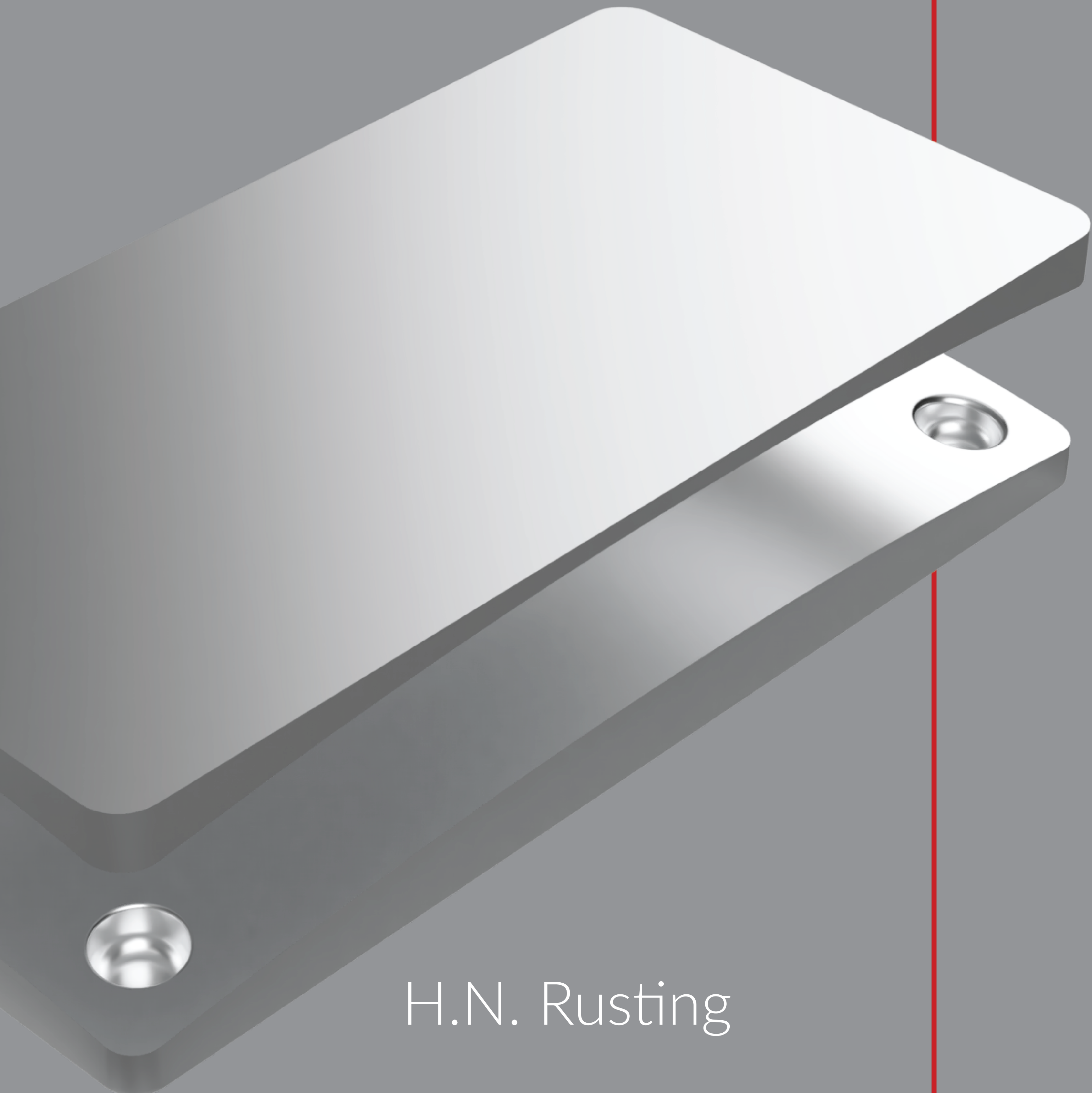
Fabrication of sustainable free form façades



H.N. Rusting

Contents

FABRICATION OF SUSTAINABLE FREE FORM FAÇADES

by H.N. Rusting
9717445

to obtain the degree of master of science
at the Delft University of Technology

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An electronic version of this thesis is available
at http://repository.tudelft.nl

TU Delft

PREFACE

i PREFACE

I would like to express my gratitude to my first mentor, Dr.-Ing. M. Bilow, who not only guided me throughout this project but also taught me a lot during the Honours Programme Bachelor and the Bucky Lab master course.

