Re[Mod]

reuse plastic & robotic modification

Ginevra Nazzarri
4744756
P2 report
03-01-2019

INDEX

1.0 BACKGROUND

1.1 Context

In the last few years, world cities have been generating about 1.3 billion tonnes of solid waste per year; and this volume is expected to increase to 2.2 billion tonnes by 2025 (Bhada-Tata et al., 2012).

The global impact of solid waste is becoming more worrying day-by-day, uncollected solid waste could encourage flooding, impact public health and air pollution; In fact, solid waste is an important source of supply of methane, a greenhouse gas that has a great impact on global warming.
The waste management industry, to deal with the problem, follows a generally acceptable hierarchy that is meant to take into account financial, social, and environmental issues
(Figure 1.1).

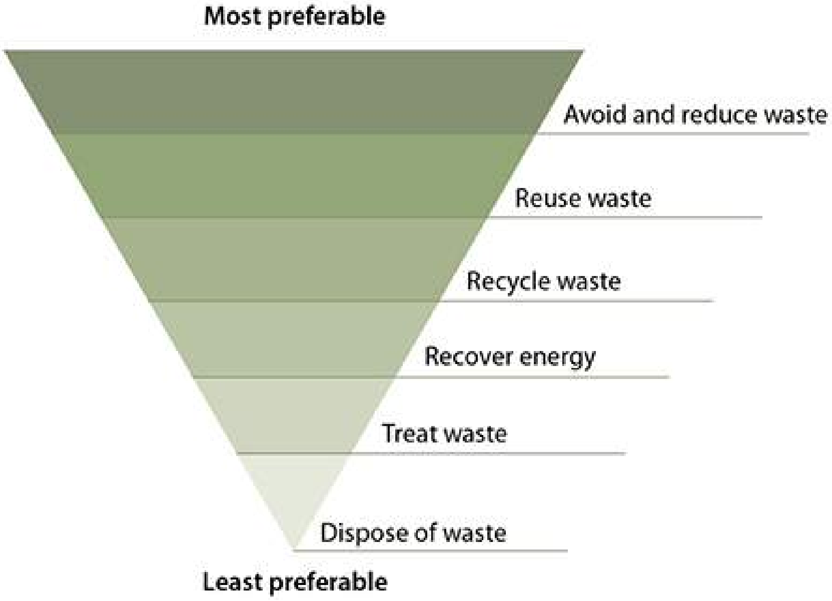


Figure 1.1: Waste hierarchy (Waste Avoidance and Resource Recovery Act, 2001)

However, even if reusing and recycling are increasingly encouraged and regulated by national and local governments, they often result more costly than landfill disposals.
In particular recycling can be considered as a good option if the environmental impact and the energy used to collect, sort, and recycle a material are less than the environmental impact and energy required to provide equivalent virgin material, plus the resources needed to dispose of the used material safely (Lave, L. B., et al. 1999). Therefore, considering also the often inefficiency of the recycling systems, reusing seems a better option.

In this context of changing climate, accelerated waste generation and large reduction of the resources, the building industry can play an important role in the system.

Indeed, the designer together with the constructor should consider since the design stage to think differently, in a more sustainable way, using in their project reclaimed or recycled materials or components, with the aim of reducing the amount of waste destined to the landfill and at the same time changing the way the building industry works.

Actually, in recent years there have been some signs of progress regarding the incorporation of recycled or reclaimed materials in the building industry. A successful case, for example, is the New Horizon together with the Urban Mining Collective, in the Netherlands, who recover useable components and raw materials from buildings demolition. In particular, Michel Baars, CEO New Horizon, affirms: *"Circular solutions demand creativity, other perspectives, and forms of application, experimentation and tried and tested methods. We want people to fall in love with a circular economy and design is essential for this. Because circular ideas offer so many opportunities but have not completely taken hold..."*
Furthermore, it is important to mention the problem of plastic composites that because of their many and different applications are now fundamental for the global world economy. While they also represent one of the biggest environmental issues nowadays.

Actually, plastics production has increased twentyfold since 1964, reaching 311 million tonnes in 2014 (Ellen MacArthur Foundation, 2017). Moreover, despite the economic crisis, the world plastics request is continuously increasing and it is expected to almost quadruple by 2050. Therefore with the increase of the plastic production, the plastic share of the global oil consumption and the plastic waste will increase as well, so much that in a business-as-usual scenario, the ocean is expected to contain by 2050, more plastics than fish (by weight).
Currently, the research about the plastic problem is on two levels, firstly the gradual replacement of oil into the manufacture of plastic materials by renewable bio-sourced materials. Secondly the organization of the end life of these plastics through recycling or reusing the products.

However recycling is not always the best option, in fact, soiled plastics and multi-layered plastic products, as an example, are often not suitable or difficult and expensive to be recycled. Therefore, these characteristics make them particularly suitable to be reused.
In this context of not recyclable plastic products, the built environment, while on one side is making a great effort trying to integrate the recycled plastic product into the construction market. On the other side is less progressive regarding the application of reused plastic product in the design; even though plastics is a suitable construction material for any application because it is lightweight and durable. Therefore, would be relevant to consider the appliance of not recyclable plastic components, as a means of construction.

1.2 Design-to-Robotic-Production

Goals of Industry 4.0

It is commonly defined as Industry the part of the economy that produces objects through highly mechanized and automatized systems. Ever since the beginning of industrialization, technological leaps have led to paradigm shifts, which today are ex-post named "industrial revolutions" (Lasi H., 2014). In particular, the first Industrial revolution was related to the mechanization field, while the second regarded the intensive use of electrical energy and the third concerned mainly the widespread of digitalization. Presently, we are in the middle of the fourth technological advancement with the rise of a new digital industrial technology called Industry 4.0.

The basis of this advancement lies in the growth of digitalization within the factories, together with the introduction of new future-oriented technologies in the field of “smart” objects, that regards modern machines and products.

Therefore, this transformation refers to modular and efficient manufacturing systems that will enable us to make processes faster, more flexible and at the same time more cost effective.
The aim of this new industrial revolution is to transform the production flow, from isolated to fully automated and integrated, increasing its efficiency and changing as well the relationship between human and machine.

Robots in this framework play a major role, in fact, even if they are already widely used in the manufactory industry; they are evolving, becoming more autonomous and responsive, and their price is expected to decrease as well.
For instance, Kuka, a European supplier of intelligent automation solutions, developed and placed on the market autonomous robots that are able to work with each other and collaborate with humans.

Likewise, another European supplier for digitally connected and enabled industrial equipment and systems had developed a two-armed robot that has the specific function of assembling products together with humans in a safe environment.

Advantages of Design to Robotic Production

From what mentioned previously, is clear that the question for the future is not anymore if robotic systems will be incorporated into building processes and physically built environment; but how is this going to happen (Bier, 2013).

In this scheme, it is important to understand that some tasks are better accomplished by humans, while others by machines; accordingly, it is crucial to develop future interaction scenarios between the two.
The aim is to involve the robot for tasks that require precision, mass production, and heavy work, while still reeling on humans regarding artistry and arrangements.

One of the most promising areas of the building construction for the employment of robot automation is considered prefabrication because some of its processes resemble the ones applied in industrial application (Vähä et al. 2013). However, there are many points to be considered that make the introduction of robots in building construction, quite demanding. Some points worthy to be mentioned, as the higher necessity in building construction for flexibility and adaptability compared to conventional industrial robot applications, the often inaccuracy of the design or the diversity of the building processes that are dissimilar for every building.

Therefore, the most suitable tasks for robots application are still represented by the ones that require a high level of accuracy, speed, constant motion and heavy loads.

2.0 PROBLEM STATEMENT

2.1 Main problem

How can computational design and robotic production help to reuse non-recyclable plastic in architecture?

As already mentioned in the introduction of the report, plastic waste is a great environmental problem that we have to face nowadays. In fact, it is not always possible to recycle plastic objects and sometimes it does not even seem the best option. Consequently, an enormous amount of plastic ends up in the landfill, polluting land and sea.

For this reason, it is becoming every day more important to apply circular economy principles in the built environment, reusing objects otherwise designated to finish in a landfill. To achieve this goal, great support could be given by employing computational design together with Design-to-Robotic-Production (D2RP) methods in order to create a system that could be applied to many different geometries, allowing a considerable amount of freedom in the design but at the same time avoiding randomness.

In fact, thanks to computational design it is possible to build a system that can be applied to many different shapes, while thanks to D2RP it is not lost the complexity and the high level of freedom in the design, because every component can be custom cut in a precise way.
This collaboration between circular economy principles together with computational design and D2RP will allow the designer to aid to the plastic environmental problem, saving many plastic objects from the landfill and at the same time originating constructions with a unique geometry.

3.0 OBJECTIVE

3.1 General objective

The general aim of this study is to contribute to the efforts in sustainable design research through the help of computational design, D2RP, and structural design.
In particular providing an alternative option to the traditional techniques applied in the building construction, promoting the practice of reuse in architectural design, delimiting as well the limits of it.
Firstly, the aim of this study is to build a system based on reused plastic components that could be applicable to many typologies of structure and geometry, allowing freedom in the design and encouraging as well geometry complexity, through the study of it in different scales, the material, the component, and the pavilion scale.
The second objective of this research is to find a few components, suitable for the design, from different points of view (strength, complexity, recyclability, shape, geometry…). In order to push forward the current research about reusing, avoiding the repetition of a single component but instead promoting the combination of different ones.

3.2 Final product

The final product of the design will be a temporary structure, in particular, a pavilion, for outdoor use during the summer season; could be employed for instance in festivals, events or even on our campus.

The design of the pavilion is highly flexible because it depends first of all on the desired shape, then on the tessellation of the faces of the pavilion, that could include the use of different polygons, such as triangles, quadrilaterals, pentagons and hexagons, and finally on the dimensions of the pavilion.

The different components will be placed within the pavilion scale according to different requirements, as structural ones, regarding the performance of the overall structure, the strength of each component and the optimal geometry. Moreover, the architectural aspects should be considered, in fact, it should be able to provide shade, therefore the transparency ratio and the number of openings should be placed in strategic locations.
Additionally, being a temporary structure, it should be easy to disassemble; therefore, all the connections should be made of solutions like snap fit or nut and bolt. Otherwise, in case the welding connection results more efficient, the size of two components welded together should be still manageable by hand.

To conclude, this typology of structures, based on components that are designated to end in a landfill, could have an interesting application in developing countries, where the construction materials are in short supply.

3.3 Boundary conditions

The main restriction for the research is certainly the application of reused components.
In fact, the research of possible components, that could be suitable to be used as a construction material, is the starting point of it.

The main requirements that would make a plastic element suitable for the design are the non-recyclability, the difficulty in reusing the objects in daily life, the strength and a wall thickness of at least 1 mm, in order to be able to perform snap-fit connections with D2RP techniques.
The connection between the components is, as expected, another important point to consider in the design, indeed to preserve the coherence of the project is preferable to avoid as much as possible the use of extra material, therefore, as stated above, snap fit and nut and bolt connections are favored.

In these circumstances, it is evalueted that the design outcome of the research should be a pavilion. Actually, is more appropriate to speculate about possible uses for the reused plastic components at a pavilion scale, avoiding the proposal of load bearing structure such as buildings. Most of all because the main material adopted for the research is plastic and even if it is a strong material, it would lead to fire safety issues.

However, even if a pavilion scale and in particular a temporary structure has certainly fewer constraints compared to a building, some requirements are still needed to be considered, such as the demountable feature, and the application of nearly zero extra material.
Moreover in terms of freedom in design, shape, and geometry, using reused components that were not entitled to be construction materials, requires from the architect more flexibility in finding a compromise between the overall design idea and the usage of existing objects.

