

Looking ate existing literature will give insight into the possibilities and limitations of 3D printing. As well as options of how the door will be made openable.

- Design process

From here on, the design criteria found in the literature study will be applied to the 3D printed door. The structural properties will be analytically tested using FEM

- Prototyping and physical testing

After the FEM results are satisfactory a small scale prototype was to be printed and tested using a robotic arm to see how the door would hold up under extended use. This information would then be used to tweak the design and a full scale prototype would be printed and tested. See Figure 2.

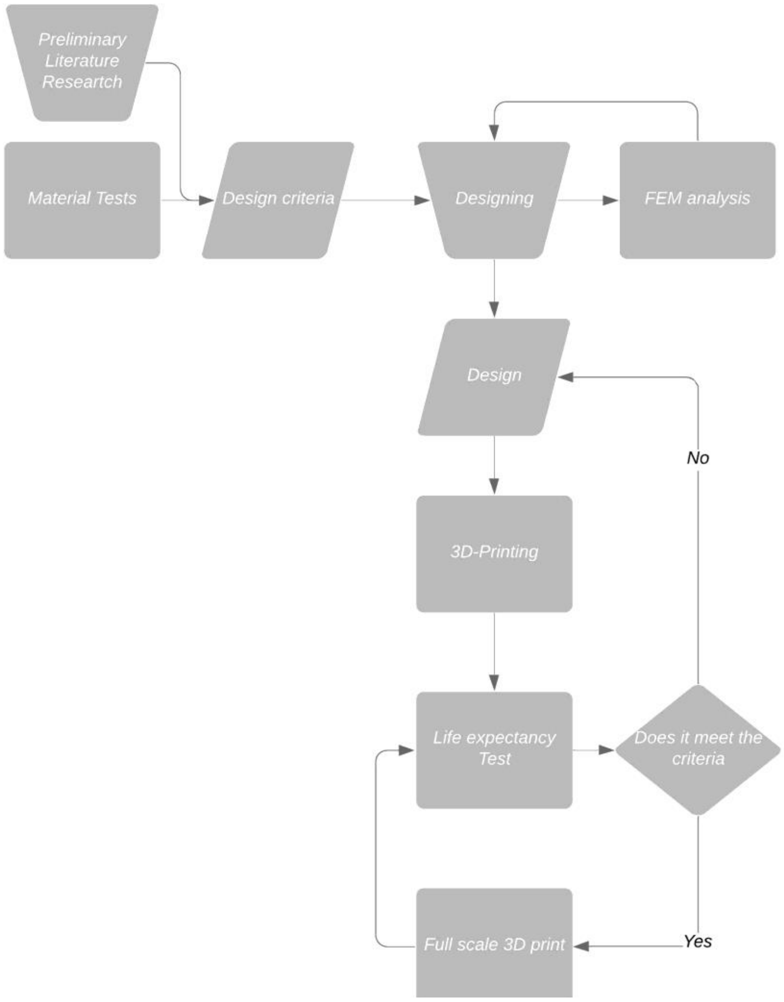


Figure 2. Proposed flowchart for the research at start project

Deviations from the proposed flow-chart:

Unfortunately the Corona-Lockdown started during the design phase. As a consequence, life expectancy tests could not be executed in the lab using the robotic arm; instead small scale tests were done at home, as was all 3D printing for tests on segments of the prototype. No full scale prints could be produced in these conditions.

To make up for these setbacks, the proposed FEM analyses have been executed more in depth.

2.5 Relevance

The idea behind this graduation project is to push for innovation in the building industry which is known to be extremely slow to change. By going into an ‘uncertain’ future scenario we can push the current knowledge and usage of common materials such as PET in a new direction. Through the choice of the mono material limitation the need is created to truly push the limitations of the material. Forcing the material to take on tasks it is not perfect for makes it so that we as designers need to step out of our comfort zone and use different means to get the intended result. Because in a mono material design, form makes function.

This project combines design with a technical approach, taking into account fabrication and function. The challenge of using new materials and utilizing innovative production techniques resulting in anisotropic structural properties, make this project fitting for the Building Technology master.

3. Preliminary research

Preliminary research was done on possible ways of opening surfaces (3.1) which then focused on movement types (3.2), after which a material analysis was done on the proposed material PET (3.3).

3.1 Functional analysis of openable surfaces

The first research that was done was to look into the current methods used to open surfaces. When thinking about openable surfaces in the current building industry the two things that come to mind are doors and windows. The assumption is made that a door and a window share their primary function and that a ‘primitive’ version of doors and windows have the same build and components. The main focus of this research will be on designing an openable surface that functions as a door would (follow-up research on openable surfaces might then look into the possibilities of creating more modern mono material window versions, like turn/tilt windows).

A common door consists of a frame, threshold, panel, handle, and a component that facilitates the movement. This element can be hinges a guiding rail or a large pivoted bearing. These components work together to facilitate the following functions:

- Structural connection to the wall
- Closing off the surface
    - Blocking wind and rain
    - Preventing draft
    - Stopping dust from entering
- Closing/locking mechanism
- Movement

In the case of a front door there are even more functions, such as an obligated level of fire resistance and a level of resistance to burglary. In this project, these functions were left out of the research, this was already mentioned above regarding the first point of fire-safety; the second was left out because design of this function was considered to be largely dependent on other decisions still to be made such as on structural features. A similar decision was made on assembling and disassembling the openable surface; considerations on this last point have been postponed to the final stage of the design. Finally, regarding the size of the openable surface of the tiny house the decision was made to maintain standard size values confirming to current Dutch building regulations.

Due to how new the chosen material and fabrication method are it was decided that the focus of this research will be on the movement, the structural connection, and the closing of the surface. The most prominent of these three functions and the one that has the largest implication on the rest of the tiny house is how the openable surface moves. Because this is both the main means of connection to the wall and source of constraints for the design process.

3.2 Movement types

Three general types of movement

There are in general three types of movement that are used for doors and windows: Hinged, rotating/pivoting, and sliding. As seen in the images below. Although the intended opening surfaces of this project will be multi-curved, the movement types generally remain the same.

Figure 3. Door types hinged, pivot, sliding

A hinged door is the most commonly seen type of doors, through the use of two or more hinges the door rotates with its point of rotation being to the side of the door panel itself.

A pivoting door is a more modern variant that turn on a most commonly metal axis inside the door panel, this type of door is mostly seen in modern luxury housing as it requires more area as the door remains in the doorway.

A sliding door can be either standing or hanging and is mostly used for indoor use or to connect the indoor to private outdoor spaces such as a terrace or garden.

There are also door types that combine two of the general means of movement. Folding doors for example use both hinges as well as guiding rails to slide the panels out of the way. Note however that the complexity will increase greatly when multiple movement systems are combined.

A fourth type of hinged movement: pop-out

Looking outside the building industry we can see a couple of other possible ways to open a surface.

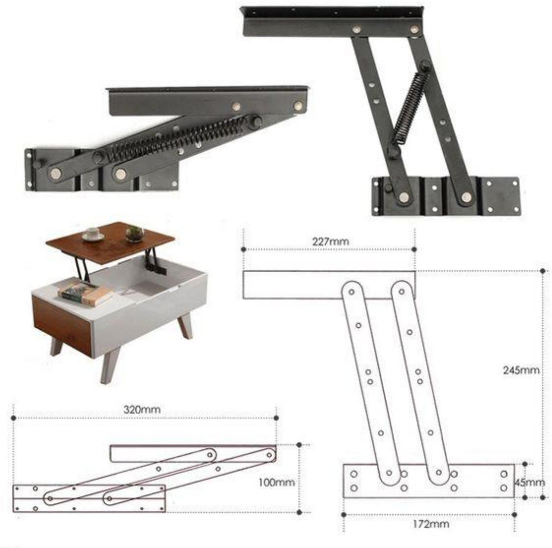


Figure 4. pop out hinges

A potential example can be found in furniture, these spring loaded hinges allow for a surface to be moved in two axes. With a physical stop to hold it into place at the top. The spring is there to help with the movement against gravity, reducing the force that needs to be applied by the user. In the application of a door this same system could potentially assist in the opening and closing as the springs would help initiate the movement. One of the concerns however is that the entire weight of the door would come to rest on the arms extending from the hinges. A second concern would be that this system more than doubles the needed amount of points of rotation. Thirdly, more moving components might require more maintenance. To sum up, the preliminary research into these special hinged systems leads to the conclusion that simplicity of the connecting system may be a good design criterion for designing a mono material opening surface.

Comparison between the four types

Taking these four types of movement into consideration a test was done by 3D modelling these, to see if these movement types could work as they were for a multi curved complex wall. For the results see figure 5. For all types modelled, the door panel is positioned in the centre of the wall. Subsequently, movement for each type of panel was added to the program, as performed manually.

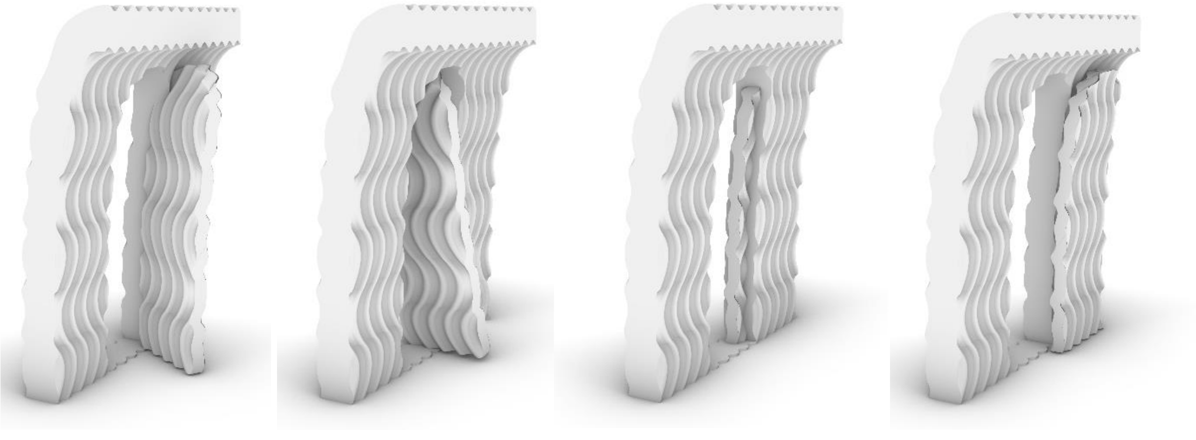


Figure 5. 3D geometry test of the movement systems

From this simple test in the 3D model it became apparent that a standard hinge system would collide with the curved wall structure if the surface opens towards the inside. The pivot system could work but the opening would need to be significantly larger (suggested by the middle picture of figure three above), which is not preferred in a tiny house where every m^2 counts. In addition, both these systems would run into building code issues if they were to move outward. According to Dutch building code article 2.76 it is stated that no moving part is allowed to turn over public space, such as roads and sidewalks.

Both the sliding system and the 'pop-out' system appear more plausible given the conditions of a curved tiny house. A sliding system would require to change the wall slightly to facilitate the panel to be moved in relation to the wall. However, as the entire tiny house will have to be constructed using FDM printing, creating such a space should not be too large a challenge. A 'pop-out' system could function, however it would require more components to facilitate the movement thus increasing the room for error.

To complete this comparison of movement types it is therefore important to consider the literature on possible ways to limit the number of components needed for movement.

Two types of research on hinged movement with limited components: flexures and compliant mechanisms.

Homogenous structures that transfer motion, force and energy without traditional hinges are generally termed flexures. If applied with a specific purpose in mind, a flexure is part of a so-called compliant mechanism. Hence if an object bends to perform a 'useful' function, it is then called a compliant mechanism. Two related types research found in the literature merit a closer look.

1. Over the years, Prof. L. Howell at Brigham-Young university (USA) has done much research into these mechanisms (Howell 2001, Howell 2015). Compliant mechanisms allow for movement through controlled bending of areas in the geometry thus reducing the amount of parts needed. An additional advantage of compliant mechanisms is that they are scalable, allowing them to be applied on microscopic scales, for example in nano sized mechanisms applied in the medical field. However, compliant mechanisms have strict conditions for the materials that can be used: these need to have both a high Young's modulus and a high yield strength. The two ways of confirming if a material can function as a compliant mechanisms are therefore either to calculate the ratio of strength to Young's modulus or to determine the so-called resilience factor (Howell, 2015). Unfortunately, both these calculation methods do not in themselves produce a baseline criterion for specifying whether a given material would be useable for the required movement as a compliant mechanism.

2. A second research group on movement components, specifically for mono-material projects is located at the Hasso Plattner institute in Germany. Their research paper from 2016 showcased a door handle and latch that were produced through additive manufacturing, following their research into so-called ‘metamaterial mechanisms’. These metamaterials can be programmed with a specifically designed internal microstructure, to allow controlled deformation in response to force (Ion et al., 2016). This deformation builds upon the principles found in the compliant mechanism research described above.

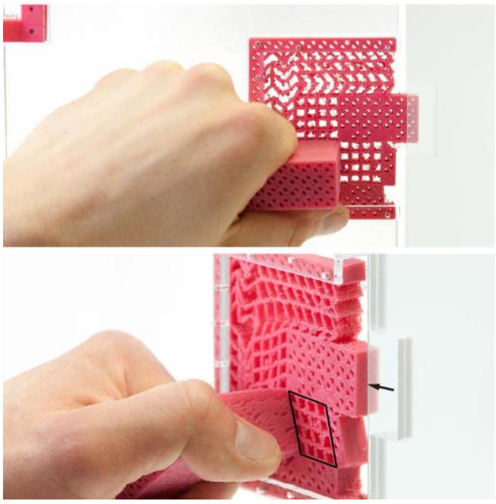


Figure 6. material door handle and latch (Ion et al., 2016)

In sum, both types of research described above indicate that it is possible to apply the hinged opening system using limited components, more specifically, internal components which facilitate the movement themselves.

Preliminary test of hinged movement using PET

To test if PET is a material that can be used for the production of compliant mechanisms using the hinged system of movement, a bi-stable switch was printed using a STL file provided by Brigham Young University on a FDM 3D printer with recycled PET as filament. The print did function for a short period of time until the material fatigue broke the delicate flexure connection between the solid parts as seen in figure 7.

this test suggests that PET is unfit for use as a compliant mechanism. However, this result could also be due to the 3D method of fabrication used in this test, because re-heating the material might have caused new material stresses in the print.

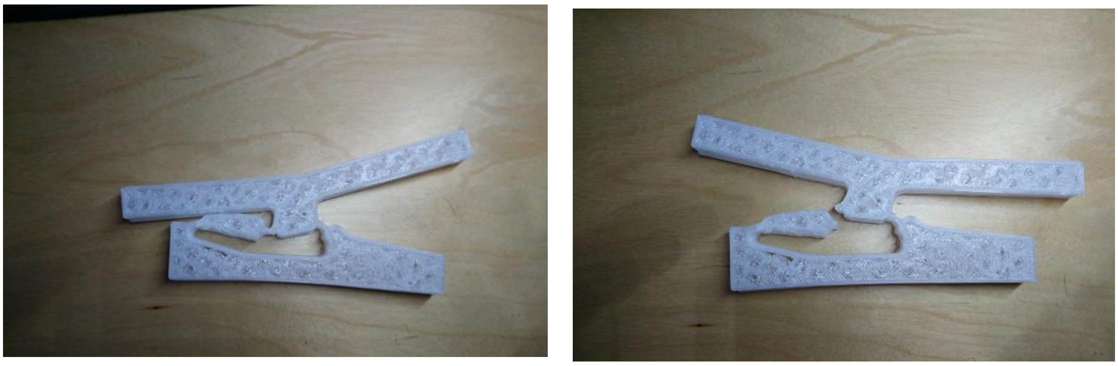


Figure 7. Flexure connection in PET before and after failure

Conclusion 3.2 on movement types

To conclude the preliminary research into potential movement systems for the moveable surface, the following points can be made.

- From the initial 3D models it was clear that both the standard hinged and pivot system would collide with the curved wall if the door opens inward (and outward movement is not allowed by building regulations).
- A pop-out system would be possible with curved walls, but this would have to consist of multiple components, increasing the complexity of the mechanism.
- An overview of the literature suggests several possibilities to limit the amount of components required for hinged movement through flexure connections; which in theory would be ideal for the mono-material design approach of this project.
- After preliminary testing PET material with a simple compliant mechanism, it can be concluded that due to its low thresholds of plastic deformation, PET does not possess the material properties needed for such an application.
- After elimination of the other three options, a sliding system remains the best option, and meets the conditions for a front door opening system set by Dutch building regulations. Thus making a sliding system the resulting candidate for this particular research project.

As a final note, be reminded that Dutch fire regulations do not allow for a common sliding door to be the emergency exit as stated in article 6.25 thereof. This is due to there being a lack of guarantee that the system will still function in the case of a fire. Again, for this research fire regulations have been kept out, as the prescribed material PET itself does not function at high temperatures.

3.3 Preliminary material tests with recycled PET

PET has been around for many years now, the first plastic bottle created from this material was patented in 1973 (US Patent *3733309,* 1973) and has seen many other applications since. However none of the applications designed thus far can be compared to what we attempt to do in the design of a PET tiny house.

Because the goal is to use recycled PET it is very important to perform preliminary material tests to better understand the material.