In fact the overall way of thinking about the design it's changing; While on one hand, in case of a design based on new materials, the design process starts from the macro scale, where the designers identify the function of the structure, the shape and in a second moment selects the material.

On the other hand, for this research, the design process starts from the Meso scale, the component scale, and after studying some objects to understand if it could be feasible to use some of them for construction purposes; it was possible to identify possible uses for a structure based on such components.

4.0 RESEARCH QUESTIONS

4.1 Main research question

The study considers the hypothesis that plastic objects that are designated to end up in a landfill, could still have the potentiality to be reused, and some of them even be applied as construction material. Therefore, the introduction of this practice into the built environment would have great effects on the problem of plastic waste and on its share of the global oil consumption. In the context of sustainable design research, the following research question was formulated:

> *How can we reuse plastic objects in the building industry in order to contribute reducing the problem of plastic waste and its share of global oil consumption?*

4.2 Sub research questions

In the context of supporting a different way of thinking about plastics, according to the fundamentals of the circular economy, the following sub-research questions were defined, in order to establish:

> *How can we elongate the life of a product avoiding the use of new materials ?*
>
> *How could we use plastic objects in an upcycle scenario?*

The research will be conducted on different scales; hence, it will also be possible to conclude:

> *Which requirements do the plastic components need to have to be used on a pavilion or even on a building scale?*
>
> *What strategies can be adapted to connect the plastic components with each other without the use of extra material?*

In the framework of a wide range of opportunities offered by the current technology advancement and the Industry 4.0, the following sub-questions were formulated:

> *How can computational design and 3D scanning assist the designer in ideating a construction system based on reused components?*
>
> *How can robotic fabrication and assembly aid to the reuse of plastic components?*
>
> *What are the limits in shape and geometry when reusing objects and how can robotic fabrication help us to overcome them?*

5.0 APPROACH AND METHODOLOGY

5.1 Case studies

Blobwall

Greg Lynn, in his project called Blobwall, used as a starting point of his design, hollow plastic toys to reinvent hollow plastic rotomolded components. In fact, by means of 3D scanning, the plastic toys are first geometrically defined in 3D and then reproduced to create freestanding walls and enclosures. Each one of the components is custom cut by Computer Numerically Controlled robot arm and is specifically trimmed to a unique shape based on how it intersects with the next one. Indeed the complex interlocking between the components is defined through a 3D model, the intersecting curves are extracted and used to program the CNC robotic arm with a cutting head that custom trims each element.

The wall is therefore assembled and heat welded from individual robotically trimmed hollow components that interlock with exacting precision, eliminating the need for glue.
To conclude, the project of Greg Lynn results particularly interesting for this research because of the system behind its creation and assembly. In fact, using only one component that was meant to be a plastic toy, he was able to create a wall structure that has a similar logic to a traditional brick wall, changing the function of the plastic components from toys to construction materials.

Figure 5.1: Blobwall (Greg Lynn, 2005)

EcoARK

EcoARK is a massive pavilion built in Taiwan, it is made of 1.5 million recycled plastic bottles. The design is so accurate that the pavilion is able to withstand fires and earthquakes. It is also powered by solar energy and was built to the mantra of "Reduce, Reuse, and Recycle."

The basic component of the design is called "polli-brick", a hollow building block that has a shape similar to the one of a bottle and it is made of more than a million recycled PET bottles. The new building components fit perfectly together and they require only a small amount of silicone sealant. Once assembled are then coated with fire and water resistant film.
Moreover, the air inside the plastic components provides insulation against the heat and their transparency allows natural light to come through the building during the day.

Figure 5.2: EcoARK (Far Eastern Group & Arthur Huang, 2010)

One Bucket at a Time

One Bucket at a Time is a project in Mexico, for an interactive pavilion made of common painter's buckets that are connected together with a system of ropes. The structure works as a malleable surface that the visitor can roll, pull together or up to a point or along a line changing its shape and geometry. It is also interesting to notice that the temporary structure was used by the population to reclaim ownership of their public space.

Figure 5.3: One Bucket at a Time (Factor Eficiencia & 5468796 Architecture, 2017)

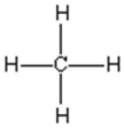
5.2 Research design

Micro - Material scale

The word plastic is used indiscriminately to refer to any artificial material, but there are thousands of different plastics.

Chemist and professionals prefer to define it in terms of its chemistry, calling it a polymer. In fact, plastic materials consist of many repeating groups of monomers in long chains and hence are also known as polymers. Its central atom is nearly always carbon, while the hydrogen atoms complete the basic molecular structure. For example, a one-carbon molecule attached to four hydrogen atoms is called "methane," a major part of natural gas that has a great impact on global warming.

The molecule methane looks like this:



Indeed the components needed to manufacture plastic are extracted from a variety of natural substances such as natural gas, petroleum, coal or other mineral and organic materials.

Plastic can be divided into two major categories:
1. Thermosetting plastics, such as polyurethanes, polyesters and epoxy resins.
2. Thermoplastics, such as polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC).

Thermoplastics represents the majority of polymers used today, in terms of recycling they are divided among 7 families. However, even if recycling is often possible, it is not always economical to do so, thus some plastics are recycled more often than others are.

Figure 5.4: Plastic packagings (BBC Analysis Data, 2018)

Meso - Component scale

The meso scale refers to the component scale and in case of a structure based on the reused object; it is the starting point of the design.

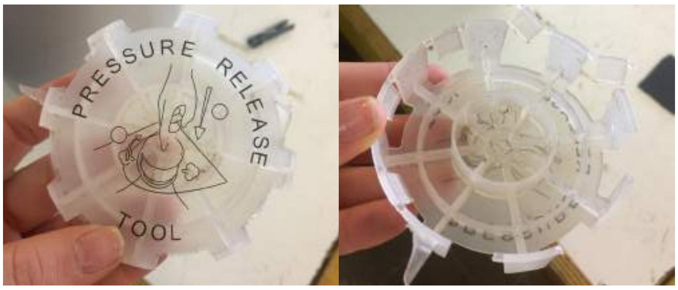
The research of possible components was performed according to some main parameters, such as the non-recyclability, the difficulty in reusing the objects in daily life, the strength and a wall thickness of at least 1 mm, in order to be able to perform snap-fit connections with D2RP techniques. Requirements already discussed in the paragraph regarding the Boundary conditions of the design.

Afterward, the research has been carried out from a physical point of view, through the exploration of different locations, however only two of them resulted relevant for the project.
The first location is called Scrap XL, a store in Rotterdam that gives to waste material a second chance. It is selling waste material such as plastic, cardboard, fabric, rubber, and others, to give to the people the occasion to build something out of it. Moreover, the shop is particularly interesting for the research because it is possible to find their many pieces of the same component. In fact, the items that are sold at the store, are coming directly from the manufacturing industry, therefore they are still in optimum condition.

The second location is a recycling shop present in different cities in the Netherlands, called Rataplan. For the purpose of the research were visited the Rataplan in Delft and the one in Spijkenisse. Despite the bigger amount of objects present in the two stores compared to the quantity available at Scrap XL, the latter appeared more suitable for the research. First because in the Rataplan is mainly possible to find objects that could easily be reused in daily life and second because is usually possible to find only one piece per each item.
After the research in the stores, some components were selected because suitable and interesting for the design.

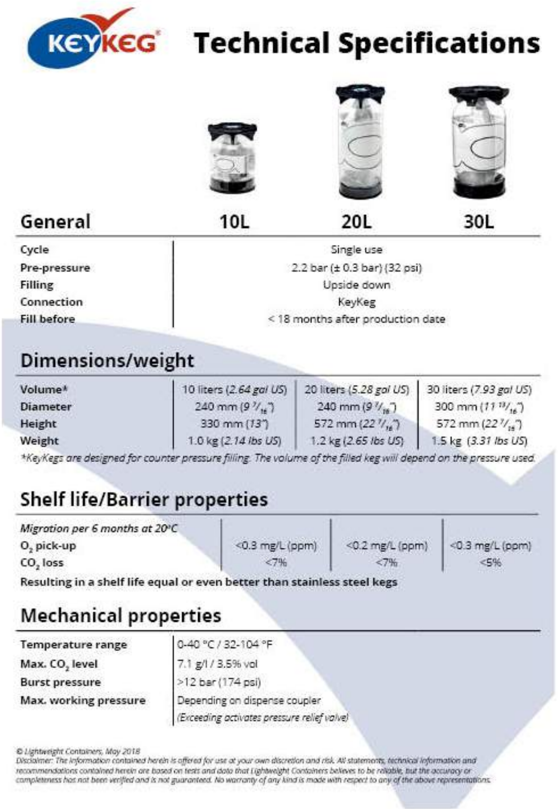
The first one is a disposable keg, which is used to store and transport beer, wine, cider, and soft drinks and it can be found in different design variations according to the brand. A pressure release tool is used to let out the air from the kegs.

Figure 5.5: disposable keg



Figures 5.6: pressure release tool (top and bottom)

Figure 5.7: different kegs design variations



KEYKEG

Technical Specifications

General	10L	20L	30L
Cycle	Single use		
Pre-pressure	2.2 bar (± 0.3 bar) (32 psi)		
Filling	Upside down		
Connection	KeyKeg		
Fill before	< 18 months after production date		

Dimensions/weight

Volume*	10 liters (*2.64 gal US*)	20 liters (*5.28 gal US*)	30 liters (*7.93 gal US*)
Diameter	240 mm (*9 $^{7}/_{16}$"*)	240 mm (*9 $^{7}/_{16}$"*)	300 mm (*11 $^{13}/_{16}$"*)
Height	330 mm (*13"*)	572 mm (*22 $^{7}/_{16}$"*)	572 mm (*22 $^{7}/_{16}$"*)
Weight	1.0 kg (*2.14 lbs US*)	1.2 kg (*2.65 lbs US*)	1.5 kg (*3.31 lbs US*)

**KeyKegs are designed for counter pressure filling. The volume of the filled keg will depend on the pressure used.*

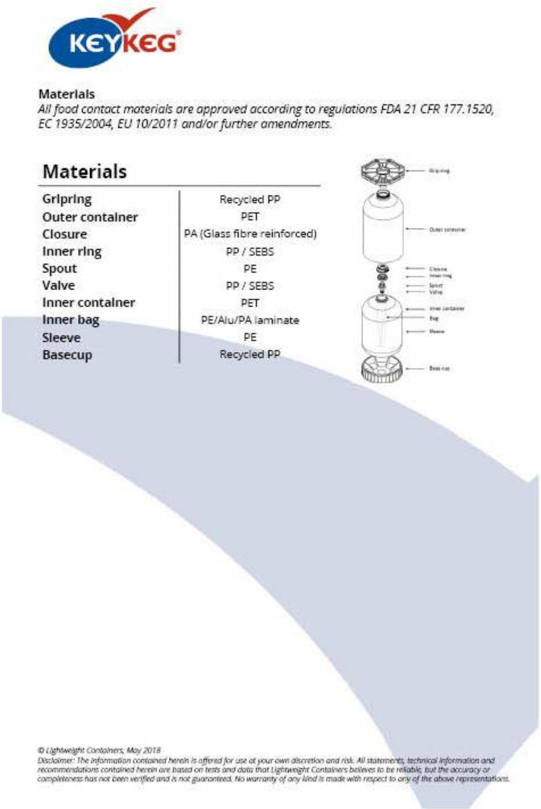
Shelf life/Barrier properties

Migration per 6 months at 20°C			
O_2 pick-up	<0.3 mg/L (ppm)	<0.2 mg/L (ppm)	<0.3 mg/L (ppm)
CO_2 loss	<7%	<7%	<5%

Resulting in a shelf life equal or even better than stainless steel kegs

Mechanical properties

Temperature range	0-40 °C / 32-104 °F
Max. CO_2 level	7.1 g/l / 3.5% vol
Burst pressure	>12 bar (174 psi)
Max. working pressure	Depending on dispense coupler *(Exceeding activates pressure relief valve)*



KEYKEG

Materials
All food contact materials are approved according to regulations FDA 21 CFR 177.1520, EC 1935/2004, EU 10/2011 and/or further amendments.