90% Recycled PET material tests

To test how recycled PET would function structurally a three point bending test was performed. This would make it possible to check some of the mechanical properties of a 3D printed element using recycled PET as filament. This test also allows it to check if the mechanical properties as stated by the producer's data, remain true after printing.

To perform the bending test a set of twenty samples was produced using FDM printing, using the slicer software's spiralisation option better known as vase mode. Allowing the geometry to be produced in a continuous motion instead of having separate z movement for every layer.

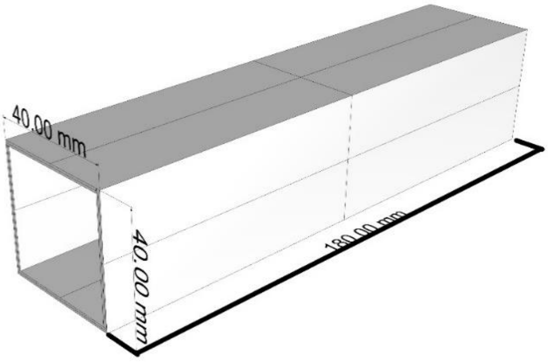


Figure 8. Material sample measurements

The printed samples had a 40mm by 40mm hollow square cross section with a wall thickness of 1.4mm and a total length of 180mm, as seen in figure 8.

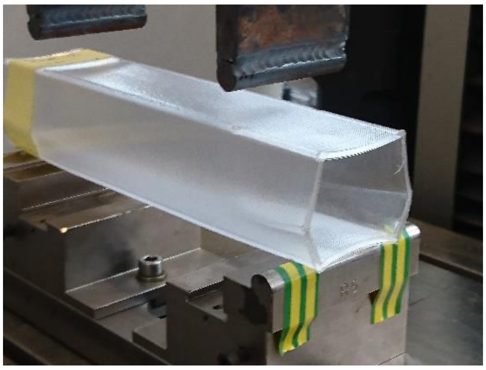


Figure 9. Deformation as result of the four point bend test

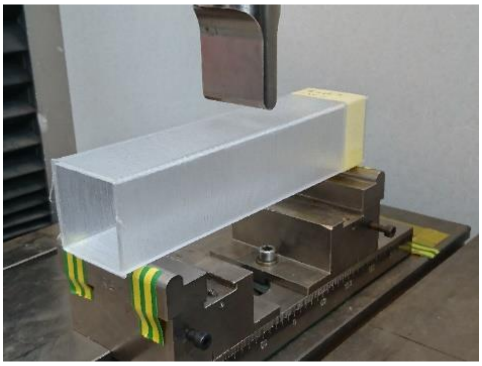
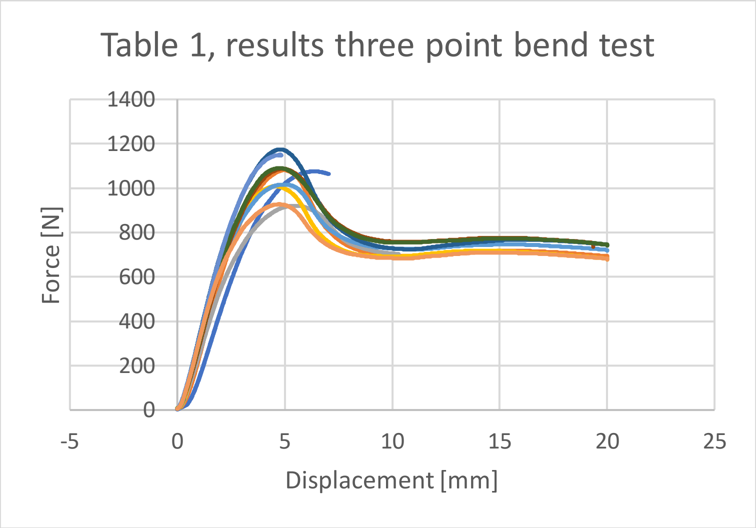


Figure 10. Three point bend test

A bend test was performed to determine the young's modulus of the recycled PET.

Out of the twenty samples printed, fourteen were placed in the three point bend test; at first a four point bend test was attempted but the length of the samples made it so that the distance between the supports and the application of force was too small to have a valid result. The samples were being squeezed together at the ends, instead of bending in the middle. The physical result of which can be seen in figure 9. The test was then switched to a three point bend test as seen in figure 10.



CES virgin PET (unfilled, semi-crystalline)	2760 – 3100 MPa
Recycled PET(Ultrafuse rPET)	1334 – 1640 MPa
Calculated based on 3 point bend test	600MPa

Results: during the bend test the applied force and displacement in the Z axis were measured. These were used to calculate the Young's modulus of the PET by rewriting the deformation equation for the corresponding load case $\delta x = \frac{P\times l^3}{48\times E\times I}$ into $E = \frac{P\times l^3}{48\times \delta x\times I}$.

Calculating the average young's modulus from the 14 samples gave us a Young's of around 600MPa. Comparing that to the given results from CES material library for virgin PET and the mechanical properties given by a recycled PET producer we can see that the result is more than two times lower than the producer specified.

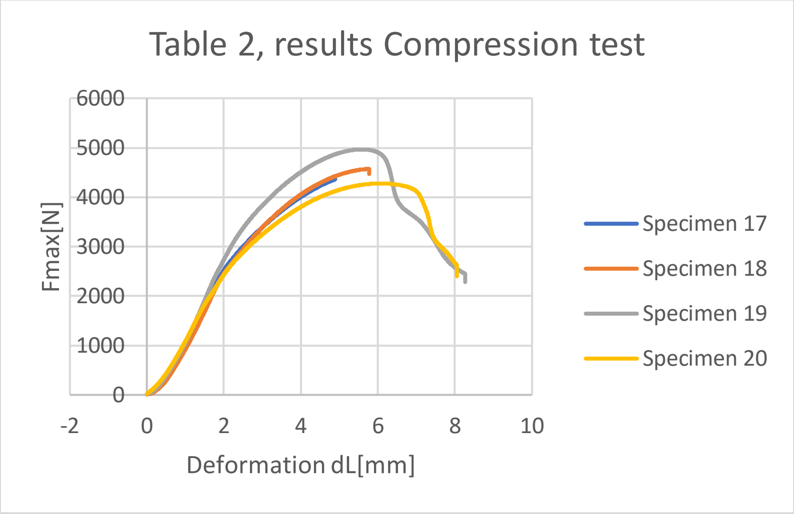
Figure 11. Deformation resulting from the three point bend test

This difference can be explained by examining the samples.

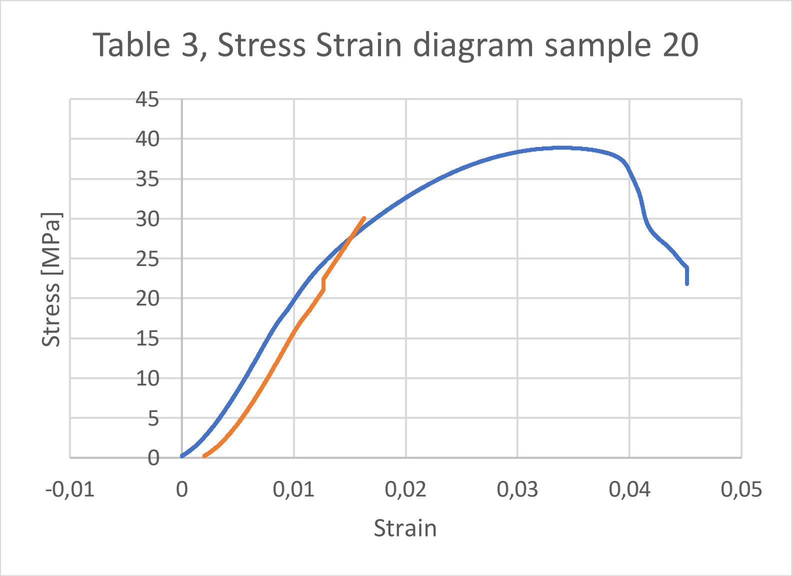
As seen in figure 11, the samples did not deform solely in the Z axis, making it so that the measured deformation and force do not relate as is required for the used equation.

The final four samples where used in a compression test, this was done to observe how the samples reacted to force applied in the same axis as the layers are stacked in.

With this test we were able to calculate the elastic limit, yield point/strength, and compressive strength.



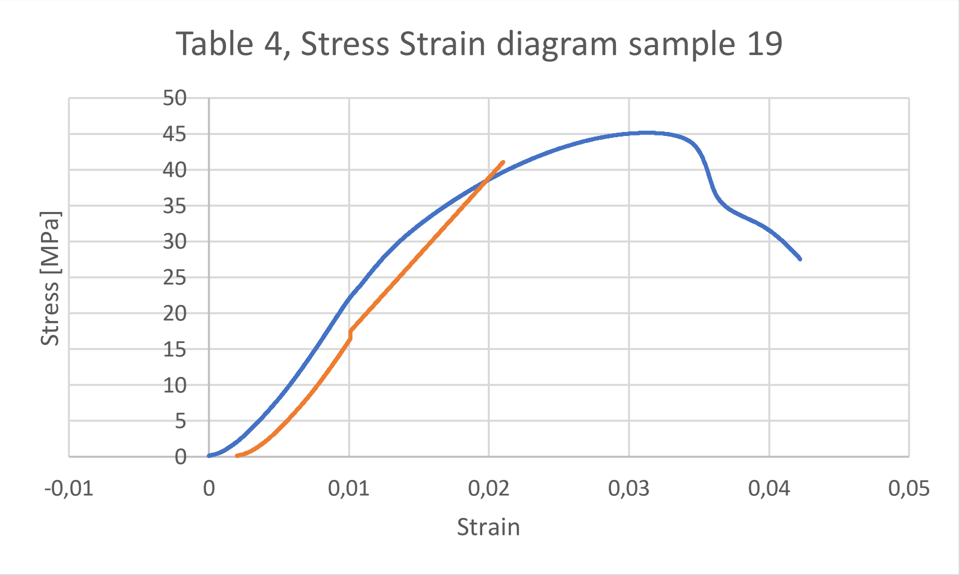
The sudden fall of in sample 17 was due to critical failure, whereas sample 18 was removed from the test to confirm if we were witnessing a plastic or elastic deformation as the results observed with sample 17 where inconclusive. Observing the sample it was concluded that it was an elastic deformation. Follow this observation samples 19 and 20 where used for the compression test.



Using the regression analysis on the stress strain curve generated from the data obtained from samples 20 gave a Young’s modulus of 2104 MPa and a compressive strength of 38.9 MPa.

Using the 0.2% offset method to find the yield point giving a yield strength of approximately 26 MPa.

A similar method was used on the results of sample 19 giving a young's modulus of 2160 MPa, a compressive strength of 45.15 MPa and a yield point of 38.8 MPa.



These values are higher than the ones given by the filament producer; However, this result may be due to the fact that these calculations were only done with two samples, excluding a third sample which had a critical failure.

To conclude this section on the preliminary material tests: the results of the 3 point bend test proved invalid for reasons explained above. The compression test also was invalid; this was due to the fact that the sample size of this test was too small to validate the results of the successful parts of this test.

To enable the continuation of this research project, it was decided to use the mechanical properties as stated by the producers in all further calculations on the printed materials as stated by Technical data sheet Ultrafuse rPET(O-BASF, 2019). Table 5 below represents these values.

TABLE 5: PET VALUES (O-BASF, 2019)	Recycled PET	unit
Density	1273	Kg/m^3
Young's modulus	1334	MPa
Yield strength	66.9	MPa
Tensile strength	38.6	MPa

4. Design criteria for the openable surface

Based on the research framework and the results of the preliminary research, the following criteria can be stated for designing the openable surface. The evaluation of the proposed design at the end of chapter 5 will refer to these criteria.

- Use period of 25 years
    - Because there is no clear definition of what a tiny house is, a law has yet to be made proscribing the expected period of use. What can be said is that people who choose to live in a tiny house do so either because of the financial reasons or because of the active choice to reduce their consumer footprint. The main reason that people move out of a tiny house is that their household composition changes, they get a partner and or get children. This would put them in the starter category of the housing market making 25 years of use more than sufficient, taking into consideration that the tiny house could be completely deconstructed and remade to order.
- As few components as possible
    - Not only is the general rule that the more components (moving parts) you have, the faster it breaks due to friction. But by reducing the amount of components in the openable surface the easier it will be to make through FDM 3D printing.
- Usability
    - In general all users should be capable of going through the openable surface. This includes ease of access. By way of a first estimation, having an openable surface that requires a force of 80 Newton or more to open would make it inaccessible for children or the physically less capable in case of emergency (NEN-EN-1125). Note however: Due to the Corona lockdown measures it was impossible to further operationalize this design criterion, since no full scale prototypes or tests were available. However, efforts have been made to limit the weight of the panel and reduce the friction-resistance as much as possible).
- Integration/ structural capabilities
    - In practice the openable surface needs to perform structurally similar as to how either a door or window would perform. The forces applied to the opening surface need to be properly distributed to the structure of the tiny house. Finally, the surface needs to be capable of staying open or closed for a period of time without hurting the structural integrity of the tiny house.
- Wind and water tightness
    - The openable surface needs to approach the function of being a barrier against wind and water.
- Maintenance
    - Maintaining the openable surface (cleaning, repair and/or replacement) should be executable by users themselves, with limited efforts.

In addition, the following production criteria have been stated to which chapters 6 and 7 will also refer:

- No sharp corners
    - This has to do with how FDM 3Dprinters and robotic arms take a corner, a sharp corner is a seen as a stop making the end effector decelerate towards it. This means that you would have to regulate the material flow into the end effector with the speed and this makes the coding a lot more complex.
- Consist of PET only
    - As stated before this is a technology showcase aiming to push current technology and thinking. Making the constraint and the process just as important as the final product.
- As light as possible
    - By aiming for it to be as light as possible not only does one save in material used but also in printing time making it more efficient to produce.

5. Design process

Following from the preliminary research the choice was made to design a sliding system which would function as a door, complying as much as possible to the design criteria set in the previous chapter. This chapter reports on seven steps subsequently taken to further design the sliding system for the PET tiny house.

5.1. Choices in panel design: complex versus uniform wall curvatures

After deciding on the movement system of the openable surface the next step is to define the surface that will be opened, the wall. As stated before the wall would be a multi-curved surface, this gives us two potential different extremes to work with (see figure 12).

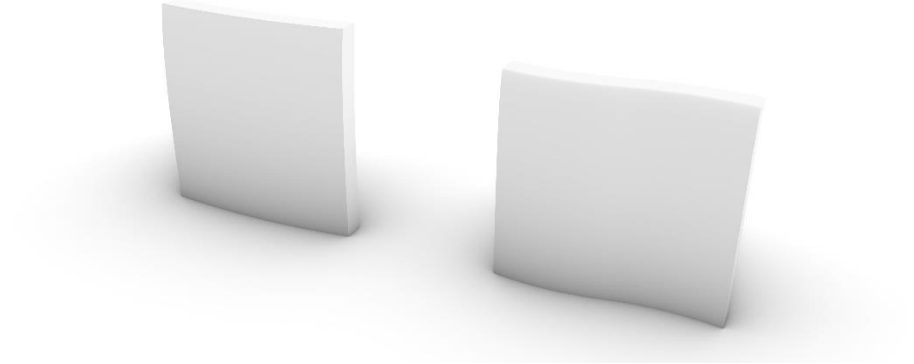


Figure 12. Multi-curved wall possibilities: uniform and complex multi-curved

The most simple model has a uniform curvature, that of the partition of a sphere. This type of curvature would be consistent throughout the wall, making the construction of a sliding system less difficult. The other extreme is a complex multi-curved surface; an example would be a flag waving in the wind. This gives a surface where the curvature is not only varying in radius and but also in directions. In principle both options, that of simple and complex curvature, could be applied to the walls of a tiny house. These two options come with different design challenges, the next step is to see if they can meet the design criteria stated above for the openable surface of the tiny house.

Looking first at the complex option of a multi curved wall, here the standard sliding system as we know it is not an option, as there is no possibility of a ridged panel moving along or within this type of wall. An alternative option to this standard sliding system could lie in 3D printed fabric, an example of which is illustrated in figure 13.

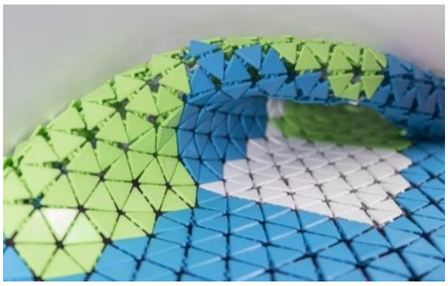


Figure 13. 3D printed triangular mesh fabric. Image by Josh Mings

Contrary to what the term 'fabric' suggests, 3D printed fabric consists of multiple ridged elements interlocking, to allow for small ranges of motion in between elements, mimicking the flexibility of cloth materials.

The complication in such a system is how to allow the ridged bodies a range of motion while they stay connected. In our scenario there is also the additional challenge of keeping the weather elements out. This would have to be solved at the joints between components. Figure 14 below illustrates two proposals on how to connect only two components while attempting to maintain a water and wind barrier function.