Materials

Gripring	Recycled PP
Outer container	PET
Closure	PA (Glass fibre reinforced)
Inner ring	PP / SEBS
Spout	PE
Valve	PP / SEBS
Inner container	PET
Inner bag	PE/Alu/PA laminate
Sleeve	PE
Basecup	Recycled PP

The second is a hollow and openable item used to transport and store a drill components and it is available in two different design variations from the same brand.

Figure 5.8: component 1 (left) and 2 (right)

Figures 5.9: open drill container

Figure 5.10: drill container

Technical Specifications

All the dimensions of the components are estimated with a measuring tape, therefore some degree of uncertainty that may come from a variety of sources should be considered.

Component 1
Bottom
Square Base: length and width of 11.6 cm
Circular base: diameter of 10.7 cm
Height: 18 cm
Thickness of the walls: 0.08 cm
Top
Circular Base: diameter of 11.5 cm
Height: 10 cm
Thickness of the walls: 0.08 cm

Component 2
Bottom
Hexagon base: side lengths of 7 cm
Circular base: diameter of 10.5 cm
Height: 15.5 cm
Thickness of the walls: 0.08 cm
Top
Circular base: diameter of 11.3 cm
Height: 17.9 cm
Thickness of the walls: 0.08 cm

The third one is used to wrap around cables of machinery to keep them in order and is available in two different heights and eight color variations.

Figure 5.11: cone component

Figures 5.12: color variation

Figures 5.13: typology 1 and 2 of the cones

Technical Specifications

As already stated above, in this case, as well as the previous one, all the dimensions of the components are estimated with a measuring tape. Therefore, some degree of uncertainty that may come from a variety of sources should be considered.

Typology 1
Circular bottom base: diameter of 7.3cm
Circular top base: diameter of 4.4 cm
Height: 23 cm
Thickness of the walls: 0.1 cm

Typology 2
Circular bottom base: diameter of 7.3 cm
Circular top base: diameter of 4 cm
Height: 26 cm
Thickness of the walls: 0.1 cm

Structural Tests

The three typologies of selected plastic components were then tested at the laboratory of the faculty of Mechanical, Maritime, and Materials Engineering (3ME) of the TU Delft, led by Dr. ir. F.A. Veer.

The tested specimens were laid in between two steel plates and subjected to the compression test. The test bench was a Zwick z10 with constant downward displacement, which was used to measure the force required for the deflection; the results were then transferred to an Excel environment. The results obtained from the compressive testing are saved in an excel file that plots the necessary force to reach a particular level of deflection. The "useful range" in which we can determine the compressive stress of our plastic components is then determined.

This is needed because once the components are compressed too much, their surface area increases resulting in a new equilibrium in which the allowable compressive strength becomes higher again, leading to inaccurate results. If such components were used in a structure, the structure would have already deformed excessively and collapsed before reaching the compressive limits.
To conclude the compressive stress is considered within the first "peak" of the F/d diagram, as such a peak is indicative that boundary conditions have changed (such as a cracked plastic component).

Results

The test performed in the laboratory were eight, where the specimens selected were eight as well but from three different typologies. In fact were tested the plastic components showed above in the meso scale; in particular, firstly two different kegs, then three drill containers and to conclude three cones of different colors.

The tested kegs showed a peak between 250 kg and 300 kg without deformations, then the kegs are deforming while releasing the gas. As expected, after the deformations the kegs start to fold on themselves, therefore the compressive strength becomes higher again because of the increased surface area.

Figure 5.14: disposable keg I test 1

Figure 5.15: disposable keg I test 2

The drill container is first tested alone, showing a peak close to 80 kg. The test highlighted that the base is the weaker part of the element; in fact, because there is a single layer, it starts to buckle out instead the central part results stronger because it is made of two layers.

Figure 5.16: drill container I test 3

The fourth test was then performed with two drill containers stacked on top of each other. This resulted in a complicated buckling test, most of all because the components are not connected but it was performed to analyze how the components interact together.
The peak was close to 75 kg and it was visible from the side, that with the increase of the load, the bottom component started to shift backward.

Figure 5.17: stacked drill containers | test 4

Afterward, the bottom component, retrieved from the previous test, was examined again, because even if the components are the same, they always behave slightly different on the buckling test.

Figure 5.18: violet cone | test 6

To conclude the cones objects were tested in three different colors, respectively violet, grey and green. The first tested cone, the violet one, showed interesting forces, with a peak around 300 kg but the plastic results brittle, in fact, it cracked. However, even when the crack is wide open, the cone still holds almost 300 kg.

Subsequently, the grey cone was tested, showing an example of perfect buckling. Indeed, how it is possible to notice also from the graph trend, the object results –more ductile than the precedent one, folding in itself and showing a peak around 450 kg.
It is clear from the test that even two plastic components that look the same but present only a small difference (in color), can have completely different behavior

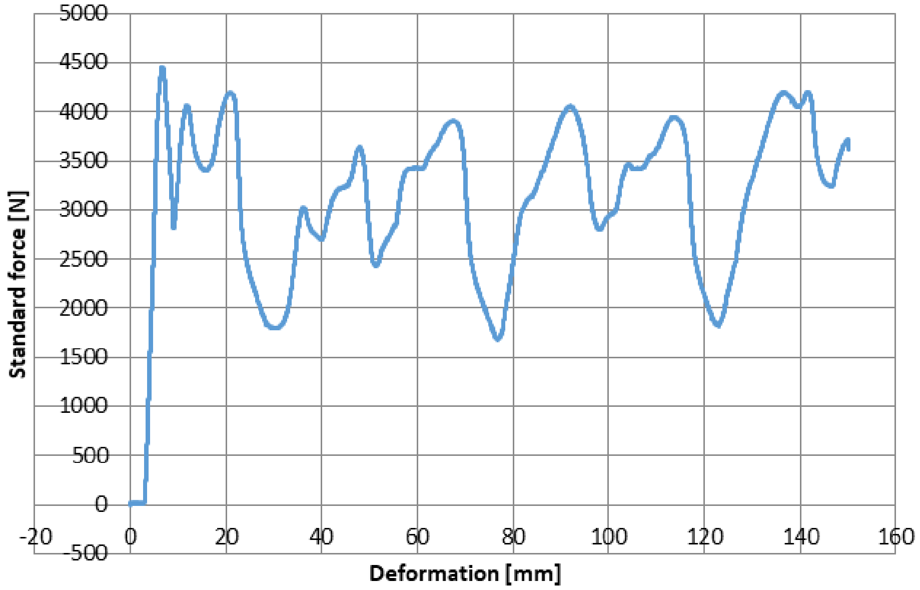


Figure 5.19: graph Force [N] / Deformation [mm] gray cone I test 7

Figure 5.20: gray cone I test 7

Figure 5.21: green cone I test 8

To conclude the green cone was tested, showing a behavior similar to the violet one, with a peak around 250 kg, when it starts to crack.

Macro - Building scale

The macro scale is the largest scale of the design and it refers to the geometrical organization of the components within the pavilion structure.
The design idea started from the analysis of the potentials of the components, to create a system and avoid randomness in the design. In particular, the concept is to take advantage of the flat base of the drill container object to create junction elements out of patterns of triangles, quadrilateral, pentagons, and hexagons to create stable structures; as it was already done by Buckminster Fuller in the '90s with the geodesic dome. In fact, a geodesic dome is a structure based on a geodesic polyhedron that is a geometry made of the repetition of triangles.

Therefore, the design was firstly studied in plan, through the positioning of the nail container object around some polygons shapes. Specifically, the system is based on the division of a random circle in different parts, where the center of the circle will be the center of the junction.
For example, if the circle is divided into three parts, it means that three components will be used for the joint and in this case, they will form a triangle in the center of the circle.
In the same way, if the circle is divided into four parts, four components are needed for the joint and together they will form a quadrilateral in the center of the circle. Likewise, applying the same system, if the circle is divided into five parts, the components will form a pentagon and if is divided into six parts, they will form a hexagon.

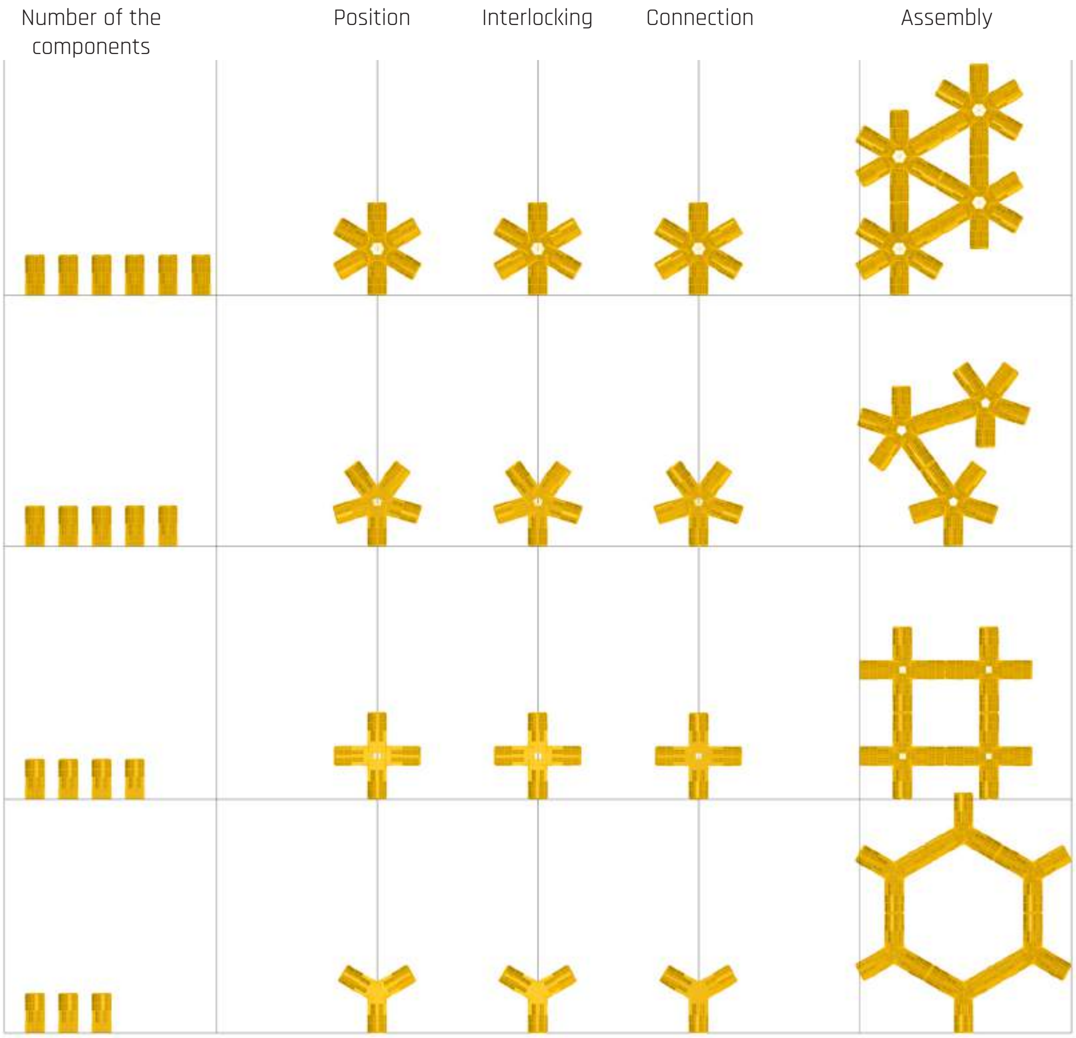


Figure 5.22: study of the design in plan

Moreover, it was studied in plan a method to connect the components together, cutting on one side the part where they overlap and leaving it on the other side, in a way to create a system based on interlocking components that could be bolted together, as is shown in Figure 5.24 for a junction made of six components.

Therefore, the junctions were repeated and assembled together vertex-to-vertex, originating as well different polygons shape, such as a hexagon for the connection based on three components, a quadrilateral for the connection based on four components or a triangle, for the connection based on six components (as is shown in Figure 5.25). While it was also discovered that the Pentagon could not be tessellated in plan (Figure 5.28) because in order for a regular polygon to tessellate vertex-to-vertex, the interior angle of the polygon must divide 300 degrees evenly.

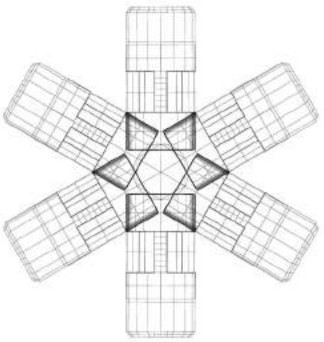


Figure 5.23: six components junction
Position

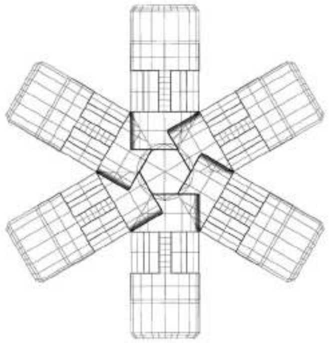


Figure 5.24: six components junction
Connection

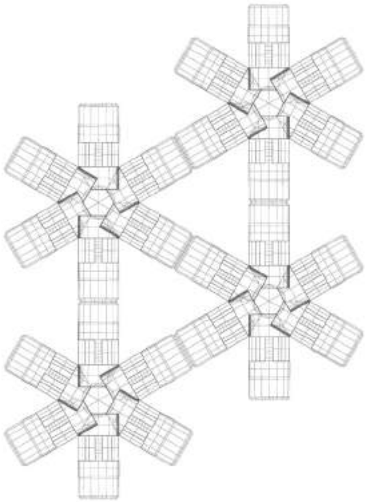


Figure 5.25: six components junction
Assembly

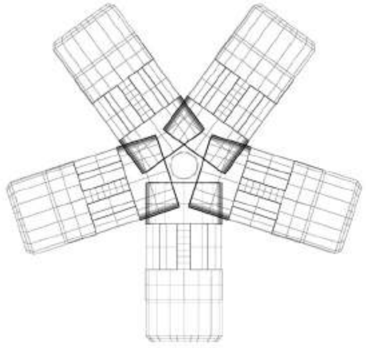


Figure 5.26: five components junction
Position

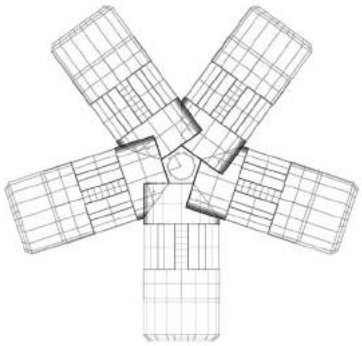


Figure 5.27: five components junction
Connection

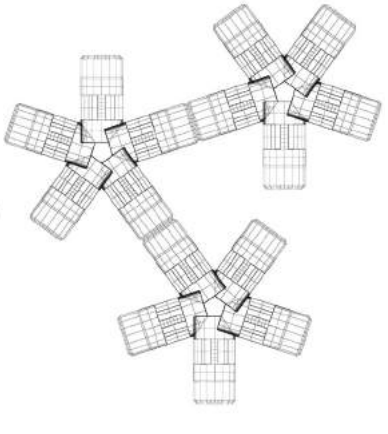


Figure 5.28: five components junction
Assembly

Consequently, the joint system based on pentagons that, as already stated, is the only one between the tested connections that is not tessellating in plan; was tested in the 3D environment, through the convex regular icosahedron, also simply called regular icosahedron. It is one of the five regular Platonic solids, which contains twenty triangular faces, with five faces meeting around each vertex. The structure is based on connections made of five components around each vertex and because of its regularity, allows all the connections to be the same.

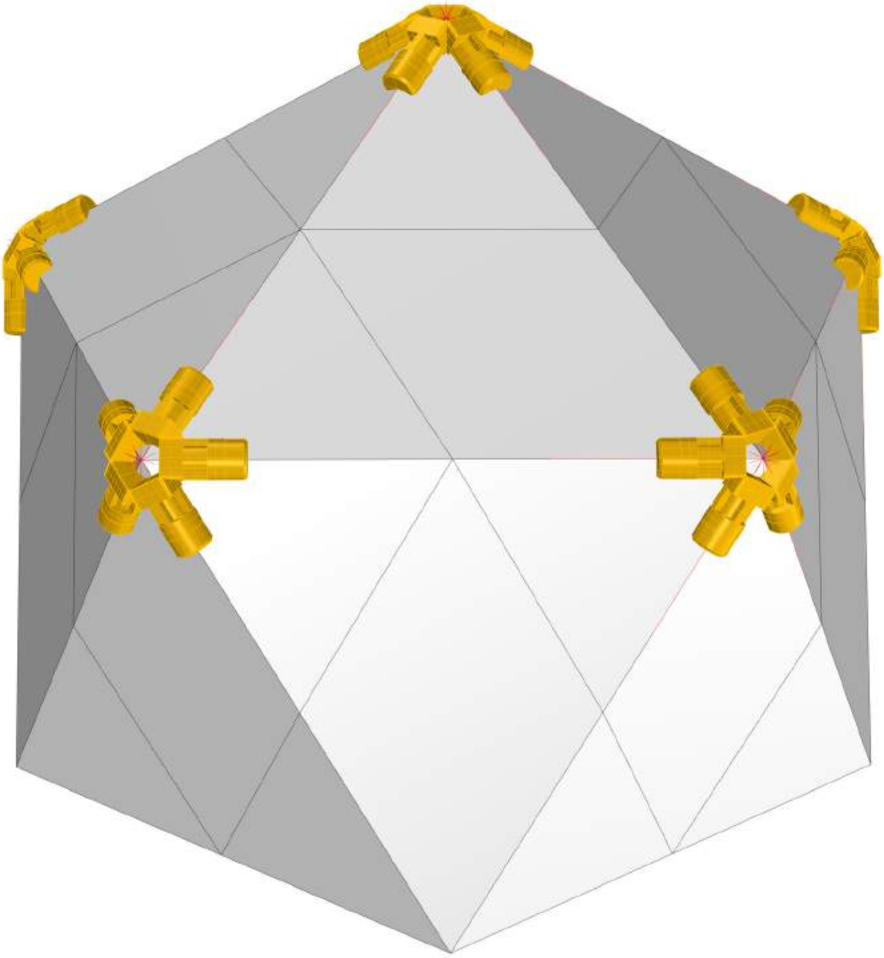


Figure 5.29: five components junctions placed on the vertex of a regular icosahedron

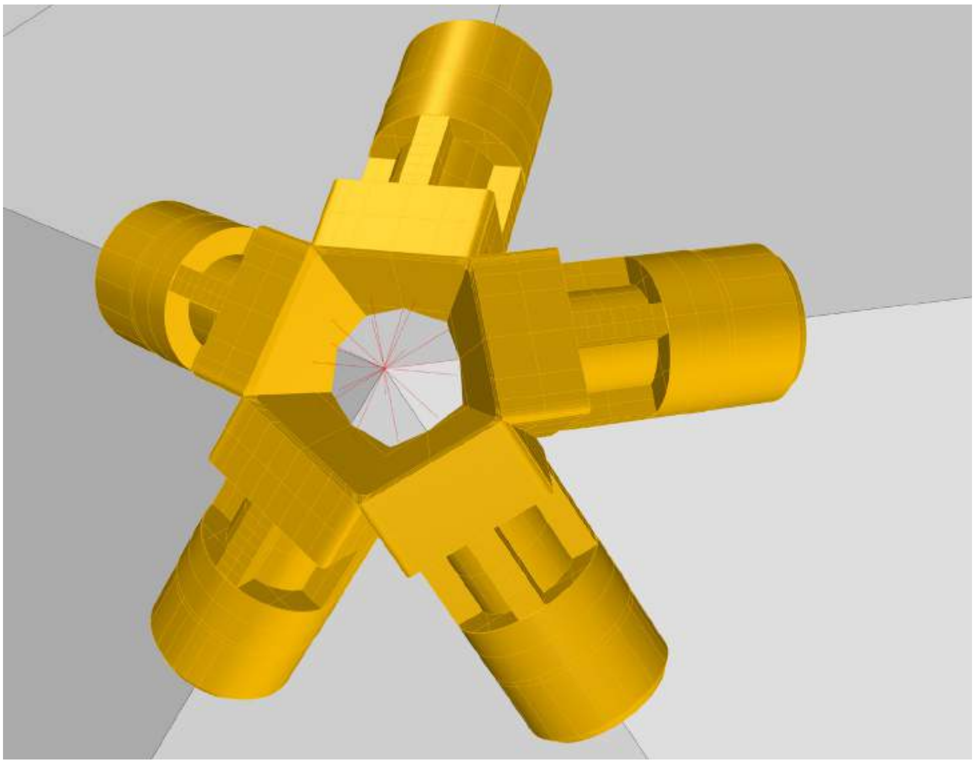


Figure 5.30: detail of the five components junction on a vertex of the regular icosahedron

5.3 Computational design

The role of computational design in the research is mainly related to aspects like simulation, optimization, and fabrication.

In fact, thanks to digital fabrication, the limits of what is possible to achieve are changing the design potentials. The designer has now the possibility to move a step forward from traditional geometry and to achieve geometry complexity through all the scales of the design (micro-meso-macro) enhancing the performance requirements and the design accuracy of the all structure.
Hence, if a digital model is optimized, is possible thanks to digital fabrication to realize a physical prototype of the exact same geometry.

Accordingly, it was ideated a script based on the idea of building a system that could tessellate every possible shape, placing the joints based on the nail container components, at the vertex of the tessellation.

The script is made of three main steps.
The first one includes the tessellation of the shape, or else the subdivision of a shape in faces based on polygons, such as triangles, quadrilateral, pentagons, and hexagons.

The second one regards the transformation from a volumetric structure to a ribbon structure, or rather extracting the ribbon structure of the tessellated shape, excluding the surfaces present on it.

The third step concerns the positioning of the components at the vertex of the structure originating the connections; the components are placed with an orientation that is perpendicular to the rib on two planes and parallel on another.

To conclude, by manipulating the input parameters (the initial shape and the ribbon structure), the outcome can be simulated for any kind of shape and therefore the best design option, with the ideal geometry and performances can be chosen.