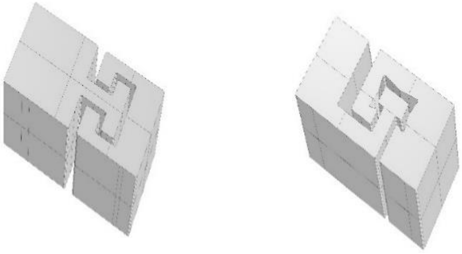


Figure 15. aiming for prolonged entry:

two concepts for the connections between two components

On the left a common solution of a slide-type of connection. On the right my alternative proposal that would further reduce the changes of draft and water entering, due to a prolonged entry-path.

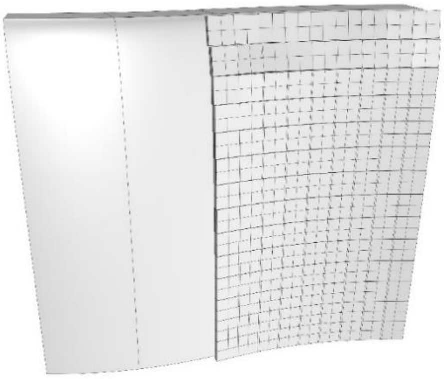


Figure 16. Segmented openable surface

For the sliding panel to be designed, the challenge would be to design a weather proof connection which connects not just two-, but four different components. This could be an interesting topic for further investigation. Such a sliding panel consisting of multiple linked components would potentially look as depicted in figure 16.

To sum up, there could potentially be a solution for a weather proof openable surface in combination with a complex multi curved wall. However, taking into consideration the other design criteria stated above, notably that of using as few components in the design as possible, this solution does not qualify here. For this project, we will proceed on the uniform model. Because the curvature is constant throughout the wall, a sliding system with a ridged panel is possible, unlike the previous case. This would allow the following design criteria to be fulfilled:

TABLE 6: comparing sliding systems for multi-curved walls	Complex curvature	Uniform curvature
Structural capability	?	V
Wind and water tight	?	V
As few components as possible	X	V

5.2. Choices in panel design: internal versus external sliding systems

There a two options for sliding systems, internal and external, as depicted in figure 17.

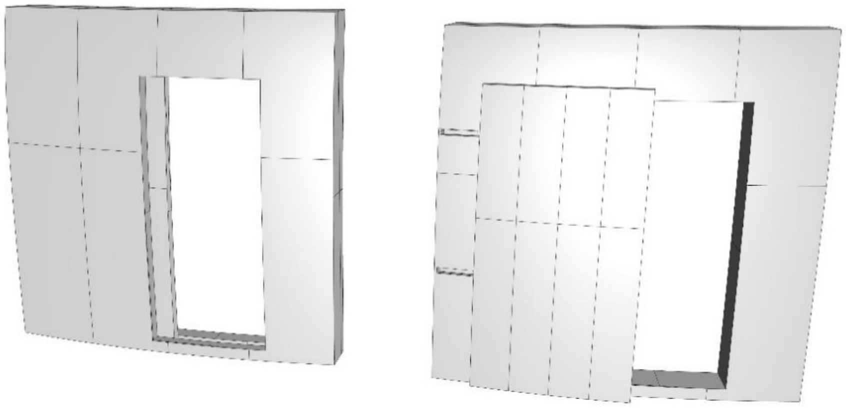


Figure 17. Sliding systems: internal and external

An internal system resides within the wall with having the panel itself slide in a rail. The external system is mounted on the outside of the wall with arms connecting to rails inside the wall. Both have pros and cons, the internal one can be constantly supported on both the top and bottom making is more structurally secured. But this also means that it is harder to replace the panel in case of damage, as taking it out and replacing it would be difficult. The external one can more easily be replaced but having the rails exposed to the elements will be a source of constant maintenance. In both cases it will be very difficult to make the system as wind and water tight as a normal door that achieves its seal through rubber gaskets. What we can do however is elongate the path that wind and water need to take to enter (as was already discussed above), this is more easily achieved with the internal system as it can make use of the wall twice to lengthen the path.

Table 7: COMPARING INTERNAL AND EXTERNAL SLIDING SYSTEMS

System	Internal	external
Structural connection with the wall	Panel is always supported from at least three sides by the wall	Panel is connected to the wall through extending arms
Repair in case of damage	Panel is harder to remove as it is built into the wall	The panel can be removed and replaced with relative ease
Maintenance	The bottom rails need to be cleaned to remove dirt collected over time	All rails need maintenance as they are exposed to the elements most of the time
Wind and water barrier	A small gap must be maintained for movement, however the depth of the rails will make a longer path for the wind and rain to pass through	A small gap must be maintained for movement, wind and rain might pass through

Taking all these things into consideration the final choice was to go for an internal system, where the problem of changing the panel after damage could be solved by making the panel strong enough to prevent mayor damage (see chapter 7), and in case of damage, by subdividing the panel in order to facilitate replacement (see section 5.6 below, with the excursion on assembly and disassembly). Table 7 above summarizes the comparisons which led to the choices made.

Excursion on improving wind and water tightness

Above, one way to make an openable surface more wind and water tight is to prolong the entry path for these elements. However, other possibilities have also been explored. One of the results was the Tesla valve. Patented by Nikola Teslas in 1920 the Tesla valve is a fixed-geometry passive check valve. The valve works without any moving parts impeding the flow in one direction while moving in the opposite direction flows freely. Tesla claimed that "The resistance in the reverse may be 200 times that in the normal direction […] so that the device acts as a slightly leaking valve" (US001329559, 1920). The reason this valve was considered for this research was because it manages flow restriction through geometry. The valves functionality is dependent on the length/the amount of segments. Tesla's patent as seen in figure 18 consists out of eleven segments, and was meant to be used with his newly designed steam engine, however both were never realized due to bankruptcy.

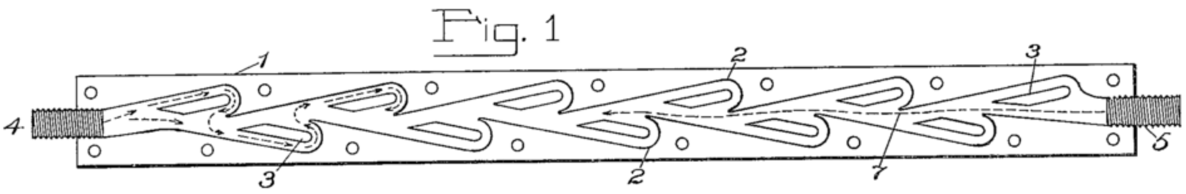


Figure 18. Tesla valve as depicted in the 1920 Patent

Although the Tesla valve could possibly be applied in the mono material tiny house the fact that the length of the valve is in direct relation to its functionality make it so that it would be hard to implement it to the moveable surface will all likeliness be the thinnest part of the tiny houses outer construction. It could however be interesting as a ventilation option in other parts of the tiny house.

5.3. Design of the rails

With the internal sliding panel a gap might have to be present in the floor between the outside and inside floor, this interruption would be approximately 65mm wide. This could cause people to hurt themselves in case they misstep. Figure 19 shows two initial options for a solution when the panel is opened. The option on the left is a simple curved profile to follow the curve of panel and wall.

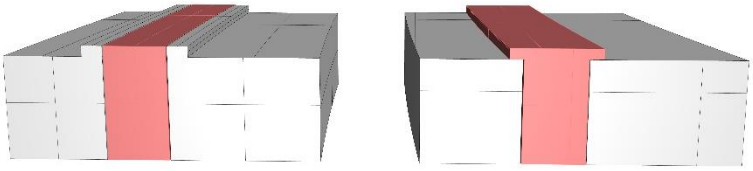


Figure 19 Two gap/plinth options

The option on the right has a similar profile but this option has an integrated plinth as to cover the gaps between the profile and the sides of the gap. It needs to be considered however that adding either of these profiles would both increase the weight of the door and add a lot of friction. While at the same time such an appendage would require more space in the wall. A different option could be that the element needs to be placed manually when needed and otherwise be stored separately. Of the two options described, the one on the left might be preferred as to still have a functioning plinth (as dirt-barrier) when the element is not placed in the gap.

After this initial design, a much simpler solution came up: to raise the rail itself above the floor, this removes the potential danger of a gap. Figure 20 illustrates the designed profile of rails, shown with the panel on top.

Figure 20 side profiles of raised rail with panel

By having the rails raised above the floor it loses some of the structural support that the deeper rails had provided. However, from a maintenance point of view this is a much better option than having the rail positioned below floor level. Not only because it works as a plinth to stop dirt and water from entering the tiny house, but also because it makes it so that the rails don't become a gutter that collects mud water and other filth. The decision thus was made to use a raised rail both because it removes a potential hazard from the design, reduces the wall space needed and brings advantages for maintenance. With this raised rail the panel will sit on top of the rails with the sides extending down to stabilize the panel and to prevent the panel from sliding off the rails. The external side of the rails has a slight taper as to allow water to flow off onto the sloped area in front of the opening.

5.4 Cavity maintenance

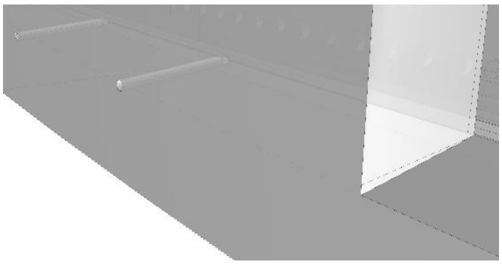


Figure 21 Bottom ventilation holes connecting the cavity with the outside

One of the problems that is created by making an internal sliding system is the maintenance of the created cavity. Because the chosen material for this project is translucent there is a high probability of condensation forming on the inside of this cavity as moisture left on the sliding panel could collect in the cavity. To prevent this from happening ventilation holes are made in the top and bottom part of the cavity, as to allow airflow to travel throughout the cavity (figure 21). This would make it so that the moisture in the air can't collect in the cavity. It is important however that these ventilation holes do not allow for the rain to enter the cavity. Also when the panel is moved out of the cavity to close the doorway, moisture form the cavity might have an easy path to the interior of the tiny house. Hence it is important that the design tries to prevent additional moisture from assembling in the cavity in the first place. The option chosen to resolve this issue is by angling the ventilation openings so that gravity would lead the large droplets out.

5.5. Design of the door handle

With the sliding system figured out, it is important to design the point of interaction with this system, the equivalent of a door handle.

Figure 23. Examples of the two handle types.

With sliding doors there are two types of handle that are commonly used. One type is a vertically oriented bar sticking out of the panel. The other is shaped as a pocket in the panel itself. Figure 22 depicts both types. For external sliding doors a combination of both types is mostly used, having the bar type on one side and the pocket type on the other side, so as to prevent the latter handle to collide with the wall.

For internal sliding systems an extended handle could be used but only in the case that the panel doesn't disappear into the wall completely.

For pocket handles in a mono material setting, further design considerations need to be taken into account. The handle is created by removing material from the panel, this makes it necessary to study the noticeability (does it catch the eye?) the usability (does the pocket allow sufficient grip?) and the transfer of force (to the panel). In view of all three criteria, a double, vertically oriented pocket grip or inset handle is applied, as shown in fig 24b.

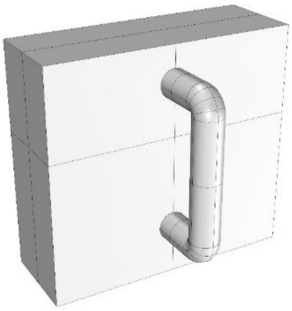


Figure 24a. Vertically orented handle

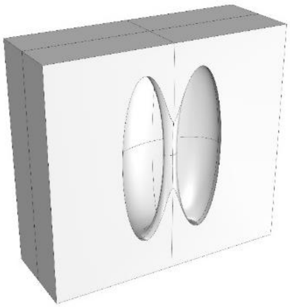


Figure 24b. Vertically oriented inset handle

A FEM analysis of the door handles from figure 24 was done in ANSYS which has confirmed this choice to be a logical one. The hypothesis tested was that applying an in-set handle in PET material would create less stress and less risk of failure when compared to a external handle. The test confirmed this hypothesis. figure 25 below compares the amount of deformation when force is applied on both types of handle:

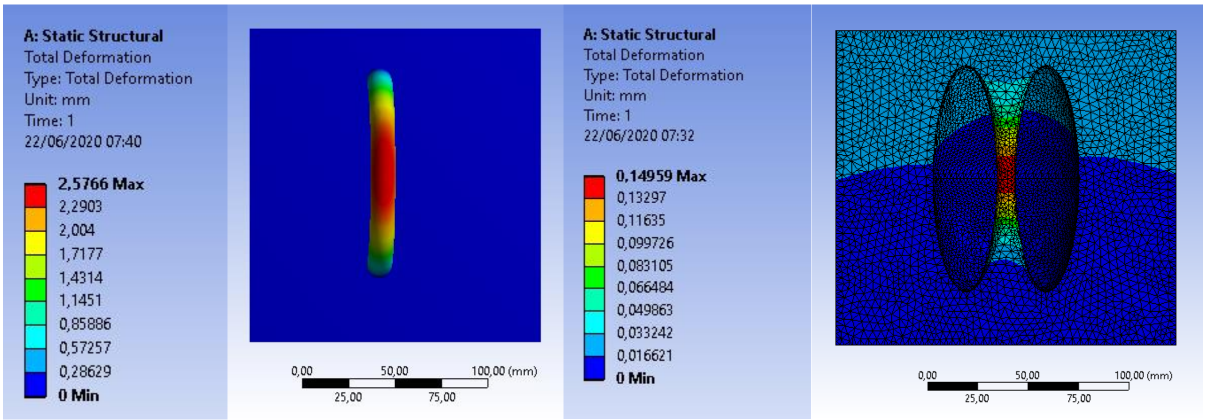


Figure 25. Structural deformation for external handle and inset handle

The deformation in the inset handle is less than for the external handle, due to the fact that the geometry of the inset handle is better capable to distribute the force applied to the rest of the panel.

Figure 26 below compares Von Mises stress values for both types of handle. This is a measure to calculate the internal tensile stress in order to determine if the yield strength is exceeded, resulting in failure.

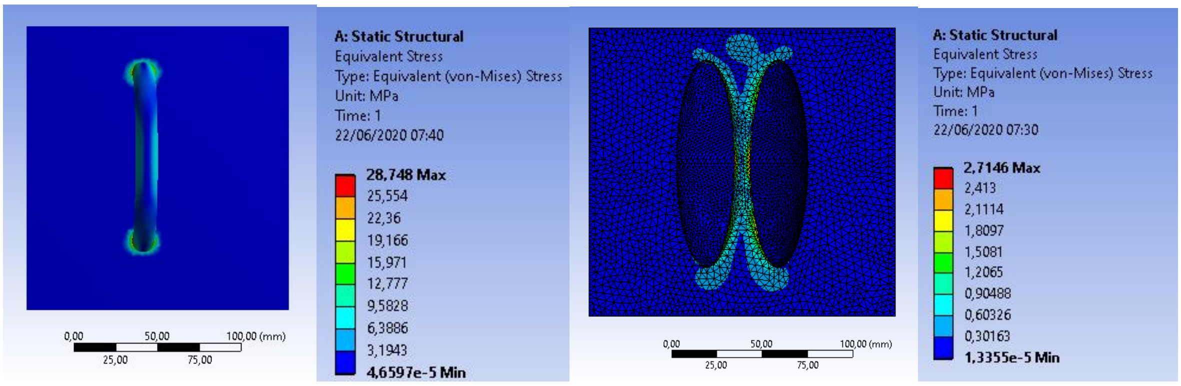


Figure 26. Von Mises stress values for external handle and inset handle

These results show that the maximal amount of stress found is much larger for the external handle than for the internal handle, which again confirms the hypothesis. Even though both types of handle would function in the sense that the stress remained below the yield strength in both cases, the internal type is clearly preferred due to the lower internal tensile stress.

To conclude the design of door handles, table 8 sums up the points on which the inset type is comparatively preferable.

Table 8: comparing handle types	External handle	Inset handle
Notability	+	+/-
Usability	+	-
Maintenance	+	+/-
Total panel weight	-	+ ?
Transfer of force	-	+

5.6. A farm door addition to the design

After the design decisions made op the sliding system, a moment of reflection was taken in order to review the current design in the context of the tiny house in its entirety.

1. One of the design constraints known for applying a sliding system is that a large portion of the wall becomes unavailable for a window opening. This problem arises both for internal and external sliding systems. In a common house this might not be a big problem as there would be enough wall area left to construct a window in. However, in the context of a tiny house this is a serious issue, given that the wall area is highly limited. Even though the amount of light entering the house is not an issue in this case, given the fact that the chosen material is translucent, other functions of a window would still be lost. The solution proposed here would be a farm door type of scenario for the moveable surface, in which the panel is split horizontally. Allowing the top part to be moved aside separately, it can function as an openable window (figure 27). By adding this functionality to the openable surface we can solve one of the restrictions that would otherwise negatively affect the habitability of the tiny house. While the external handle remained as in the single-panel design, an additional handle was added on the interior side, for the user to interact with top and bottom parts. And the extra gap in the surface was made wind and water tight by using a rails system similar to that used at the bottom of the single panel design.

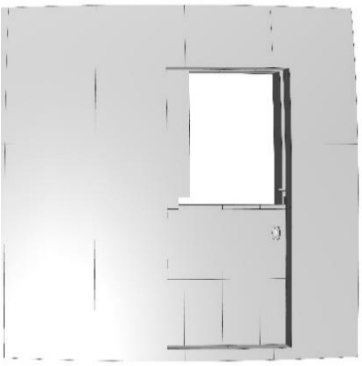


Figure 27. Farm door with the top half opened

This additional farm door feature however did bring three further design challenges, notably when working in mono material.