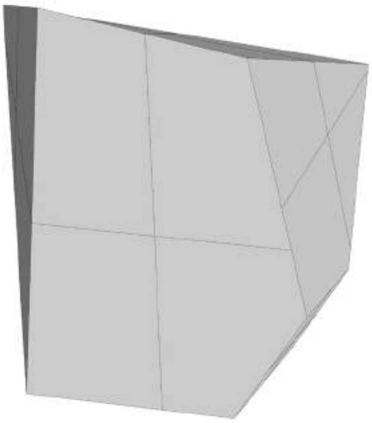


Figure 5.31: first step - tessellation of the shape

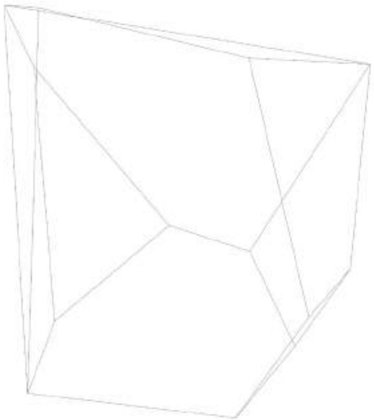


Figure 5.32: second step - transformation from a volumetric to a ribbon structure

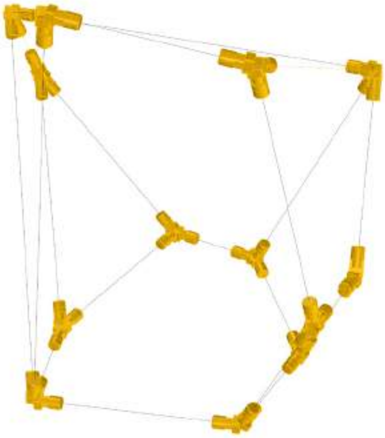


Figure 5.33: third step - position of the components at the vertex of the structure

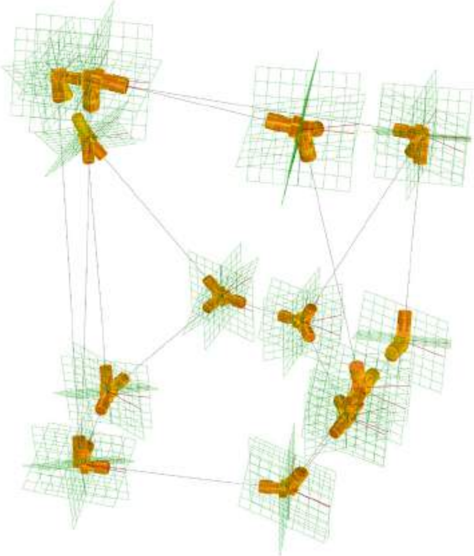


Figure 5.34: third step - orientation of the components according to the planes

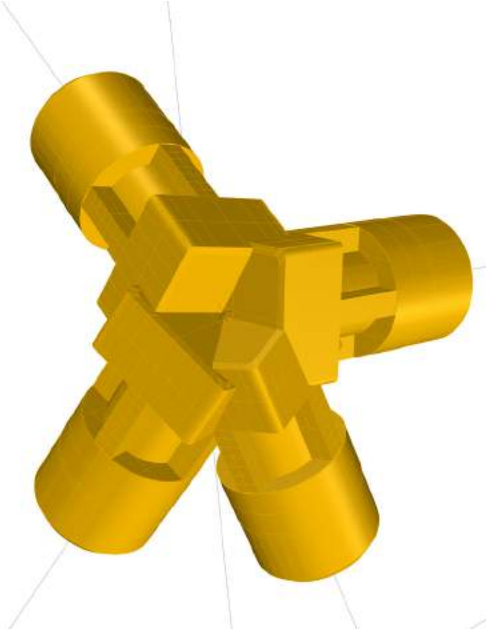


Figure 5.35: detail of one of the joint

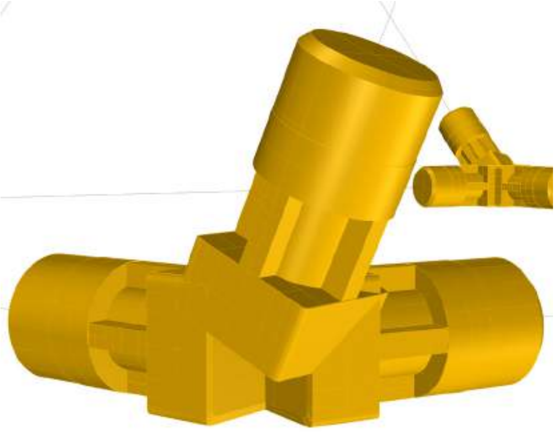


Figure 5.36: detail of one of the joints placed at the base of the structure

5.4 Design-to-Robotic-Production

Experimentation with robotics in architecture started with the use of animation software for design and later on the move was made from animation to scripting. Together with the use of scripting tools for procedural modeling, it started also to grow an interest towards form generation and digital fabrication. In fact, industrial robots are not new but have been in existence since the 1954 Ultimate, and the 1969 six-axis Stanford arm with computer controlled electronic movement (Testa P., 2017).

Moreover, robots have been used since the 70s for many manufacturing processes but only lately universities started to recognize their potential, exploring their application in architecture. Nowadays many academies are engaging industrial robots for the production of 1:1 prototype of building components, which will be integrated into buildings that are still designed and constructed in a traditional way.

Instead, D2RP aims to integrate robotic production in the building industry, individuating where is needed from the early stage of the design. Indeed D2RP facilitate the creation of a feedback loop between the digital design and the 1:1 scale prototype; starting from the already optimized digital model, it is possible to convert the design into robotic tool path to add, cut out or transform a material so as the researched design can be physically visualized.

On this purpose, starting from the best design option, with ideal geometry and performances, originated from the script; two D2RP tests will be performed for the connection of the components with each others.

The first D2RP test regards the robotic removal of a part of the component, in order to create a space to interlock (or fit) the components into one another. The connections are optimized according to the angle between the components, and thanks to the robot, the component can be cut at a specific optimum angle in an extremely precise and accurate way, while increasing speed.

Figure 5.37: part of the component to be robotically removed

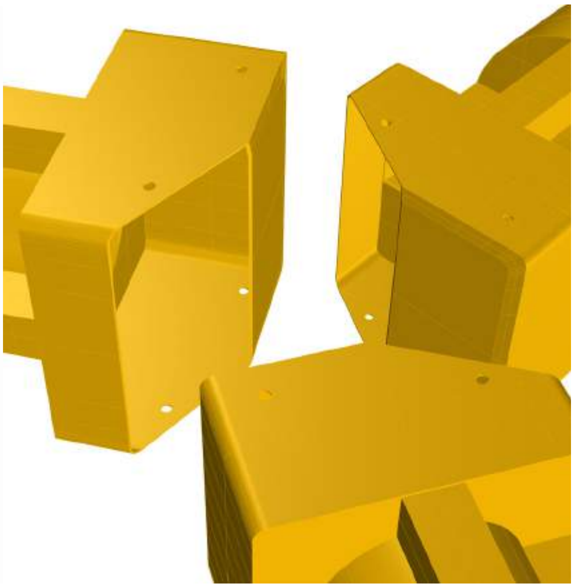


Figure 5.38: detail of the part of the component to be robotically removed

Moreover, the use of the robots results necessary for the kind of structures shown in the chapter above. In fact, thanks to the script, it is possible to apply this connection system based on recycled components for a wide range of complex geometry. However, just for the complexity of the geometry, all the components that form the connections need to be custom cut at a specific angle, thus the use of robotic fabrication will make the process more accurate and faster compared to traditional methods.

The second D2RP test concerns the robotically drilling of one hole on top and one on the bottom of the parts that are overlapping between the components, to ensure a stronger connection.

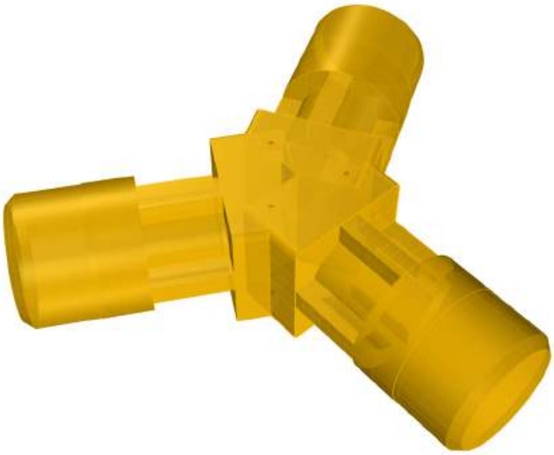


Figure 5.39: position of the holes to be robotically drilled

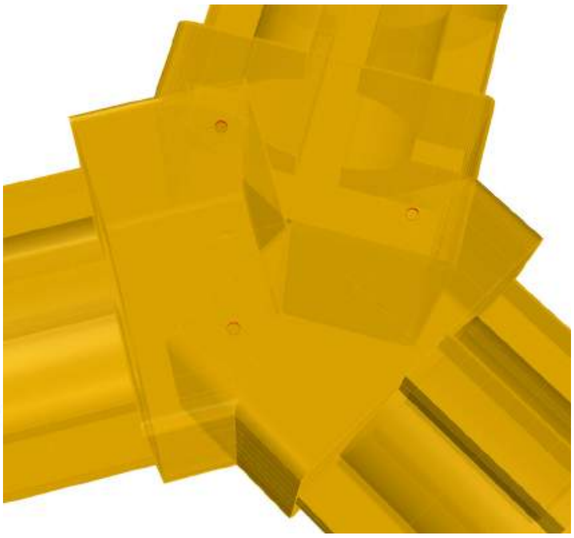


Figure 5.40: detail of the position of the holes (top and bottom) to be robotically drilled

The third D2RP refers to a technology that is particularly relevant when the designer is working with already existing objects, called 3D scanning, in particular, 3D scanning with the robot.
The abovementioned process will be explained more in detail and compared to other 3D scanning methods in the next paragraph.

To conclude, it is relevant to mention that robots technologies applied to the built environment, are still at their beginning so more research is required to develop prototypes that function at their maximum efficiency.

5.5 3D Scanning

3D scanning is a process that allows collecting data that can be used to realize a digital 3D model through the analysis of the shape and the appearance of a real-world object or environment. However, different techniques can be applied to compute 3D coordinates, such as geodetic surveying or photogrammetry; therefore, it is difficult to find a generally accepted definition of which instrument can be considered a 3D scanner.

Nevertheless, from the point of view of the user, can be considered a 3D scanner every instrument that automatically collects 3D coordinate of a given region of an object surface at a high rate and in real time. There are different typologies of 3D scanners because they can be used in fixed positions, as a mobile system on tripods or similar or as airborne systems for topographic applications (Boehler, W., 2001). Moreover, 3D scanners have different applications in many fields, they are widely used in heritage recording as well as 3D photography, remote tourism, construction industry, design process, and others.

For the purpose of the research, an Autodesk software called Recap Photo was employed. It is a desktop application, which utilizes Autodesk's upgraded Photo-to-3D cloud service to create a cloud-based solution tailored for UAV photo capturing processes and drone photo. Therefore, it is possible to create photo-textured meshes, photo-based point clouds with geolocation, and high-resolution orthographic views with elevation maps.

The workflow is basic; firstly, some photos of the object have to be taken for the reconstruction process. For the student, version is only possible to upload maximum of 100 pictures per project, while the minimum amount is the same as the subscriber's version that is 20 pictures per project. In principle, reconstruction is accurate within a ±1 pixel of the input images. However depending on the accuracy and resolution of the camera, lens system, camera shake, plus other related variables, and on the number of the pictures; as a result, the resolution of the model will change. After the uploading of the photos, a 3D mesh model will be originated on the cloud and then it will be ready to be downloaded.