2. To find a reliable support for the opened window part. One possible solution was to hang the window inside the wall; this was rejected however because the structural support for the hanging system would take considerable additional space (the cavity would have to be much higher and deeper). The better solution was the design of a wider bottom panel which then supports the window part even in opened position, accepting that the bottom part of the cavity would become wider.
3. A further challenge was to prevent the top panel from sliding off the bottom panel.

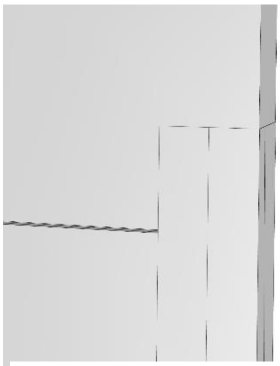


Figure 28. Rail stops

As a solution, rail stops were added on both ends of the bottom panel, as shown in figure 28. These would not only stop the top panel from sliding off but also help with alignment of the panels for when the openable surface would be closed.

4. Finally, a system was needed connecting both panel parts in case the entire surface is closed.

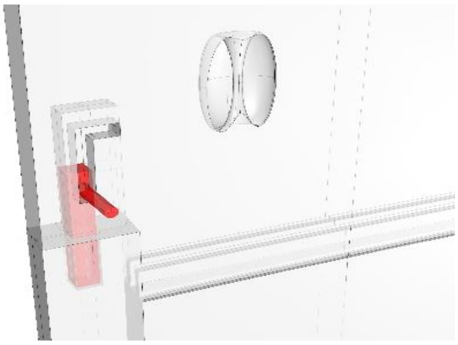


Figure 29 shows one possible design to realize this connection, in which a simple peg is used to connect the panel halves at the point where there is a rail stop.

Figure 29. Connection for the system panel halves

Excursion on assembly and disassembly

When the design choice is made for a farm door solution, extra possibilities do arise for the assembly and disassembly of the sliding panel. A general drawback for internal sliding systems generally is that a panel is hard to place and hard to replace in case of damage. For the PET tiny house, the initial placement problem could be tackled by positioning the panel prior to completion of the wall. But this would leave the replacement issue unresolved.

However, when the panel is divided horizontally in two parts, possibilities arise to further subdivide each part vertically. This allows the farm door to be assembled and disassembled (for example in case of damage) while leaving the wall intact. This would not be an option with a singular panel as the panel would be taller than the opening in the wall.

To conclude this excursus, figure 30 shows the proposed subdivision of each panel and the building sequence for assembly.

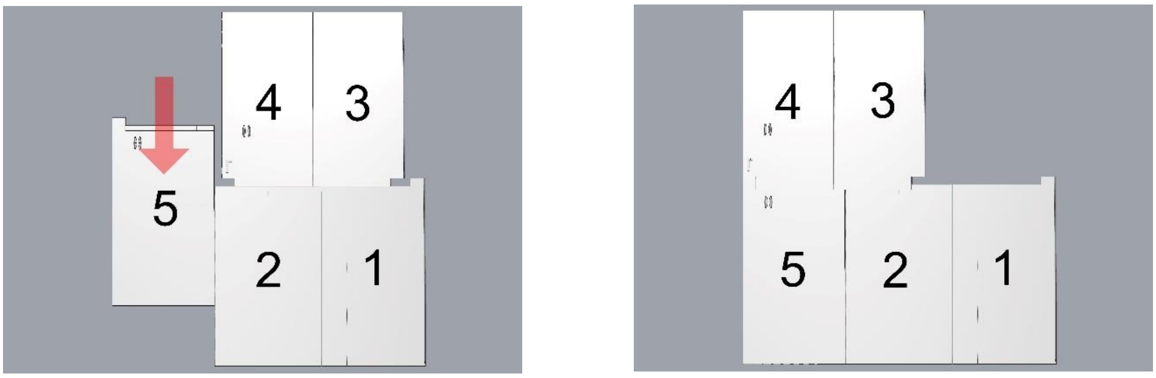


Figure 30. Proposal for subdivided farm door panel parts: assembly sequence and position when closed

5.7. Conclusion

This finalizes the design process which has led to the farm door sliding system proposal as illustrated by Figure 31 below.

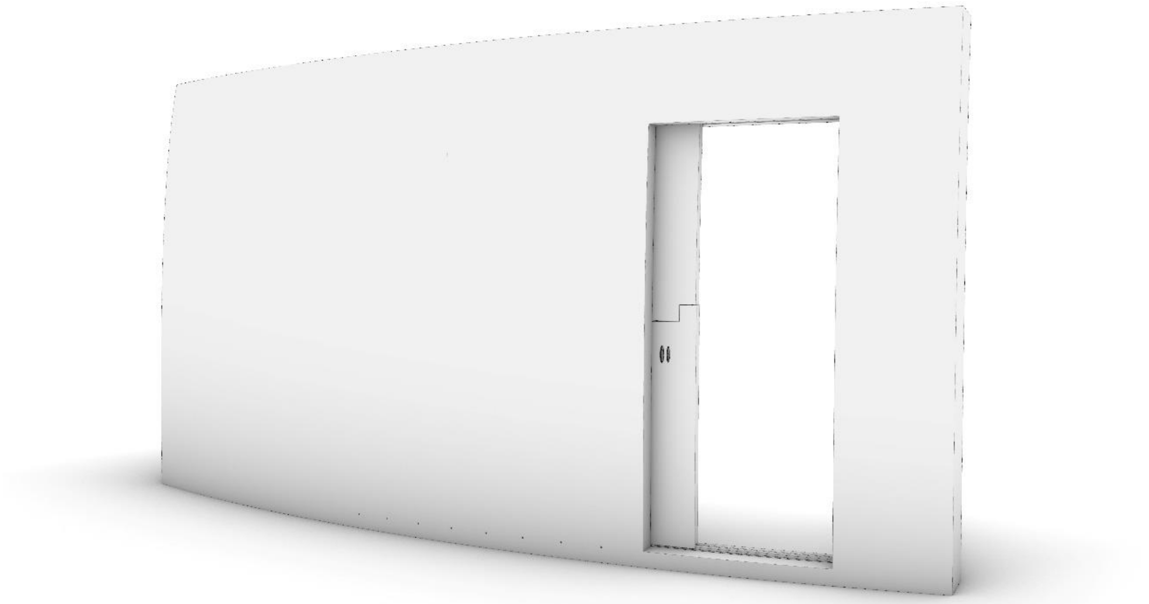


Figure 31 final farm door design

Table 9 sums up the choices made for this design, these are evaluated and then briefly explained, using the six design criteria which had been stated in chapter four.

TABLE 9: evaluation of the PET farm door based on all design criteria	
Design criteria	Realization in PET farm door design
1. Use period of 25 years	?
2. Limited number of components	+/-
3. Ease of use	++
4. Integration/ structural capabilities	+
5. Wind and water tight	+/-
6. Maintenance	++

<u>Ad 1.</u> The criteria of use period is difficult to assess in simulation, a physical test of the farm door in 1 to 1 scale is advised to evaluate this criterion.

<u>Ad 2.</u> A single panel door with the railsystem described in sections 5.1 would have the best score on the criterion because the farm door adds more components to the design. The advantages in functionality and usability however outweigh this criterion, as was explained in section 5.6.

<u>Ad 3.</u> Both the choice for a sliding system (already established in chapter 3) and the choice for the handle (in section 5.5) have brought positive results on the criterion of usability. Regarding the

amount of force needed to operate this system, further analysis will be done in chapter 7, since this aspect of usability highly depends on the weight of the system.

Ad 4. With the internal sliding system, the best distribution of force to the wall has been chosen, compared to the other movement types. Further assessment on this criterion will be done in chapter 7, where the amount of infill in relation to the weight of the system will be analyzed.

Ad 5. Although no certain method was found to make a mono material system complete wind and water tight (forbidding any rubber or other types of gaskets) this design criterion has operationalized further by creating elongated paths for wind and water to pass through the system (sections 5.1 and 5.2).

Ad 6. Maintenance should require limited effort and should be executable by the users themselves. The design choice of an internal sliding system limited the maintenance needed compared to external systems, since the rail is exposed less to the external environment. By raising the rail and by ventilating the cavity, most of the maintenance issues which water could create in an internal sliding system have also been minimized. Finally, in case damage would arise after all, a proposal for easy disassembly and assembly has been added (excursion to 5.6).

6. Fabrication

Having designed the sliding system, this chapter explores the fabrication of the sliding system through the FDM printing process. Due to the Covid-19 lockdown, all this research had to be done at home with less than ideal equipment. Originally the plan was to make use of the universal robot 5 for the small scale experiments to ensure consistency throughout the tests. As this was no longer possible all test setups have been redesigned for them to be performed at home. I am thankful for LAMA, the laboratory for additive manufacturing in architecture of the TU Delft, for allowing me to take home one of their Delta FDM printers for this adjusted research. After a brief summary of how the thorny path of calibration was walked, three sets of tests are reported in more detail:

- Sliding test: effects of production methods (notably print layer orientations) on the functioning of the sliding parts.
- Roll tests: following results of the sliding test, additional contact elements were added to see if these could manage the problem of non-ideal print layer orientations of the sliding system parts.
- Wear and Tear test: to measure the effects of prolonged use of the material as sliding system.

6.1. Choice of 3D Printer

As stated before FDM stands for fused deposition modelling. It is a 3D printing method in which a thermos plastic filament is fed from a spool into a heated extruder and deposited on a print bed thus building up the 3D print. The LAMA lab offered a choice between two printers. Characteristic of a Delta 3D printer is that it uses three stepper motors in the Z axis move the extruder whereas the more common Cartesian 3D printers have a singular motor for every axis, X, Y, and Z respectively. Both types of printers have their pros and cons; because most printers are handmade by their users, results can vary. In general it is said that a Cartesian printer is easier to repair, slower but less prone to errors when the print head moves. While Delta printers have a larger print volume and a higher printing speed but are therefore more susceptible to errors in the positioning of the print head.

For this research and the production of the small scale tests the larger print volume and higher printing speed were desirable, therefore a Delta printer was chosen over a Cartesian printer. The Delta printer in this project has a print volume of 5654866.776 mm^3 with a maximum print height of 180mm. It has a semi enclosed printing chamber with an aluminium heat bed as printing surface. The used extruder has a 1,2mm nozzle diameter.

A common misconception on 3D printing is that it is a fast process, that any 3D model is easily turned into a printed prototype. This is partially because 3D printing is often referred to as rapid prototyping. In one way 3D printing can be called rapid prototyping as it made it possible for designers to not be dependent on an external party to produce the prototypes thus reducing the waiting time. The process of calibrating the 3D printer and the actual print times however takes longer that most people realise.

6.2. Calibration

Before printing the small scale tests the printer had to be calibrated. There are numerous settings that can be tweaked to make the resulting print have the desired level of detail. These settings include but are not limited to: extruder temperature, print bed temperature, print speed, flow rate, retraction speed, retraction distance, coasting distance, nozzle wipe distance, extrusion width, layer height, and the speed of the cooling fan.

Even when after calibration settings where as desired and print tests came out well, these setting almost always needed adjusting the following day as the moisture content of the filament had changed overnight, the air being more humid and or the room temperature having changed. Temperature was less of an issue in the case of the Delta printer as it has a semi enclosed printing chamber, allowing the temperature to be more consistent during the printing process.

In 3D printing generally, printing errors commonly seen when starting a new project are: under-extrusion, over-extrusion, gaps in the top layer, stringing/oozing, overheating, warping, poor bridging, and vibrations and ringing.

When using PET, one common error related to this particular material most is stringing/oozing. This is due to this material being highly hydroscopic, resulting in the filament to stretch into an unintended thin line after exiting the nozzle.

Specifically in the (home) context of this research project, errors that occurred most frequent where: under-extruding and poor bridging, alongside frequent stringing/oozing of the PET. Of each type of error that occurred, a brief description is given:

- Because 3D printers do not provide any feedback about how much plastic actually leaves the nozzle, it frequently occurred that less plastic was exiting the nozzle than what the software expected. This process, known as under-extrusion, results in unwanted gaps between adjacent extrusions of each layer.
- The process of extruding plastic between two points without any support from below, is called bridging. The process consists of plastic being extruded across the gap and then

quickly cooled to create a solid connection. Bridging is also required in case of printing overhanging structures. For larger bridges, one needs to print support structures but generally one should be able to print short bridges without any supports, to save material and print time. For the design of the curved panels, with large overhanging areas due to the curvature, it is crucial to get the bridging right. However, in the home situation this often proved to be a burdensome job, as it required to establish a precise ratio between the extrusion temperature, extrusion speed and the amount of cooling applied.

- Stringing, otherwise known as oozing (or whiskers, or "hairy" prints) occurs when small strings of plastic are left behind on a 3D printed model. This is typically due to plastic oozing out of the nozzle while the extruder is moving to a new location. When working with PET, stringing is almost inevitable. With sufficient possibilities to retract the filament while moving the nozzle, deformation of the geometry due to this oozing can be prevented. Unfortunately, the Delta 3D Printer used in the home setting of this project did not allow for such quick retraction. This was caused by the fact that it uses a Bowden tube extrusion system, resulting in a slower retraction speed.

Figure 32 shows the calibration test specifically for minimizing oozing. This model was obtained from https://www.thingiverse.com/thing:2080224 uploaded by user 'Loohney' in febuari 2017.

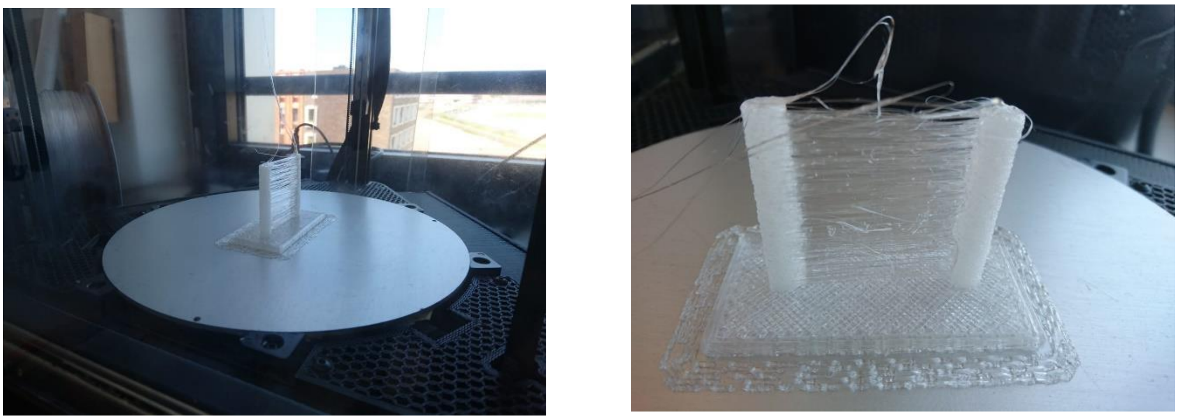


Figure 32: Calibration tests to minimize oozing

Although the strings were easily removed, the main issue was that the oozing negatively affected the geometry of the 3D print. 14 test prints were required to sort this out.

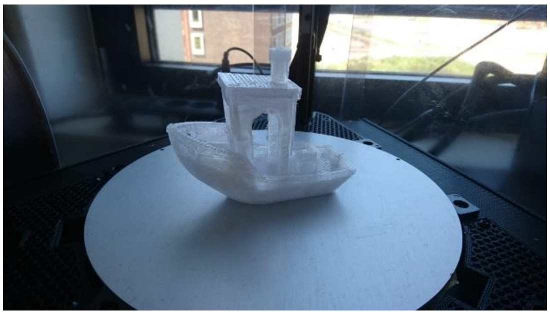
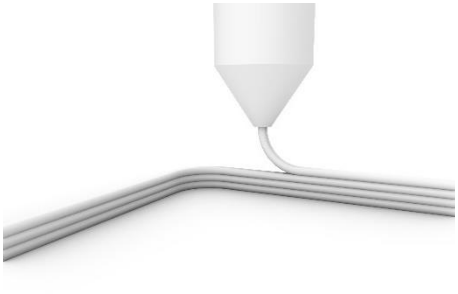


Figure 33: 3D Benchmark test

Figure 33 shows the 3D benchmark test, which was performed twice after minimizing the possible errors mentioned above. This model was obtained from https://www.thingiverse.com/thing:763622 uploaded by user 'CreativeTools' in April 2015.

6.3. Sliding test



When one manufactures an object trough FDM printing it will always consist out of layers added on top of each other. Making it so that there would not be a perfectly smooth surface to interact with. Figure 34 illustrates that the resulting surface will never be entirely smooth.

Figure 34: 3D printing layers

For this reason a sliding test was performed, to observe how the interaction between two different objects changes while sliding, due to the orientation of their layers resulting from the printing process.

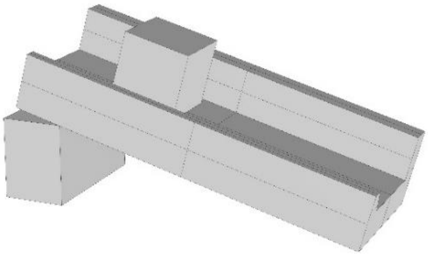


Figure 35: sliding test with cube

Two rails where printed in PET with one rail having its layers oriented parallel to the direction of movement, the other rail had its layers perpendicular to the direction of movement. A cube was printed that would allow for both types of orientation to be tested with this same object, as illustrated by figure 35. The test was performed four times for every combination of orientations: parallel-parallel, parallel-perpendicular, perpendicular-parallel, and perpendicular-perpendicular.

The rails where attached to the work surface on one end with tape while a nylon wire was connected on the other end in the central line of the rails 10mm from the end. The wire was used to slowly pull up the rails increasing the angle until the cube would start sliding. This is shown in figure 36.

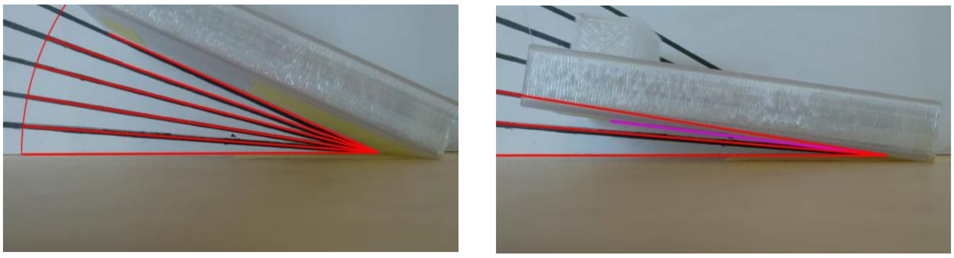


Figure 36: changing the angle of the rails

The hypotheses was that both tests involving the perpendicular rail would reach a higher angle than the tests performed using the parallel rail before the cube would start sliding, regardless of which orientation the cube itself was given. This on the assumption that the cube (in any cube-orientation) would be obstructed by the perpendicular layers of the rail.

What was observed in the tests however was that the chosen orientation of the cube was equally significant as the chosen orientation of the rail: there was no significant difference in the angle where the cube would slide, as long as one of the interacting elements (either rail or cube) had its layer-orientation parallel to the direction of movement.

The angle at which the cube actually moved for the perpendicular-perpendicular tests was between 15 and 25 degrees. Whereas the angle for movement was between 6 and 15 degrees when an element had layers parallel to the direction of movement.

The large range that was observed in the angles where movement occurred can be explained by the unhappy home-conditions in under which the tests had to be performed. The fact that the rails had to be moved manually, meant that the speed at which the rails moved and the rate of acceleration could not be guaranteed to be consistent throughout the test. And therefore it is not possible to be certain if significant difference would occur when the sets were oriented parallel-parallel, compared to parallel-perpendicular, and perpendicular-parallel orientations.

What can be concluded with certainty however is that there is significant improvement in sliding movement when one of the interacting objects has its layers oriented in the direction of movement.

6.4. Roll test

The sliding tests have shown the importance of how printing layers are oriented. This orientation could be a limiting factor in the production process of the entire system when the ideal orientation (being the layers parallel with the direction of movement) would not be the ideal orientation for the production. Bear in mind that bottom and top layers of a panel generally will be printed in multiple directions so as to assure sufficient filling, resulting in higher structural capabilities.

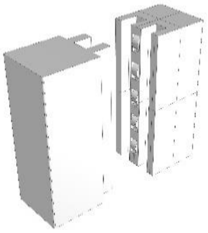


Figure 37: Roll test elements

One possible way to solve this issue would be to print both panels in a flat position; however, this would require an excessively larger printing surface while much more support material would be needed during printing to ensure the curvature. Another problem when printing in this flat position would be that the resulting orientation of the internal structure (infill) would create different structural properties. Chapter 7 charts some of the issues of structural capabilities.

To see if there would be alternative options preventing this unwanted fabrication setting to be necessary, a second test was performed. Here elements, printed in the ideal sliding orientation, were added to interacting side of the panel in order to function as intermediator.

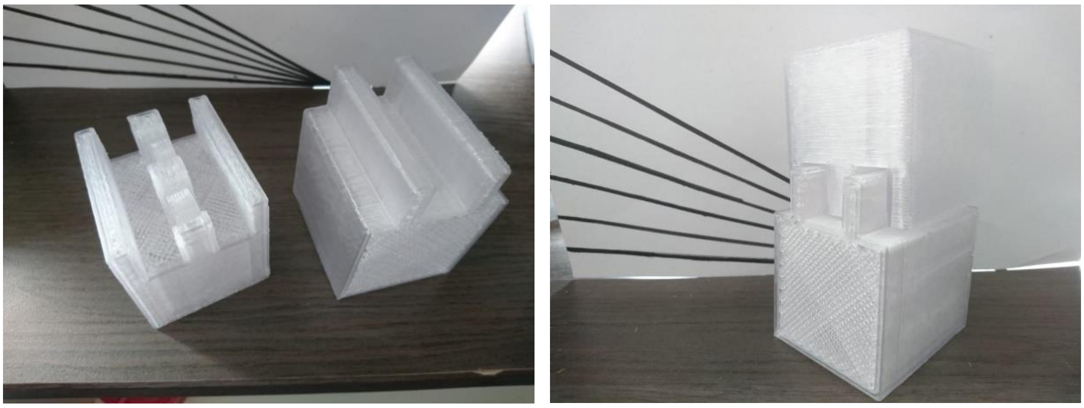


Figure 38: 3D printed elements used in roll test

The idea behind this was to mimic in a mono material what is conventionally done to minimize friction between two surfaces moving along one another: add wheels or ball bearings.

The setup of this roller test was as follows: a small section of the panels was printed on 1 to 1 scale with small discs inserted into the underside of the top panel (i.e. the window section of the farm door design). The discs were without axels. This not only facilitated printing but also prevented additional issues to arise when the weight of the panel would have to be carried entirely by small PET-axels. The purpose of the test was to see if the movement would be smoother, compared to a sliding movement without intermediator. One of the sections (the bottom panel section) was deliberately printed in the orientation of having its layer perpendicular to the direction of movement. For this is most likely the orientation in which this panel can be manufactured most efficiently, given its proportions (recall that the bottom farm door panel is wider than it is tall).

Results: when manually sliding the two panel sections along one another, respectively with and without the discs, it was observed that there is a slight decrease of resistance when discs are added.

Unfortunately, it was impossible to quantify the specific contribution of the discs under the current conditions of production and testing. To test properly, a wider section of the panels would have to be printed than was possible with the Delta printer available. Subsequently a test similar to the slide test would have to be performed in the lab, using a Newton force meter.

6.5 Wear test

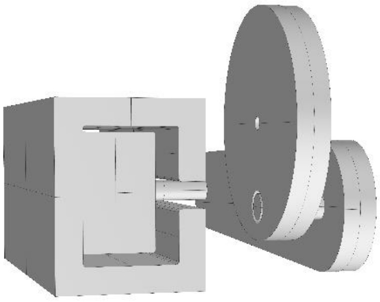


Figure 39: Wear test design

Figure 40: Wear test setup with printed elements and electric drill

Taking the results from the sliding test we can see that in principle, as long as one of the interacting surfaces has the optimal orientation, a smooth movement of the PET panels can be realized. However, one also has to take into account the effects in wear and tear on the surface area of the interacting elements. This has to be investigated under varying orientations of the interacting elements.

A wear test was therefore warranted. This test consisted of a rail printed in the optimal sliding orientation and an object that would repeatedly be moved back and forth in the rail for a prolonged period of time. The moving object was printed three times in different orientations, the first with the layers perpendicular to the layers of the rails. The second with the layers parallel to the layers of the rails. The third object was printed so that the interacting surface resembled the bottom layers of the printed panel: these layers were printed with an infill angled at 45 degrees. The test was executed (under non ideal home conditions) by using an 18Volt electric hand drill at full drilling speed of 800RPM to spin a disk with a hinged rod which ensured the moving object to follow a lateral movement within the rail. Each of the three printed objects object was put in the system for the duration of one hour.

The two hypotheses for this experiment were as follows: 1. having the layers of the moving object being perpendicular to the layers of the rail will cause the largest damage in sliding capabilities (when compared to the other objects tested); and 2. the object with the layers printed in parallel orientation to that of the rail will cause the most wear, as this object has the largest amount of contact area with the rail.

Results were inconclusive. After the tests no wear was observed on any of the objects nor was there any wear to be seen on the rails. An (unlikely) explanation might be that PET material is sufficiently resistant to wear due to friction. A more likely explanation however is that the objects that were moving had insignificant mass too maintain continuous connection with the (short) rails. The fact that no robotic arm could be used for the movement was also not helpful. Nevertheless, the fact that there was no observable damage to the rail notwithstanding three hours of full testing, might be seen as a hopeful result for future working with PET sliding systems.

7. Structural analysis

This chapter reports on the research done to find acceptable ratios of the weight (as defined by infill percentages) and the structural capabilities of the farm door designed, consisting of a top and bottom sliding panel.

First, both panels have been fed into a slicer simulation program, using an standard infill of 30%. This results in an estimated weight for each panel.

Secondly, based on these estimations a structural analysis has been attempted in 3D FEM using ANSYS software; this however resulted in several unresolved issues, partly related to the setup of the student-software used but which would needed further inquiry.

Thirdly, a much more simplified model consisting of 2D sections of the panel was fed into ANSYS in order to calculate possible effects of various infill percentages on the structural capabilities for each panel.

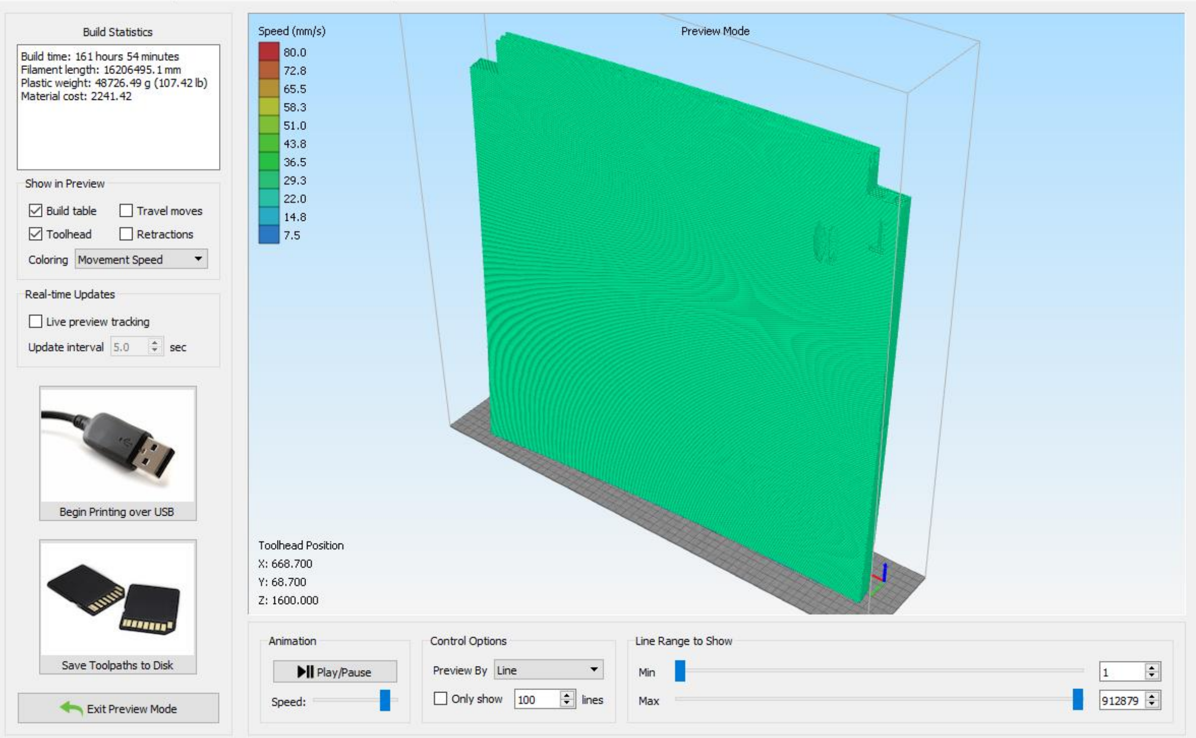
By way of conclusion, an estimate is given for the amounts of deformation for three different infill percentages of the panels, based on standardized infills. Even though these results are provisional, they may also be relevant for future research using locally optimized infill.

7.1 Weight estimates using standard 30% infill

The first step in the structural analysis of the farm door design was to find an indication of what each of the two panels would weigh. To do this the 3D model (see figure xx) of each panel was exported as a STL file and uploaded into the used slicer software ‘Simplify 3D’. The print settings used were as follows: an infill of 30%, two perimeters, four top and bottom layers, a layer height of 1.2mm, and an extrusion width of 2mm. The chosen infill percentage of 30% is at the bottom range of the most commonly advised infill percentages for 3D printing of objects with structural functions, this in view of the design criterion (see chapter four) to keep the weight of the panels as low as possible.

The weight calculated in Simplify 3D is 48.7 kg for the top panel, and 79.6 kilo for the bottom panel (bear in mind that the bottom panel is around 75% wider than the top panel).

This is bad news for both panels and doubly so for the entire system, taking into consideration that the weight of a common interior sliding door (combining wood and glass) is around 80kg. Sliding doors generally are heavier than hinged doors (weighing between 35 and 50 kg); however, a total estimated weight surpassing 100 kgs does raise concerns for usability and functionality of the PET sliding system.



Build Statistics

```
Build time: 161 hours 54 minutes
Filament length: 16206495.1 mm
Plastic weight: 48726.49 g (107.42 lb)
Material cost: 2241.42
```

Show in Preview

☑ Build table ☐ Travel moves
☑ Toolhead ☐ Retractions
Coloring: Movement Speed

Real-time Updates

☐ Live preview tracking
Update interval: 5.0 sec

Toolhead Position
X: 668.700
Y: 68.700
Z: 1600.000

Control Options

Preview By: Line
☐ Only show 100 lines

Line Range to Show

Min: 1
Max: 912879

Figure 41 top panel modeled in 'Simplify 3D'with the resulting weight

This result indicates that the relation between weight/infill and structural capabilities should be analyzed further. The commonly advised 30 % infill simply results in too much weight for the PET sliding system. To properly assess the effect of the infill reduction to the weight, the 3D models were imported in slicer software. For the top panel, the resulting (full scale) weight was calculated for various infill percentages. This proved not directly possible for a full scale bottom panel, as this panel was too wide to fit in the workspace allowed by the software. This problem was solved through indirect calculation as follows: for both panels, data were entered in the slicer program for 50% downsized versions, so that a weight ratio could be established between both panels (this ratio was double-checked by establishing volume ratio's as well). Then, using the assessed weight of the full scale top panel as reference, the weight of the bottom panel could also be calculated. Results of the weight-calculation through use of the slicer program are summarized in the table 10 below.

Table 10: Panel weight based on infill

Infill %	Top panel	Bottom panel
30%	48.7 kg	79.6 kg
25%	40.8 kg	71.1 kg
20%	35.7 kg	62.3 kg

7.2 3D simulation of the panels in ANSYS

Once the weight assessment had been made, the next step was to test the structural properties of the design for each panel with different infill percentages. An initial attempt was made to simulate a simplified 3D panels in ANSYS Finite Element Method software, as illustrated in figure 41 for the bottom panel.

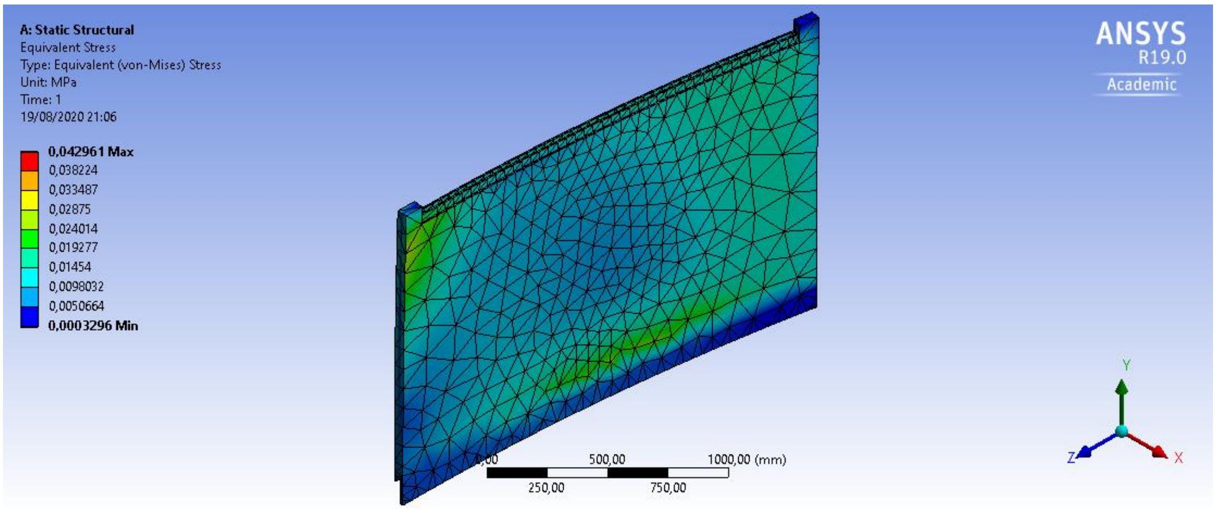


Figure 42 full 3D simulation of a simplified model bottom pannel

Here a force was simulated of 80 Newton on the panels to represent the maximally allowed force to open a sliding door (this condition has been explained in the design criteria in chapter 4). In this first attempt, a solid panel was simulated with no infill values added yet.