Below are shown the first attempts of 3D scanning of the drill container component (showed in the paragraph called Meso-Component scale) with the Recap Photo software according to different variables.

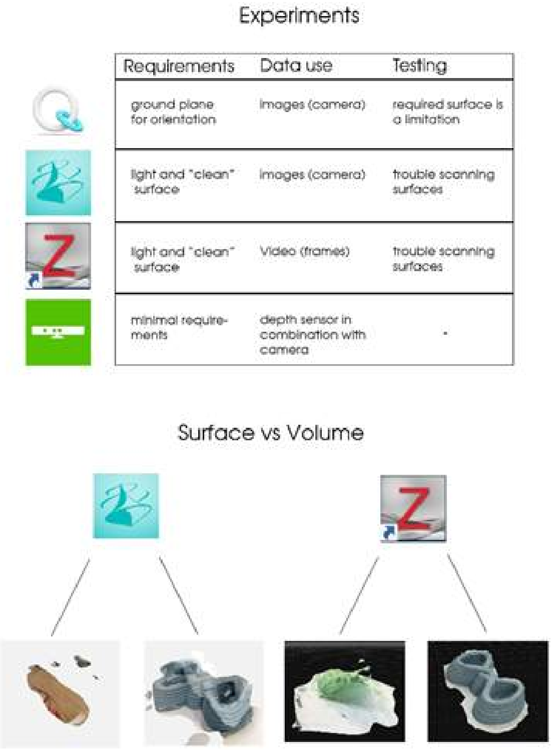
First test
Number of photos: 22
Camera: iPhone 5S, 8-megapixels, size of the pixels equal to 1.5 microns
Background: neutral-white

Second test
Number of photos: 20
Camera: iPhone 5S, 8-megapixels, size of the pixel equal to 1.5 microns
Background: neutral-white, image cropped to fit only the component

Third test
Number of photos: 33
Camera: iPhone 5S, 8-megapixels, size of the pixel equal to 1.5 microns
Background: colorful base, top view images included

From these first attempts is clearly visible that, as already stated above, the higher the amount of the images, the better the resolution of the model. Moreover, is also possible to notice that the resolution of the model improves with a background that creates some contrast with the component.

Concluding, is important to mention that during the course of the design and of the research, more 3D scanning software will be tested to find the most suitable for the project. Taking into account also the research carried out by Sina Mostafavi at the Robotic Building studio of TU Delft regarding 3D scanning, the solution that concern 3D scanning with the robot results the most promising one, considering the results obtained (Figure 5.42).



Experiments

Requirements	Data use	Testing
ground plane for orientation	images (camera)	required surface is a limitation
light and "clean" surface	images (camera)	trouble scanning surfaces
light and "clean" surface	Video (frames)	trouble scanning surfaces
minimal requirements	depth sensor in combination with camera	-

Figure 5.41: research regarding 3D scanning possibilities (Robotic Building, TU Delft, 2017)

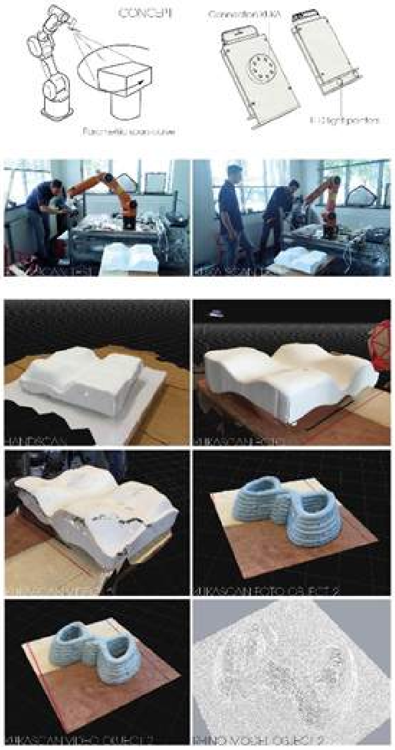
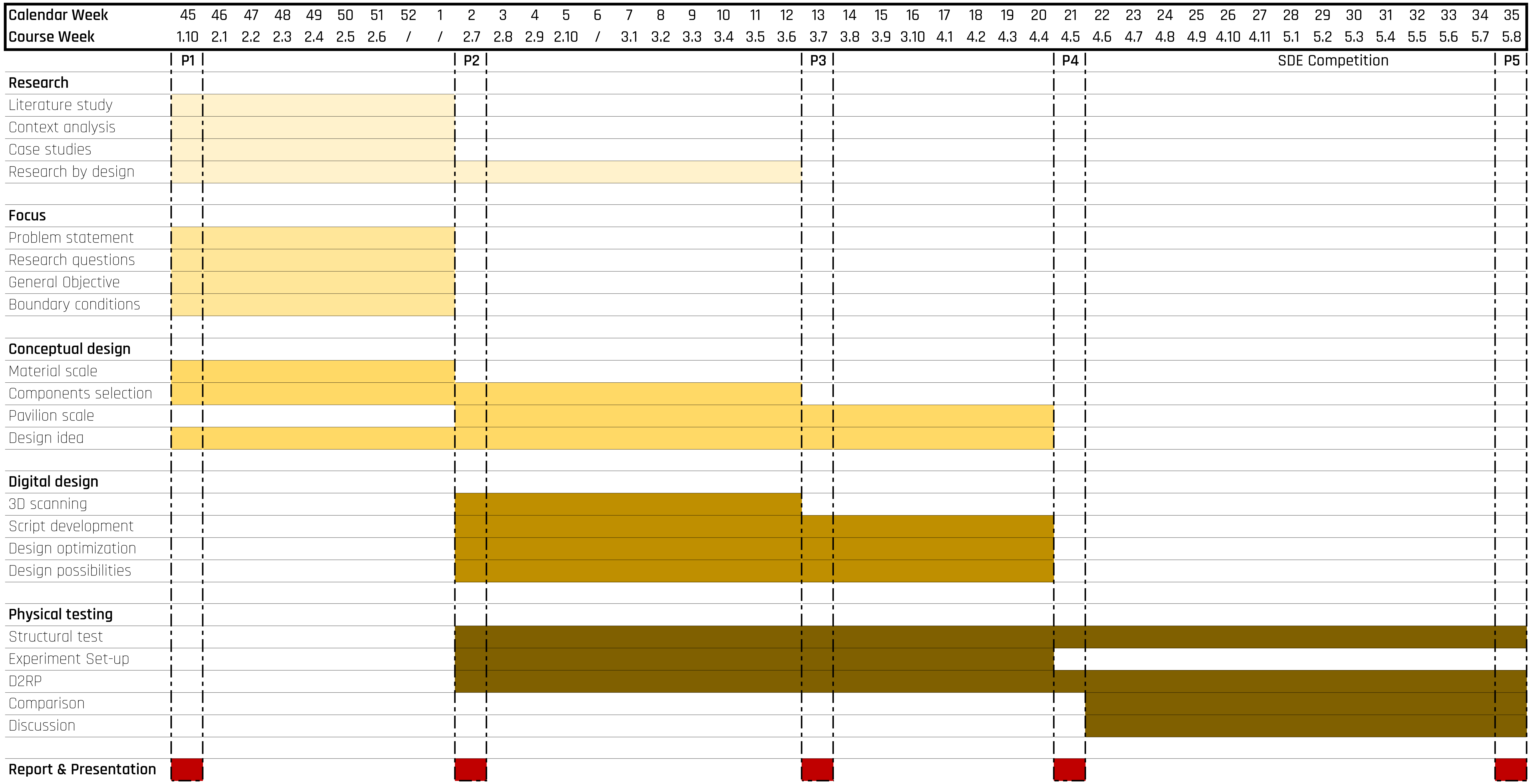


Figure 5.42: 3D scanning with the robot (Robotic Building, TU Delft, 2017)

6.0 PLANNING AND ORGANIZATION



Calendar Week	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Course Week	1.10	2.1	2.2	2.3	2.4	2.5	2.6	/	/	2.7	2.8	2.9	2.10	/	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	4.10	4.11	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8
	P1									P2											P3								P4							SDE Competition							P5
Research																																											
Literature study	■	■	■	■	■	■	■	■	■																																		
Context analysis	■	■	■	■	■	■	■	■	■																																		
Case studies	■	■	■	■	■	■	■	■	■																																		
Research by design	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																							
Focus																																											
Problem statement	■	■	■	■	■	■	■	■	■																																		
Research questions	■	■	■	■	■	■	■	■	■																																		
General Objective	■	■	■	■	■	■	■	■	■																																		
Boundary conditions	■	■	■	■	■	■	■	■	■																																		
Conceptual design																																											
Material scale	■	■	■	■	■	■	■	■	■																																		
Components selection	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																							
Pavilion scale										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															
Design idea	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															
Digital design																																											
3D scanning										■	■	■	■	■	■	■	■	■	■	■																							
Script development										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															
Design optimization										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															
Design possibilities										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															
Physical testing																																											
Structural test										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Experiment Set-up										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															
D2RP										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Comparison																														■	■	■	■	■	■	■	■	■	■	■	■	■	■
Discussion																														■	■	■	■	■	■	■	■	■	■	■	■	■	■
Report & Presentation	■									■											■								■														■

7.0 RELEVANCE

7.1 Societal Relevance

Plastic has become the most common material used in the modern economy, because of its practical properties and the low budget needed. Its use increased in the last half-century by twenty-fold and it is expected to increase even more in the coming twenty years. Indeed nowadays, every person around the world is exposed to plastic multiple times during the day on a regular basis.

Moreover, also Catherine Novelli-, the U.S. undersecretary of state for Economic Growth, Energy and the Environment states:
"Plastic products have an undeniably important role in our society. Plastic waste should not. Not only does plastic waste pollute our land and ocean but the loss of plastic from the current plastic economy is an economic drain. Plastic waste is a problem we can solve and need to solve now. And the solutions are many. Near-term benefits will be made by better waste management and less use, especially single-use, of plastic. But ultimately this problem requires a circular economy approach, where used plastic becomes a feedstock rather than a waste"

In this context, the research aims to contribute to a sustainable future based on circular economy principles through the employment of reused plastic object in the built environment. In fact, in a world where sustainability aspects are being integrated into several scientific fields, the construction industry plays a highly contributing role. Furthermore, even if the plastic problem has been discussed extensively, it is still not widely embraced by designers through its employment as construction material. Therefore, the value of this graduation project is to underline the role of the built environment in the plastic problem, and most of all to individuate a system in order to make use of waste plastic objects in the architecture field.

7.2 Scientific Relevance

From a scientific point of view, the research will provide a reliable methodology to produce complex architectural geometries through the reuse of plastic components in the built environment, in particular on a pavilion scale. Additionally, the study promotes the use of computational design together with D2RP (Design-to-Robotic-Production) technologies to provide a system in order to reuse plastic objects according to their properties, originating a wide range of complex architectural shapes.

Thus, the main innovation of the research is firstly the use of waste components as construction material, even if the knowledge in this field is still lacking, and it still considered easier to build with new materials. Secondly the introduction of D2RP techniques in remodeling and connecting the components, in order to create intricate architectural shapes, or pavilions, avoiding the use of extra material.

8.0 REFERENCES

Bell, M. and C. Buckley (2014). Permanent Change: Plastics in Architecture and Engineering, Princeton Architectural Press.