Already a problem occurred, due to the limits set on the ANSYS program under student license: the minimal mesh-refinement needed for a realistic simulation of the panel already required too much to calculate. This was due to the relatively strict limits set on the amount of polygones available to the student license-version of ANSYS.

Furthermore, it became clear that this problem would exacerbate as soon as the infill values would be added, since a reduction of infill below 100% would immediately increase the amount of faces the programme would have to add to the mesh generation. This would result in a sharp increase in the amount of polygones required to run the simulation.

Unfortunately, all three simulation software programs currently available for doing structural analysis (ANSYS, DIANA and KARAMBA) have a limitation on polygone counts in their student license versions. This result left no other option then to redo the structural analysis of the panels with the ANSYS program, but now to switch to 2D.

7.3 2D simulation of the panels in ANSYS

To get a proper 2D representation in the simulation, for both panels a horizontal and vertical cross-section was defined. These cross sections where analysed with the vertical cross sections as a solid infill and the horizontal sections with three lower infill percentages (hence 100%, 30%, 25% and 20% infill). The reasoning behind the decision for the vertical section was as follows: It is very unlikely to get a proper result when one tries to faithfully analyse a vertical cross section through an infill pattern. The forces that are applied perpendicular to the infill don’t travel trough the cavities in the pattern, but are properly distributed sideways. This however does not happen in a 2D vertical section. The reason to not take the solid infill into account for the horizontal section is due to how ANSYS requires the location of supports and forces on the model. In the case of the solid panel additional subsection would need to be created in the model, resulting in a skewed mesh making the results questionable.

The chosen models were fed into ANSYS for conditions resembling a closed state of the panel. Secondly, a force was applied resembling the initiation of opening the panel. This was done for each panel in both orientations, an example of the resulting analysis is depicted in figure 43.

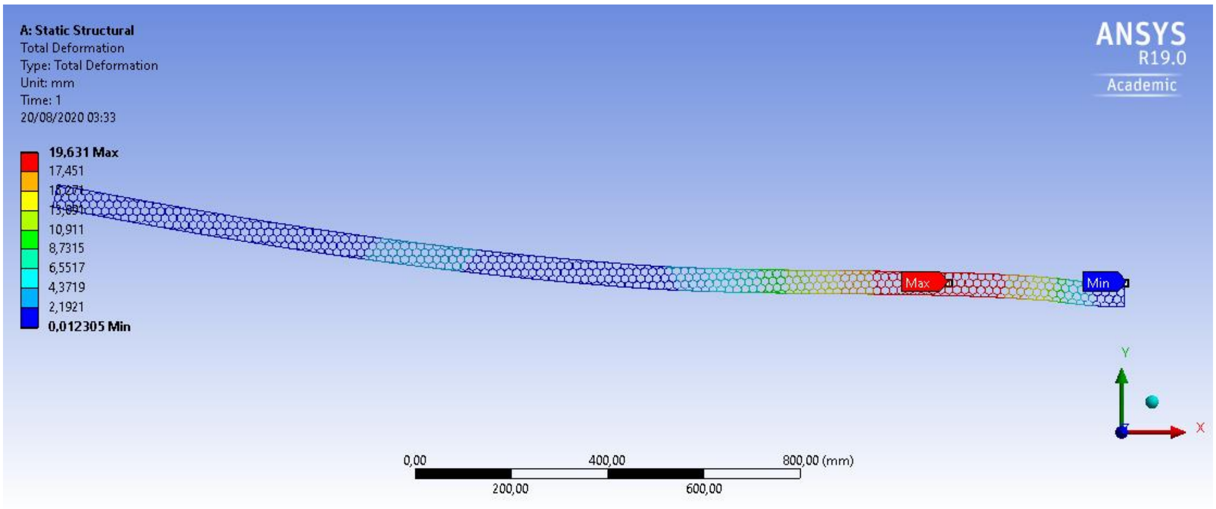


Figure 43 resulting deformation for the horizontal secton of the bottom panel with 25% infill

The hypothesis is that the lower the infill% the higher deformation and resulting stress, the stress would increase due to the forces traveling a less ideal path through the section.

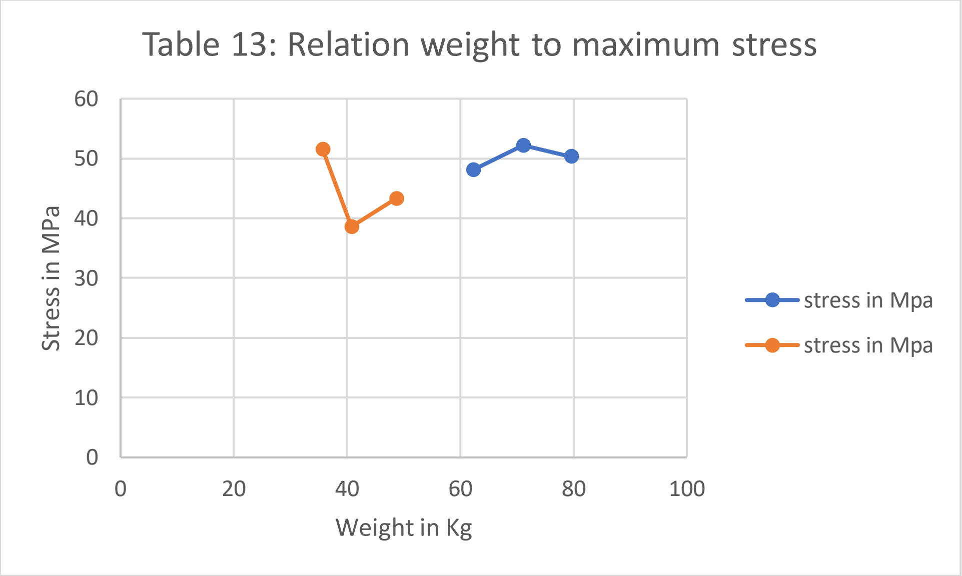
In tables 11 and 12 one can see the resulting deformation and equivalent stress of each of the analysed models.

Table 11: ANSYS results 2D bottom panel				
Cross section	Vertical solid	Horizontal 30%	Horizontal 25%	Horizontal 20%
Deformation	24,4 mm	12,9 mm	19,6 mm	15,3 mm
Stress	65,8 MPa	50,3 MPa	52,2 MPa	48,1 MPa

Table 12: ANSYS results 2D top panel				
Cross section	Vertical solid	Horizontal 30%	Horizontal 25%	Horizontal 20%
Deformation	31,9 mm	12,5 mm	11,7 mm	16,6 mm
Stress	23,1 MPa	43,3 MPa	38,6 MPa	51,5 MPa

Looking at the results it becomes clear that there are inconsistencies in the analysis as the ‘best’ performing infill % differs between the panels, this can be explain due to the fact that there was no exact location specified in the horizontal cross sections where the supports where placed, the same applied to the location of the applied force, although a template was used in the software to be within a couple of millimetre from one another this still made a big difference in the final results.

When graphing the weight/infill % against the internal stress it become clear that the found value’s are very inconsistent. Making is difficult to take any specific conclusions from the preformed simulations.



7.4 Conclusion on structural analysis

Four points merit attention when one does interpret the results from the ANSYS simulation.

Firstly, under all three infill percentages analysed, the internal stress of the panel did no exceed the yield strength of 66,9 MPa which that was provided by the producers of PET. This suggests that no permanent deformation is to be expected under normal use of this design.

Secondly, even though no failure may occur, deformation of the system varies considerably with the amount of infill. Because of the rails and interaction with the wall it is very unlikely that the found deformation could lead to misalignment between the panel and the wall. Therefore an assessment has to be made, based on user experience testing of the design, to indicate the amount of deformation deemed acceptable for this type of opening system. A full scale model would be required for such a test.

Thirdly, as the figure 43 illustrated, not every part of the panel requires the same amount of infill in order to function structurally. Based on the 2D simulation results , it can be predicted that a locally optimized infill can lead to significant reductions in weight with minimal loss of structural capabilities. This would require future research into topological optimization of the infill. An example of such research is the work done by Wu, Wang, Zhang, and Westermann(2016, p.35).

Finally, the simulation in this structural analysis has been performed under assumption of normal use of the opening system. Therefore another requirement for follow up research would be to perform an impact test on a full scale model of the proposed design.

8. Conclusion

The main research question of this research set out to solve was: “How can an openable surfaces be included in a mono material 3D printed tiny house, using FDM 3D printing?”

Based on the research the following points can be concluded

in a mono material tiny house made of PET, an durable openable surface can best be included through a sliding system. This system brings the least material stress in opening and closing when compared to the alternative movement systems explored. Even within curved walls which were assumed to be part of this project, a sliding system can be applied, provided that both the wall and the openable surface have a constant curvature on their horizontal and vertical axes so as to prevent collision.

Since door handles are points of interaction where most force will be applied by the user, a structural analysis has been applied. It was found that integrated, indented handles (vertical pockets) are subject to less mechanical stress and deformation, compared to extended handles.

Taking into account that this is a tiny house where the cavity holding the panel in opened position will take up a significant part of the total wall area, this will limit the amount of area available for windows. Although the PET used allows for daylight, opportunities for other functions provided by windows (like ventilation and viewing) would then be missed. To tackle this issue, a farm door solution was applied to the panel, allowing the top part to be opened separately, facilitating these latter functions if so desired.

A sliding system similar to that of a single panel door could be applied to the relative movement between the two elements of the farm door. The interlocking of the two elements may be arranged in several ways. A specific proposal has been suggested for a sliding pin. This solution however will require physical testing with a printed prototype.

Regarding the structural capabilities of the curved sliding panel, analysis has shown that an in-fill percentage of 30% commonly used in AM may lead to excessive weight of the panel, which would limit the usability and bring unnecessary strain on the sliding parts. A general reduction of infill for the entire panel was tested in simulation and was shown to be potentially feasible. However the found data was inconsistent and a more in depth research into this Also, other studies show that further weight reduction can be realized through localized in-fill optimization (in specific parts of the panel).

The fabrication of this type of sliding system through FDM 3D printing has been researched through small scale tests in PET; which led to the following conclusions:

- Since the sliding parts require high precision, production requires a controlled environment for printing in order to prevent the need of recalibration due to external changes in temperature, moisture content, and potential vibrations.
- A wear test on PET performed on small scale models in non-ideal conditions revealed no significant damage after 1 hour continuous sliding movement.
- Given the ways in which FDM printing generates geometry, the print-orientation proved to be a crucial factor in producing effective sliding elements. Several combinations of orientation proved possible, while the results of sliding tests showed that at least one of

the interacting elements has to be printed with its layers parallel to the direction of movement.

- From the previous conclusion, limits would follow for the production method available for the curved sliding panel: this would have to be printed in a sub-optimal orientation (laying flat) which would require a large print area, substantive support materials and potential limitations to the infill options of the panel. To prevent this problem form occurring, a solution was designed and tested in which it was shown that if wheels are added, these become the surface of interaction, thus taking the problem of printing orientation away from the panel.

9. Reflection

Looking back at the research process it becomes clear that the process differs quite a bit from the originally proposed process as it was depicted in the flowchart shown in 2.4. This can be explained for the most part by the lockdown due to the covid-19 pandemic. Another aspect that influenced the direction of the research was due to my initial underestimation of the time fabrication processes would require. Although I had prior knowledge with FDM 3D printing, the required time for recalibrations (now under exceptional external conditions) was much longer than I anticipated.

The conclusions in the previous chapter already indicated that not all initial sub-questions proved of equal relevance to answering my research question in the course of the design process. A brief reflection on specific answers found to these sub-questions from chapter 2.3, will explain why this was the case.

- How can geometry allow for a surface to be moved?

Geometry can facilitate movement through flexures, which are components designed to elastically deform when force is applied. These flexures bring very specific requirements for the material used; the initial tests quickly proved that PET is not suitable for such applications.

- How does the openable surface connect to the structure of the 3D printed tiny house?

The design-choice for an internally sliding surface has been explained above. This option assures that there is no fixed connection to the structure. The openable surface is structurally supported by the wall. However, this only occurs when force is applied to the panel.

- How does a 3D-printed openable surface hold up under use?

This question has been certainly important throughout the design process. The small scale tests that I was able to perform under limited conditions at home showed no signs of wear, however these results cannot be seen as representative for the final product. Larger scale tests would have to be done over a prolonged period of time to truly test the life expectancy of a 3D printed openable surface.

- How can one optimize geometry for large element 3D printing?

This question also proved highly relevant throughout my research, under exceptional conditions, both qualitatively as well as quantitatively. To begin with, as was mentioned in chapter 3.2. my initial material test was inconclusive. Time failed to redo the test with a larger sample size and different cross section, in order to see if the material properties provided by the manufacturer are maintained after the FDM printing process. Secondly, to optimize for FDM printing on any scale, the printer needs to be thoroughly calibrated before the actual fabrication can take place. Due to the Corona restrictions, prototypes had to be printed in non-ideal conditions, proving once more the importance of calibration. Thirdly, only very small scale prototypes could be printed at home to perform tests on. Moreover, no robotic arm was available for testing. This further increased the number of uncontrolled variables during these tests. Due to these exceptional conditions, no firm conclusions can be drawn from this research on the optimization of geometry for printing large elements. A follow-up research with a 1 to 1 scale model would be required to truly validate the design. Also, as was already mentioned in the conclusion , the weight of the final panel is crucial for a good functioning but also relevant for printing: the lighter the panel, the faster the production. Although my research added in the final phase does suggests possibilities of general weight reductions, further research under better conditions is needed to find the balance between infill percentages and structural properties in different parts of the curved panel which was designed for this project.

After commenting on the answers found to my specific sub-questions, let me close with two general reflections on this research.

Regarding the design process as a whole, one aspect I underestimated is that designing in mono materials makes certain criteria much more important than initially might be thought. Additional criteria are needed to tackle the new challenges that mono material construction would bring. This is due to the integrated nature of a mono material construction. Notably the aspect of maintenance proved much more prominent during the design phase than I originally thought. For example simple rubber gaskets to keep out dust and dirt are no longer an option when working in PET. Also, fairly late in the process it became clear that the cavity for the door should have openings at the bottom to allow water draining, and at the top as to allow for ventilation. Although recycled PET does not degrade due to water ventilation was needed to prevent fungal growth in the cavity. Adding specific design criteria on maintenance in an earlier stage would have improved the flow of the design process.

Secondly, the unexpected conditions under which I had to work have made me fully aware that this research is unfinished business. In order to truly assess the potential of the proposed design, follow-up research is necessary. Several possibilities have already been mentioned throughout this report. The most important of these (which could be embarked upon by future students of the graduation track) I consider to be the following:

- Structural analysis through physical testing of a full scale model of the farm door design.
- Structural analysis of the wall and floor. No door hangs in the air by itself. Without a structural analysis of the elements with which the design interacts, the results of this research cannot be validated.
- User experience research of the completed PET tiny house. Specifically in relation to my reported research, this could focus on explorations of life expectancy and it could further test my findings on different aspects of usability of the proposed design of the openable surface.

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Appendix

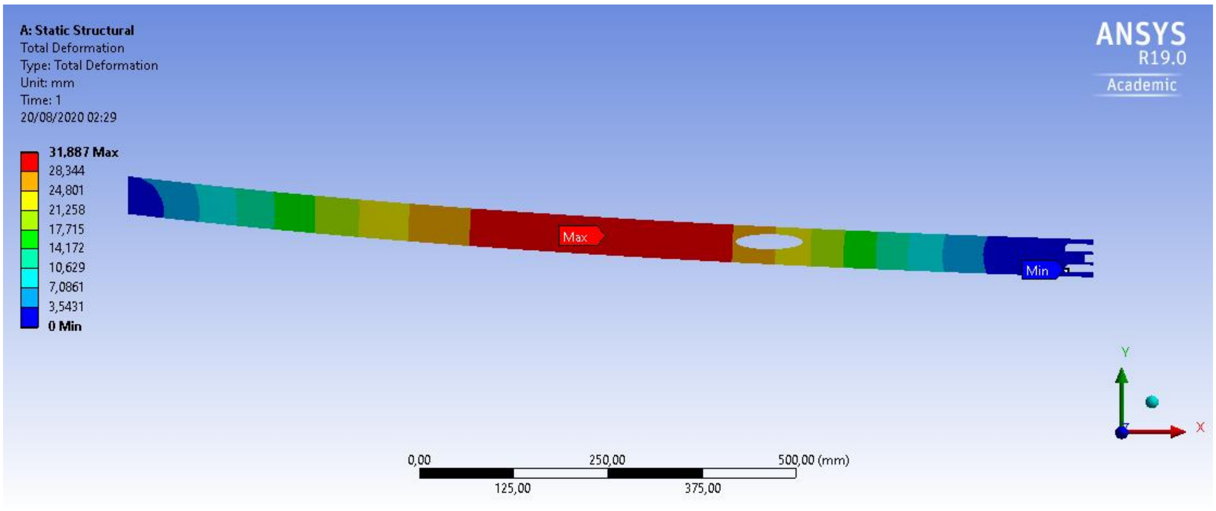
Results preliminary material tests.

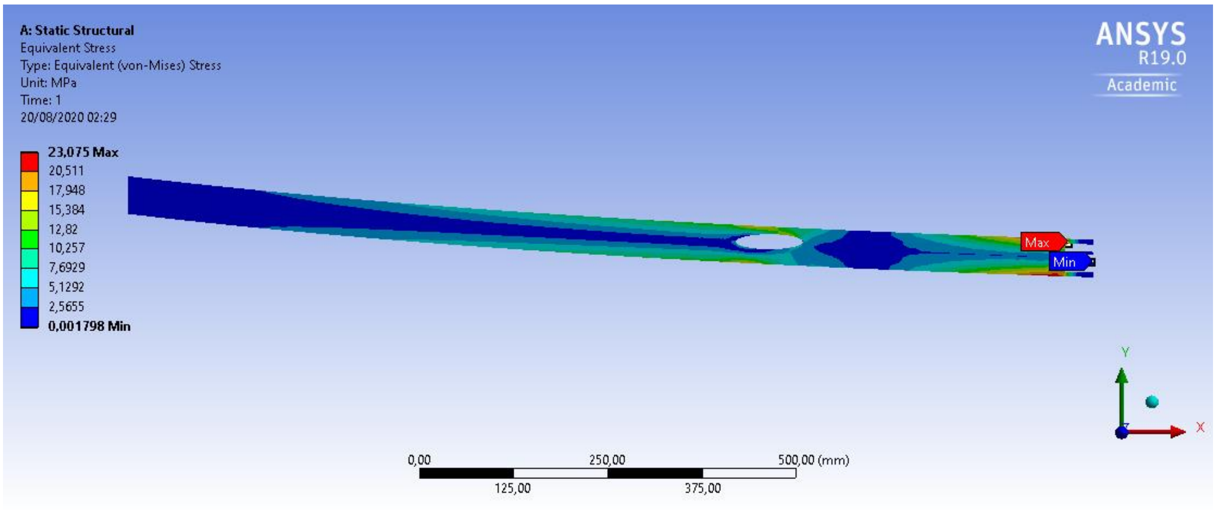
	F_{MAX}	ΔL AT F_{MAX}	F_{BREAK}	ΔL AT BREAK	TEST TYPE
	[N]	[mm]	[N]	[mm]	
SPECIMEN 1	1104,469	4,063222			4 point
SPECIMEN 2	1535,898	4,504811			4 point
SPECIMEN 3	1075,206	6,385003	1062,294	7,054975	3 point
SPECIMEN 4	1080,554	4,948217			3 point
SPECIMEN 5	920,692	5,511632	703,3525	10,30467	3 point
SPECIMEN 6	1008,944	4,589853			3 point
SPECIMEN 7	1015,215	5,058311			3 point
SPECIMEN 8	1174,542	5,379889	670,0541	12,12464	3 point
SPECIMEN 9	970,8277	5,193062	688,7646	19,10278	3 point
SPECIMEN 10	1087,455	4,913312	735,9935	19,36102	3 point
SPECIMEN 11	1271,836	5,394829			3 point
SPECIMEN 12	1064,921	4,533411			3 point
SPECIMEN 13	1174,617	4,796674			3 point
SPECIMEN 14	1089,876	4,771688			3 point
SPECIMEN 15	1148,911	4,794992	1148,655	4,851274	3 point
SPECIMEN 16	926,8436	4,732786			3 point
SPECIMEN 17	4363,576	4,889732	4363,576	4,889732	Compression
SPECIMEN 18	4572,379	5,767719			Compression
SPECIMEN 19	4968,19	5,618406			Compression
SPECIMEN 20	4278,357	6,063689			Compression

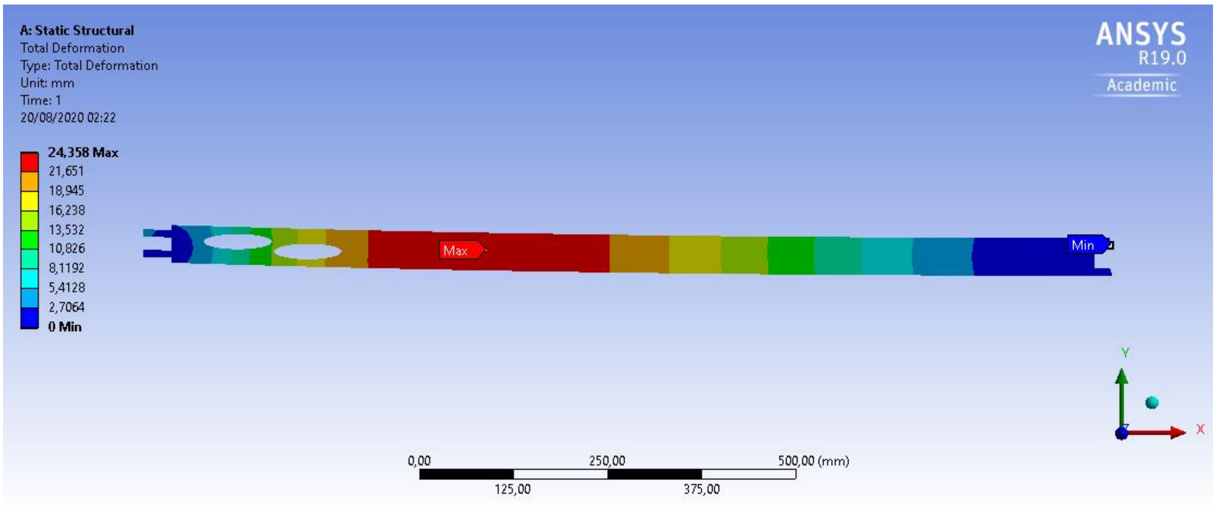
Small scale slide test results

TEST	DEGREES
PARALLEL-PARALLEL 1	12°
PARALLEL-PARALLEL 2	11°
PARALLEL-PARALLEL 3	12°
PARALLEL-PARALLEL 4	13°
PARALLEL-PERPENDICULAR 1	12°
PARALLEL-PERPENDICULAR 2	15°
PARALLEL-PERPENDICULAR 3	13°
PARALLEL-PERPENDICULAR 4	6°
PERPENDICULAR-PARALLEL 1	11°
PERPENDICULAR-PARALLEL 2	7°
PERPENDICULAR-PARALLEL 3	10°
PERPENDICULAR-PARALLEL 4	9°
PERPENDICULAR-PERPENDICULAR 1	24°
PERPENDICULAR-PERPENDICULAR 2	20°
PERPENDICULAR-PERPENDICULAR 3	25°
PERPENDICULAR-PERPENDICULAR 4	15°