Engelsmann, S., et al. (2012). Plastics: in Architecture and Construction, Birkhäuser.

Bier, H. (2018). Robotic Building, Springer International Publishing.

Kula, D., et al. (2013). Materiology: The Creative Industry's Guide to Materials and Technologies, Birkhäuser.

Daas, M. and A. J. Wit (2018). Towards a Robotic Architecture, ORO Editions.

Brownell, B. (2013). Material Strategies: Innovative Applications in Architecture, Princeton Architectural Press.

Maas, W., et al. (2015). Barba: Life in the Fully Adaptable Environment, nai010 publishers.

Oosterhuis, K. (2003). Hyperbodies, Birkhäuser.

Addington, D. M. and D. L. Schodek (2005). Smart Materials and New Technologies: For the Architecture and Design Professions, Architectural Press.

Bontempi, E. (2017). Raw Materials Substitution Sustainability, Springer International Publishing.

Colabella, S., D'Amico, B., Hoxha, E., & Fivet, C. (2017). Structural Design with Reclaimed Materials: an Elastic Gridshell out of Skis. Proceedings of the IASS Annual Symposium 2017. Retrieved from http://infoscience.epfl.ch/record/231033

Brütting, J., Desruelle, J., Senatore, G., & Fivet, C. (2018). Optimum Truss Design with Reused Stock Elements. Proceedings of the IASS Symposium 2018, Creativity in Structural Design, 8. Retrieved from http://infoscience.epfl.ch/record/255199
Freinkel, S. (2011). Plastic: A Toxic Love Story, Houghton Mifflin Harcourt.

Ellen MacArthur Foundation, (2017). The new plastics economy: Rethinking the future of plastics & Catalysing action. Retrieved from http://www.ellenmacarthurfoundation.org/publications

World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company,(2016).The New Plastics Economy – Rethinking the future of plastics
Retrieved from http://www.ellenmacarthurfoundation.org/publications

Superuse Studios. "Harvest Map." Retrieved 20/12, 2018, from https://www.harvestmap.org/.

Stiho, R., Elektroned, Knauf, Tetris, JLL, TGN, Wavin, steenfabriek Douveren, de Ruttegroep, het NIBE, ABN AMRO en Thinkle. "URBAN MINING COLLECTIVE." Retrieved 10/11, 2018, from http://urbanminingcollective.nl/.

Bhada-Tata, Perinaz; Hoornweg, Daniel A. (2012). What a waste? : a global review of solid waste management (English). Urban development series knowledge papers; no. 15. Washington, DC : World Bank Group. http://documents.worldbank.org/curated/en/302341468126264791/What-a-waste-a-global-review-of-solid-waste-management

Lave, L. B., et al. (1999). "Municipal Solid Waste Recycling Issues." Journal of Environmental Engineering 125(10): 944-949.

Addis, B. (2006). Building with Reclaimed Components and Materials. London: Routledge.

Testa, P. (2017). Robot House: Instrumentation, Representation, Fabrication, Thames & Hudson.

Boehler, W., Heinz, G., Marbs, A., 2001: The potential of noncontact close range laser scanners for cultural heritage recording, XVIII. CIPA Symposium, Potsdam, Germany, Proceedings. Retrieved 31/12, 2018, from http://www.i3mainz.fh-mainz.de.

Lasi, H., Fettke, P., Kemper, HG. et al. Bus Inf Syst Eng (2014) 6: 239. https://doi.org/10.1007/s12599-014-0334-4

9.0 APPENDIX A

Figure 5.14: disposable keg test 1

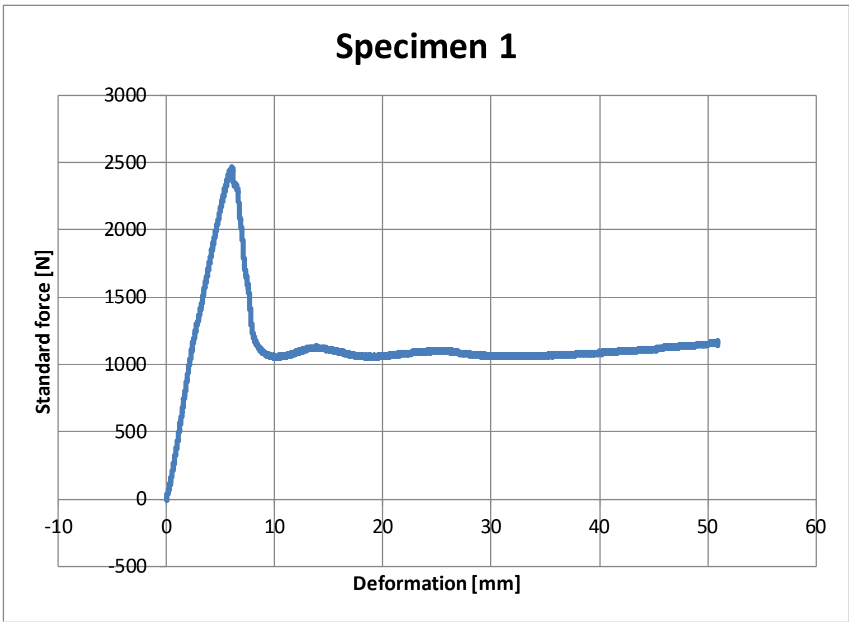


Figure 9.1: disposable keg test 1 - first loading

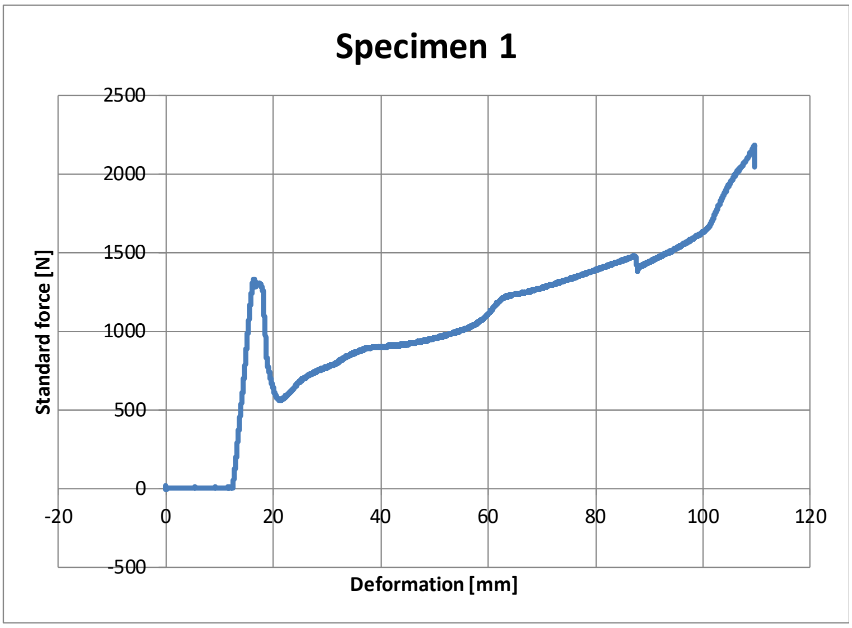


Figure 9.2: disposable keg test 1 - second loading

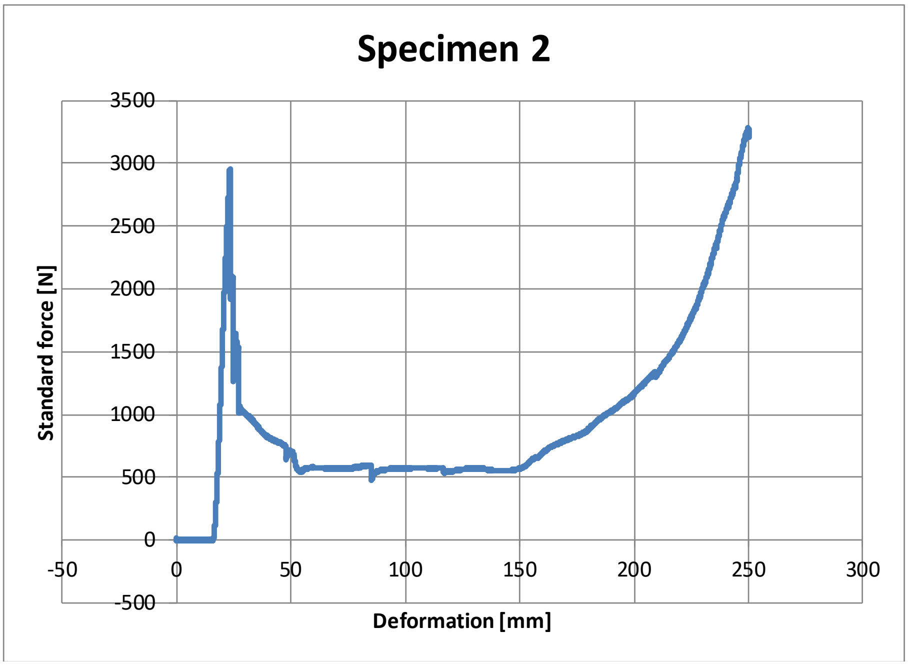


Figure 9.3: disposable keg
test 2 - first loading

Figure 5.15: disposable keg
test 2

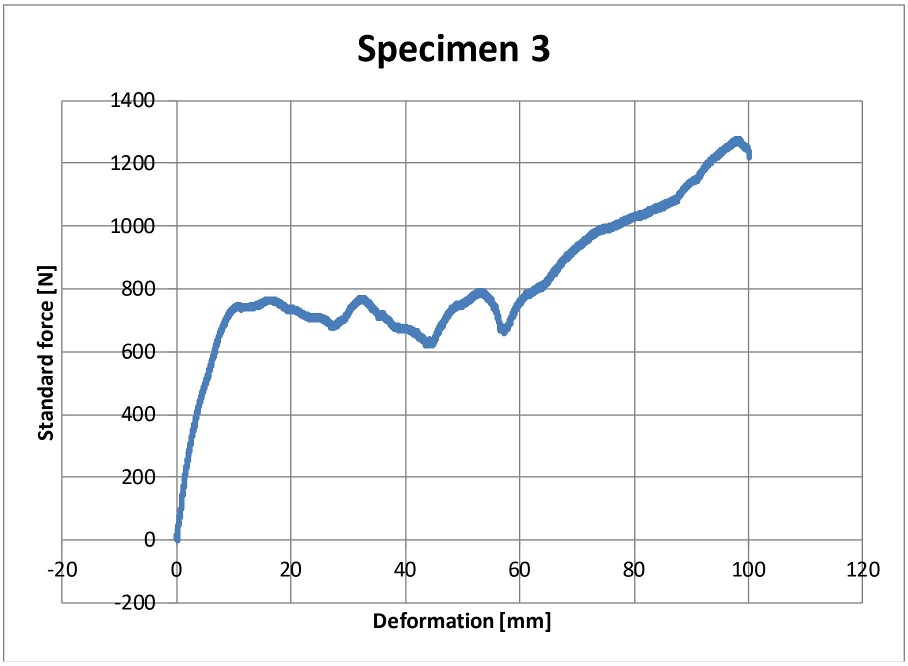


Figure 9.4: drill container
test 3 - first loading

Figure 5.16: drill container
test 3

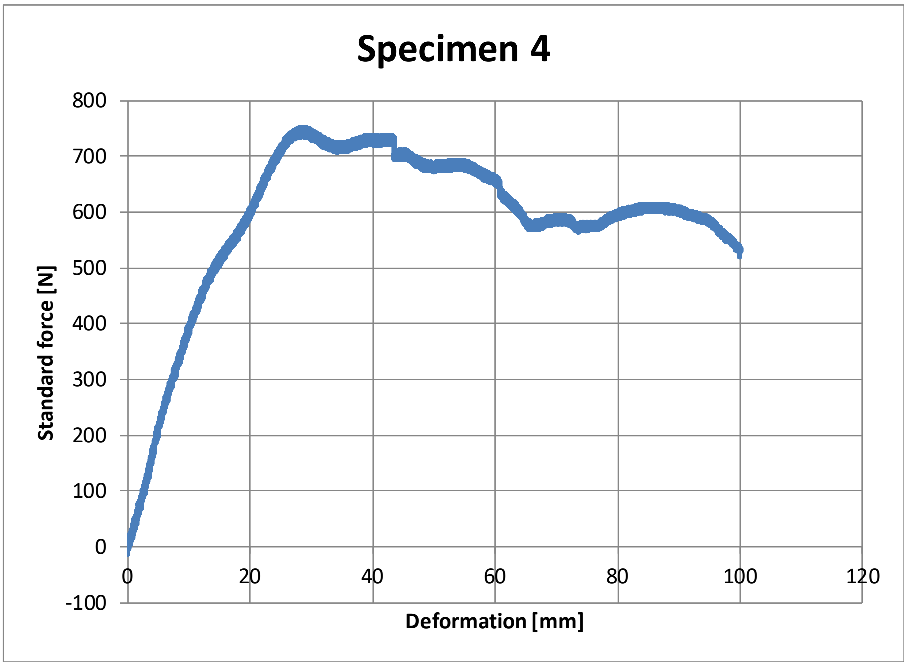


Figure 9.5: stacked drill containers
test 4 - first loading

Figure 5.17: stacked drill containers
test 4

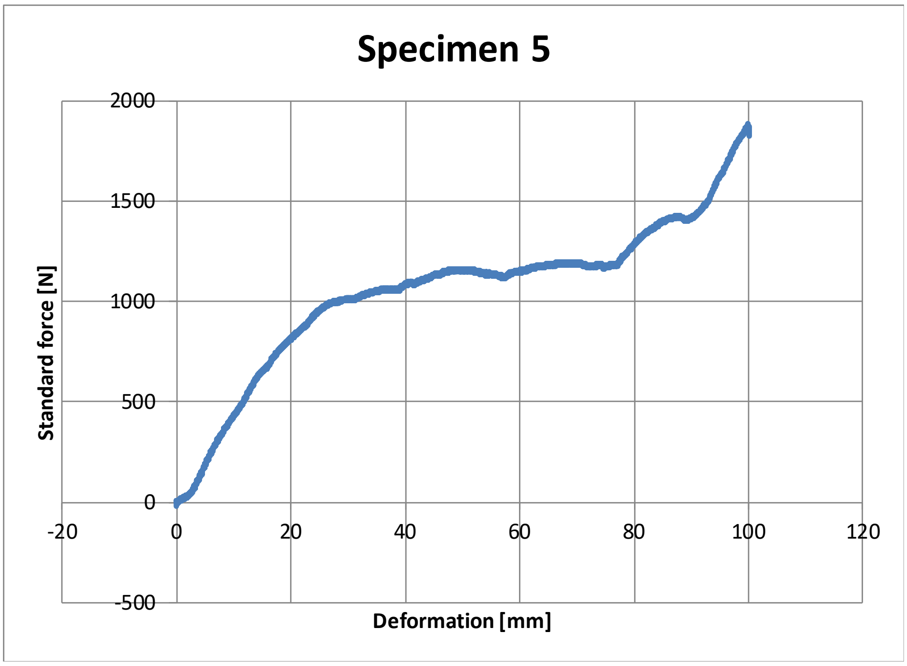


Figure 9.6: drill container
bottom component- retrieved from previous test
test 5 - first loading

Figure 9.7: drill container
bottom component
retrieved from previous test

Figure 5.18: violet cone test 6

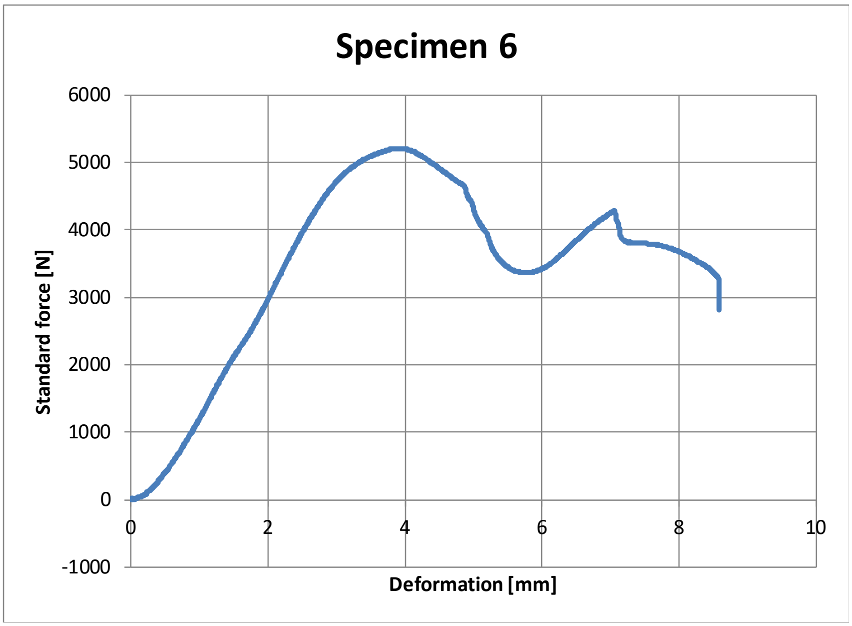


Figure 9.8: violet cone test 6 - first loading

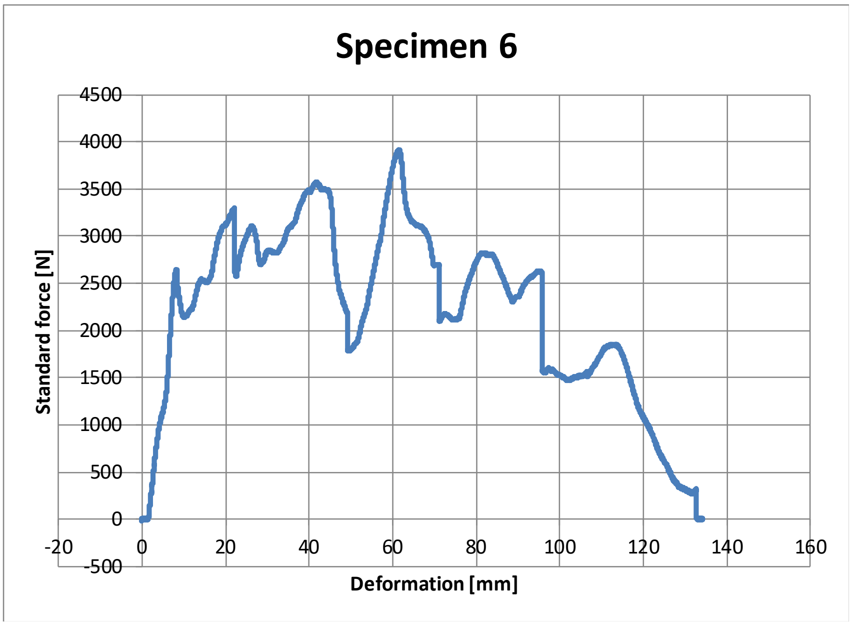


Figure 9.9: violet cone test 6 - second loading

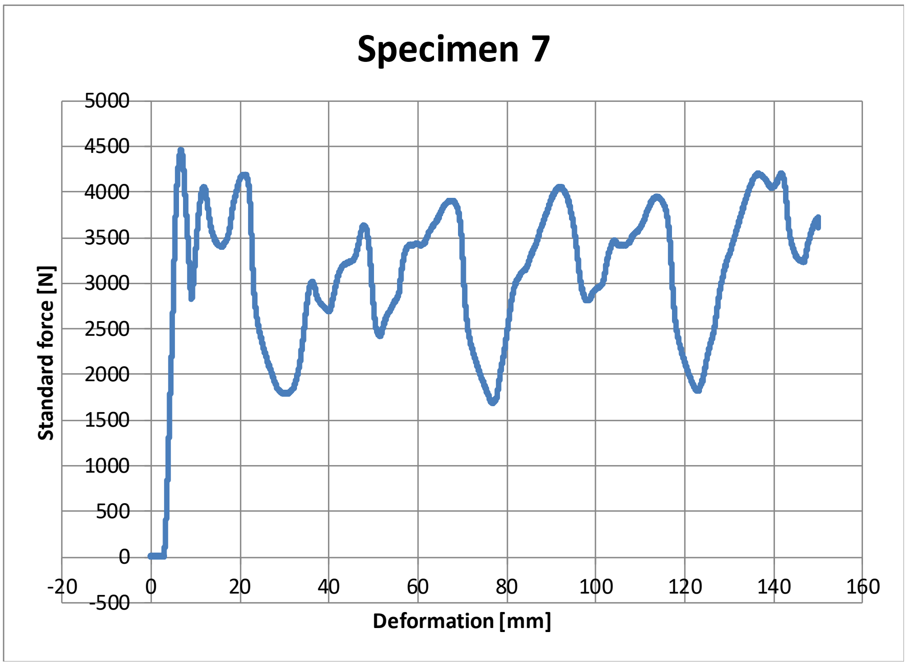


Figure 9.10: gray cone
test 7 - first loading
perfect buckling

Figure 5.20: gray cone
test 7
perfect buckling

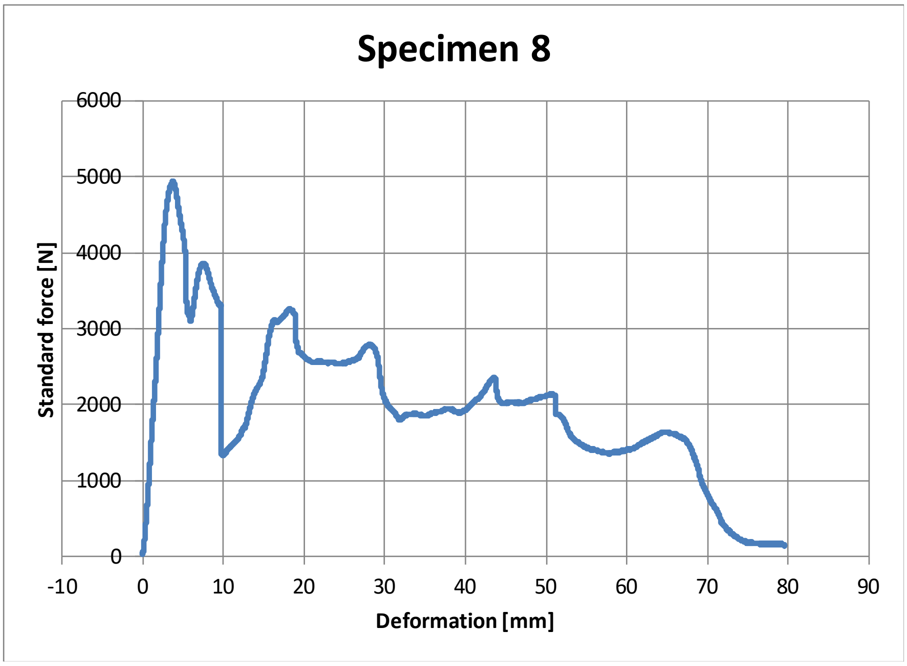


Figure 9.11: green cone
test 8 - first loading

Figure 5.21: green cone
test 8