Ansys results



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Total Deformation
Type: Total Deformation
Unit: mm
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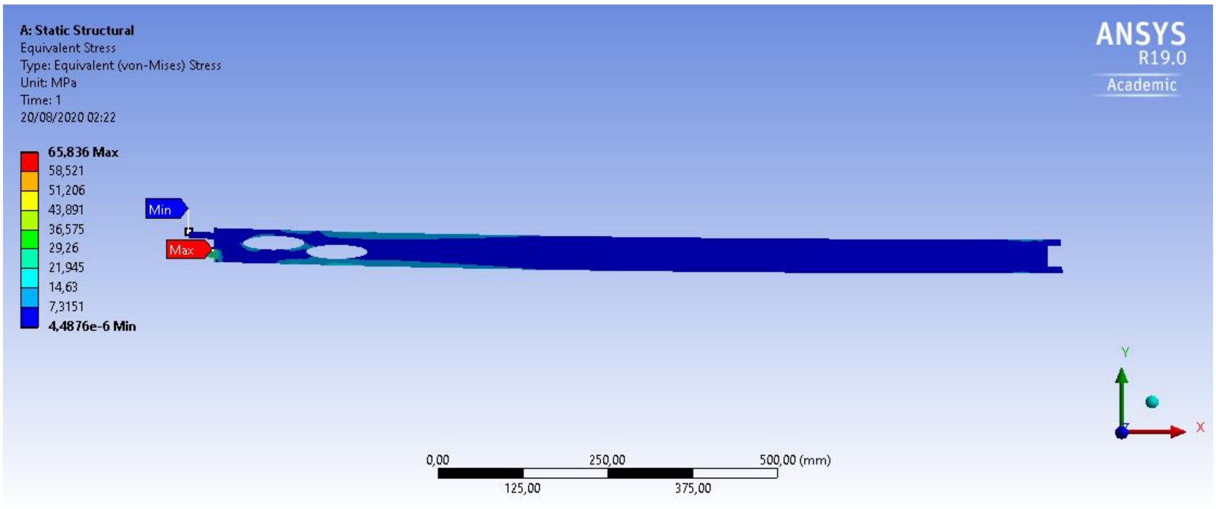
20/08/2020 02:22
24,358 Max
21,651
18,945
16,238
13,532
10,826
8,1192
5,4128
2,7064
0 Min
Max
Min
ANSYS
R19.0
Academic
Y
X
0,00
250,00
500,00 (mm)
125,00
375,00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Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
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20/08/2020 02:22
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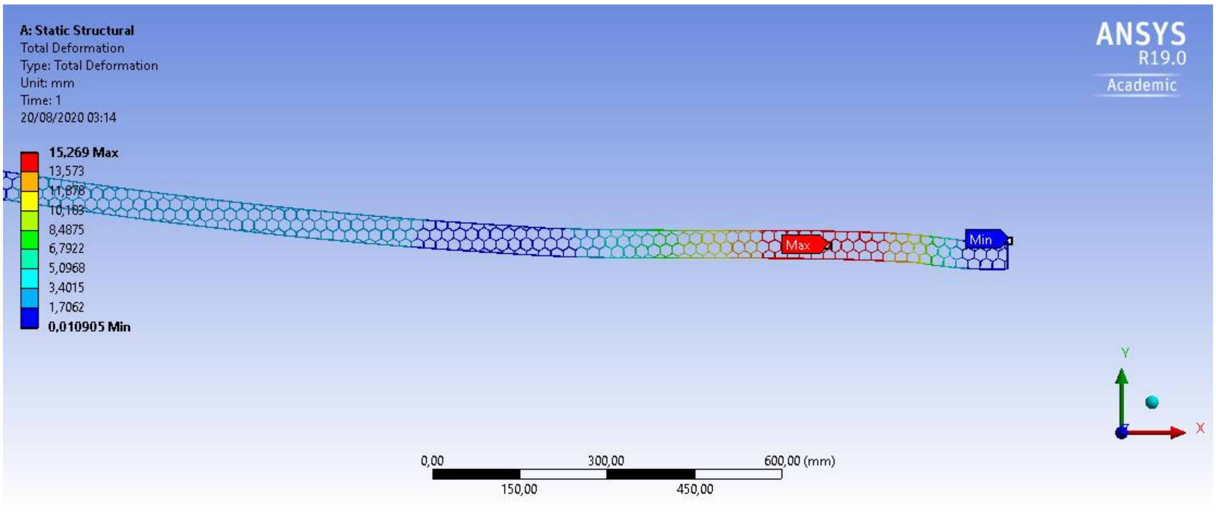
58,521
51,206
43,891
36,575
29,26
21,945
14,63
7,3151
4,4876e-6 Min
Min
Max
ANSYS
R19.0
Academic
Y
X
0,00
250,00
500,00 (mm)
125,00
375,00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Total Deformation
Type: Total Deformation
Unit: mm
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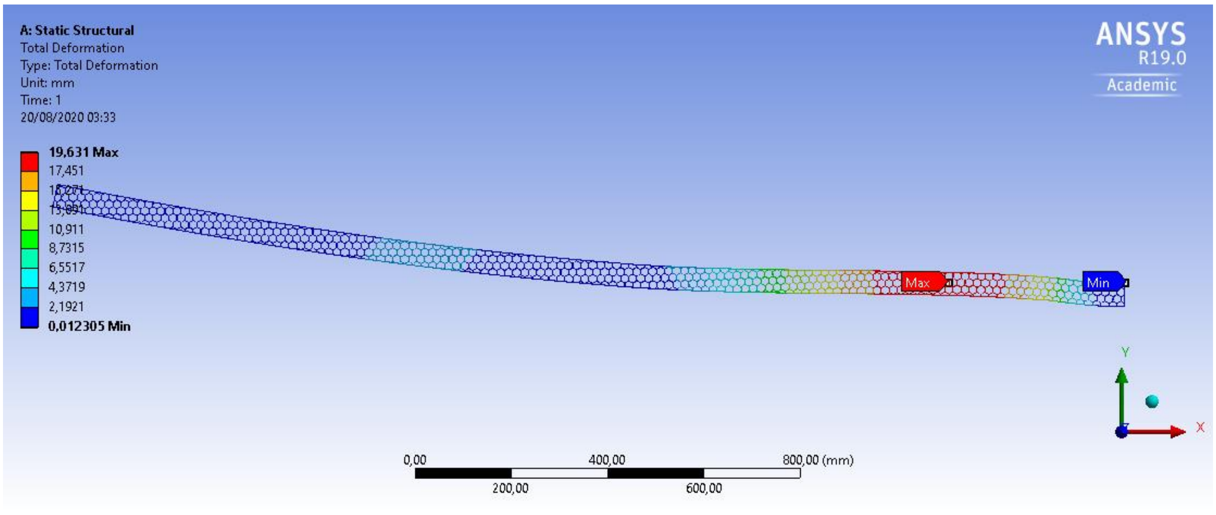
11,878
10,183
8,4875
6,7922
5,0968
3,4015
1,7062
0,010905 Min
Max
Min
ANSYS
R19.0
Academic
Y
X
0,00
300,00
600,00 (mm)
150,00
450,00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Total Deformation
Type: Total Deformation
Unit: mm
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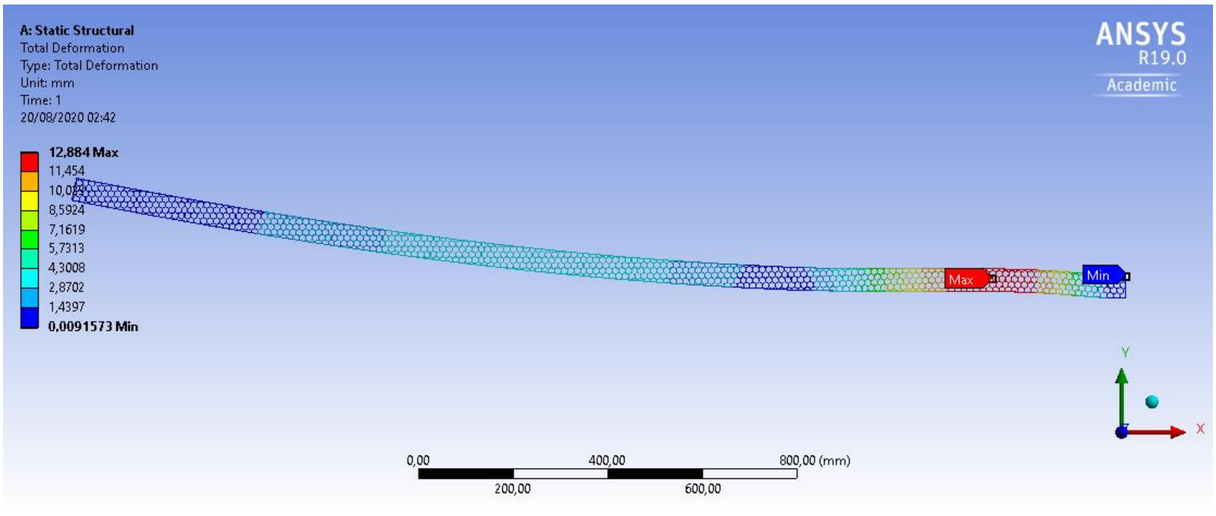
15,271
13,091
10,911
8,7315
6,5517
4,3719
2,1921
0,012305 Min
Max
Min
ANSYS
R19.0
Academic
Y
X
0,00
400,00
800,00 (mm)
200,00
600,00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Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
20/08/2020 02:42
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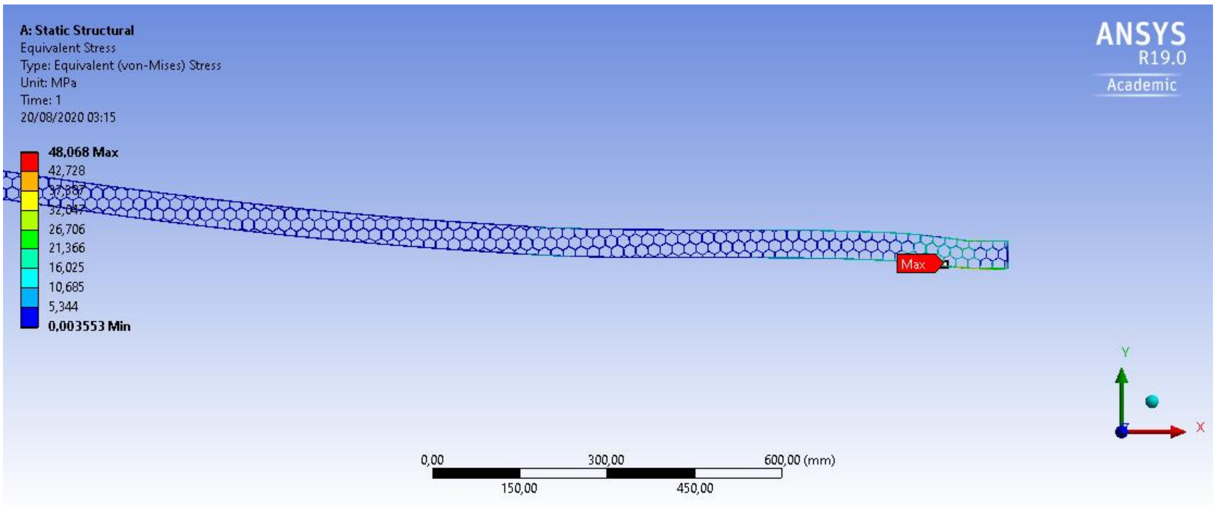
10,023
8,5924
7,1619
5,7313
4,3008
2,8702
1,4397
0,0091573 Min
Max
Min
ANSYS
R19.0
Academic
Y
X
0,00
400,00
800,00 (mm)
200,00
600,00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Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
20/08/2020 03:15
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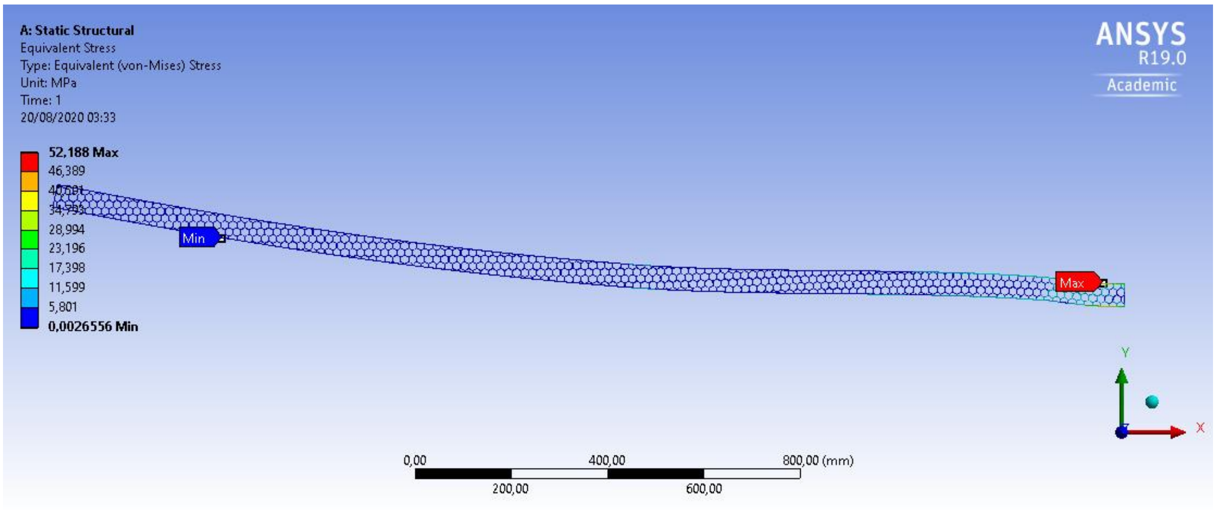
42,728
37,387
32,047
26,706
21,366
16,025
10,685
5,344
0,003553 Min
Max
ANSYS
R19.0
Academic
Y
X
0,00
300,00
600,00 (mm)
150,00
450,00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Equivalent Stress
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Unit: MPa
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20/08/2020 03:33
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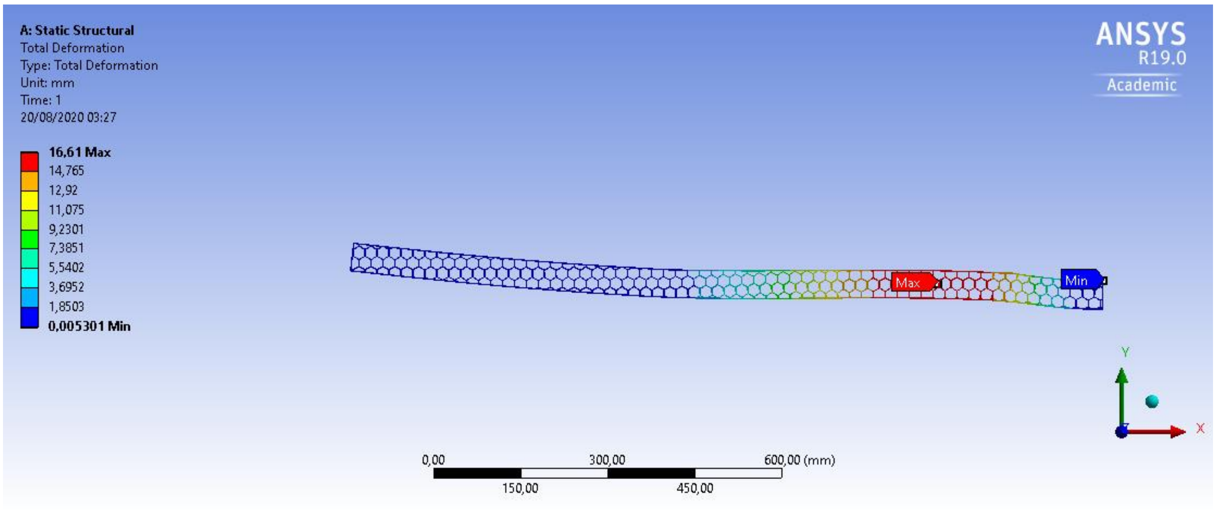
46,389
40,591
34,793
28,994
23,196
17,398
11,599
5,801
0,0026556 Min
Min
Max
ANSYS
R19.0
Academic
Y
X
0,00
400,00
800,00 (mm)
200,00
600,00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Total Deformation
Type: Total Deformation
Unit: mm
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20/08/2020 03:27
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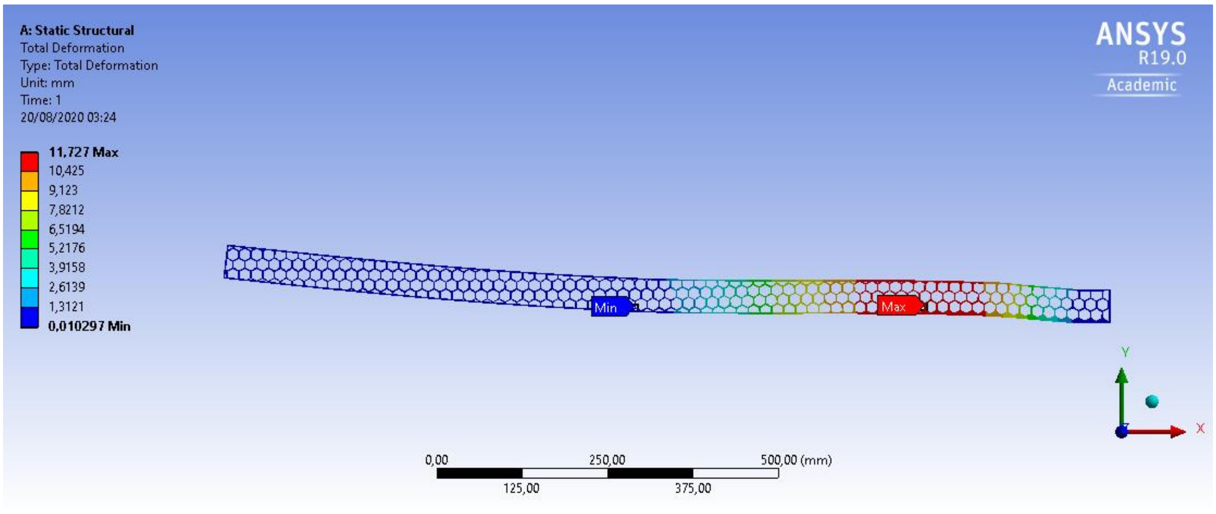
14,765
12,92
11,075
9,2301
7,3851
5,5402
3,6952
1,8503
0,005301 Min
Max
Min
ANSYS
R19.0
Academic
Y
X
0,00
300,00
600,00 (mm)
150,00
450,00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Total Deformation
Type: Total Deformation
Unit: mm
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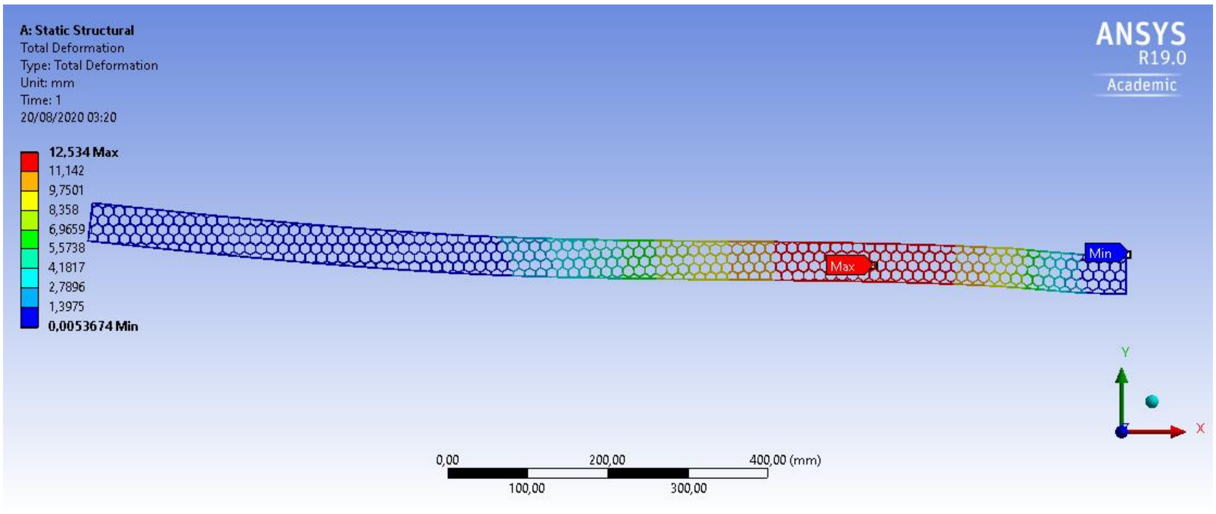
9,123
7,8212
6,5194
5,2176
3,9158
2,6139
1,3121
0,010297 Min
Min
Max
ANSYS
R19.0
Academic
Y
X
0,00
250,00
500,00 (mm)
125,00
375,00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Type: Total Deformation
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20/08/2020 03:20
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9,7501
8,358
6,9659
5,5738
4,1817
2,7896
1,3975
0,0053674 Min
Max
Min
ANSYS
R19.0
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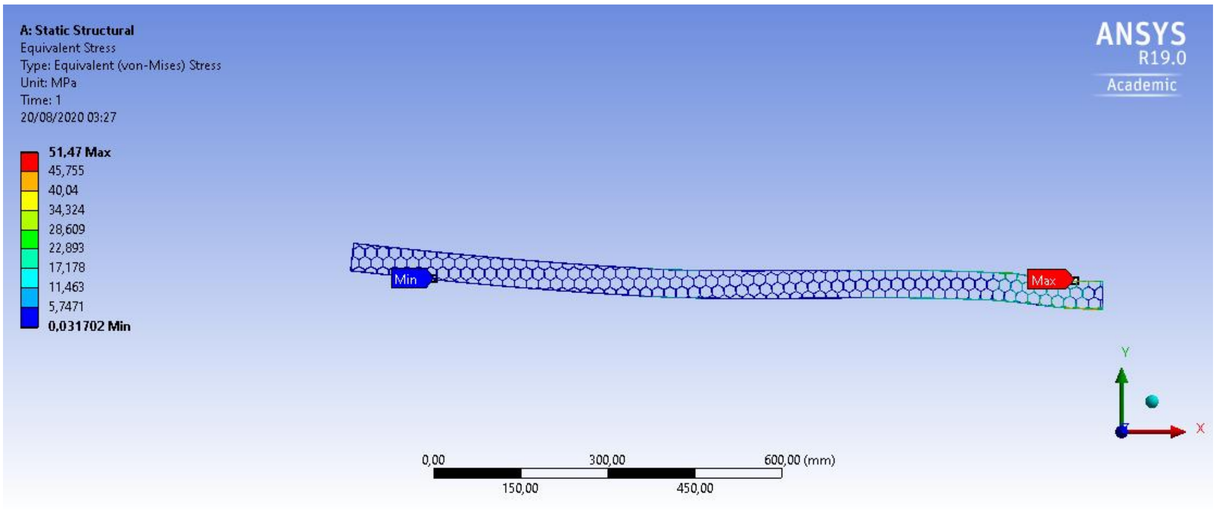
Y
X
0,00
200,00
400,00 (mm)
100,00
300,00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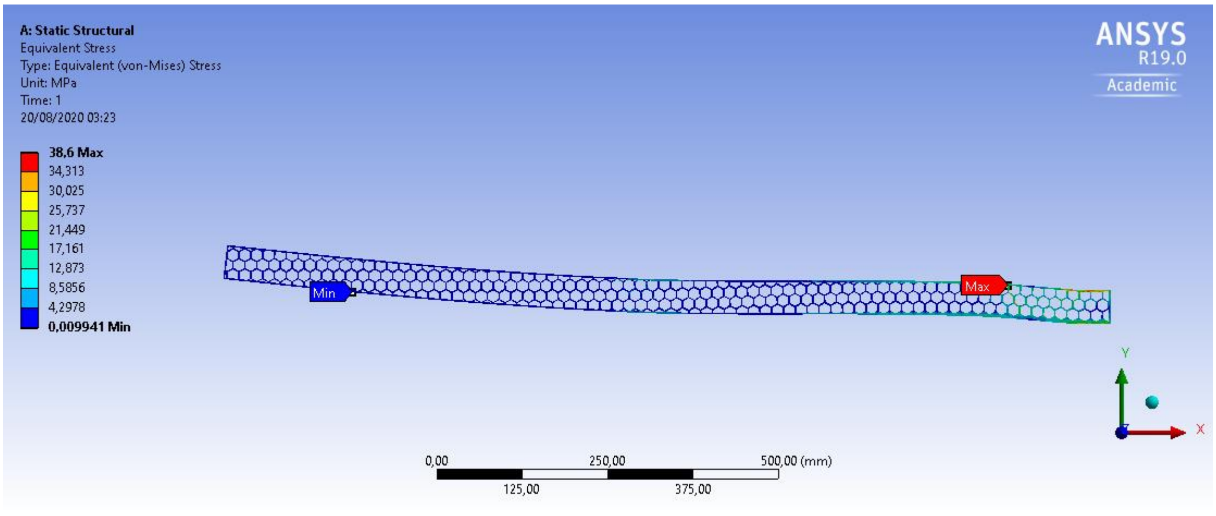
20/08/2020 03:27
51,47 Max
45,755
40,04
34,324
28,609
22,893
17,178
11,463
5,7471
0,031702 Min
Min
Max
ANSYS
R19.0
Academic
Y
X
0,00
300,00
600,00 (mm)
150,00
450,00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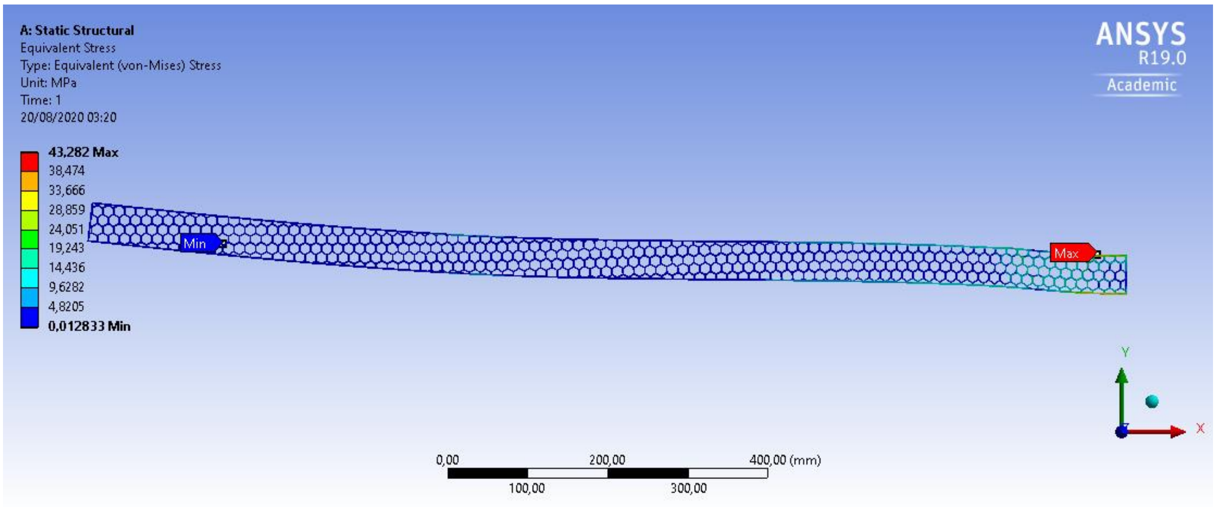
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
20/08/2020 03:23
38,6 Max
34,313
30,025
25,737
21,449
17,161
12,873
8,5856
4,2978
0,009941 Min
ANSYS
R19.0
Academic
Min
Max
Y
X
0,00
250,00
500,00 (mm)
125,00
375,00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Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
20/08/2020 03:20
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38,474
33,666
28,859
24,051
19,243
14,436
9,6282
4,8205
0,012833 Min
ANSYS
R19.0
Academic
Min
Max
Y
X
0,00
200,00
400,00 (mm)
100,00
300,00