Also many thanks to ir. P. de Ruiter, my second mentor, for the guidance and the great discussions during this project but also during the Beyond 3D course.

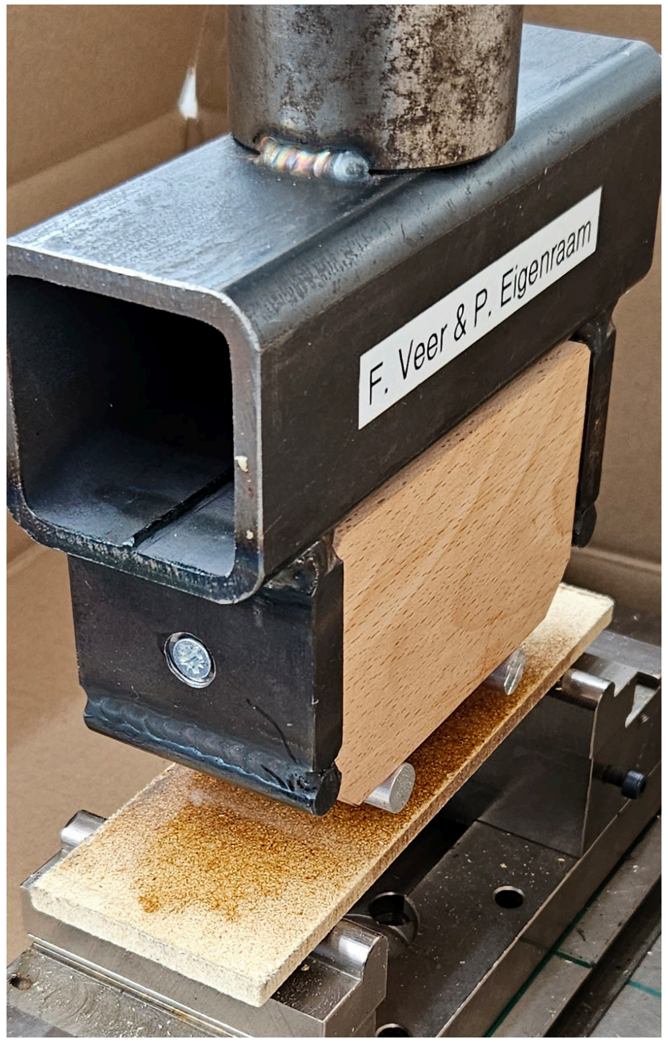
Of course many thanks to the teachers of the Honours Programme Bachelor and the members of the Honours Committee. The extra hours have been more than worth it!

I would also like to thank ir. T.R.H. Liebrand for his help and support during my graduation.

The number of people who assisted either on or off campus is too large to mention separately. They have been added on the next page. Your knowledge, skills and help have been indispensable. Thank you!

A special thank you for Cenk Batuhan Özaltun, Myrthe Peet, Francien Fons, Daphne Vlak, Daphne Naaktgeboren and Dani Vu. Also to Job de Vogel and Jirri van den Bos. It has been fun!

And last but certainly not least. Many thanks to my wife Mariske and amazing children Tom and Rosalie for their unwavaring support and understanding. Love you!



"LOOK FOR THE HELPERS. YOU WILL ALWAYS FIND PEOPLE WHO ARE HELPING."

FRED ROGERS

Many thanks to (in alphabetical order):

Roy Awater
Faculty of Aerospace Engineering (AE)
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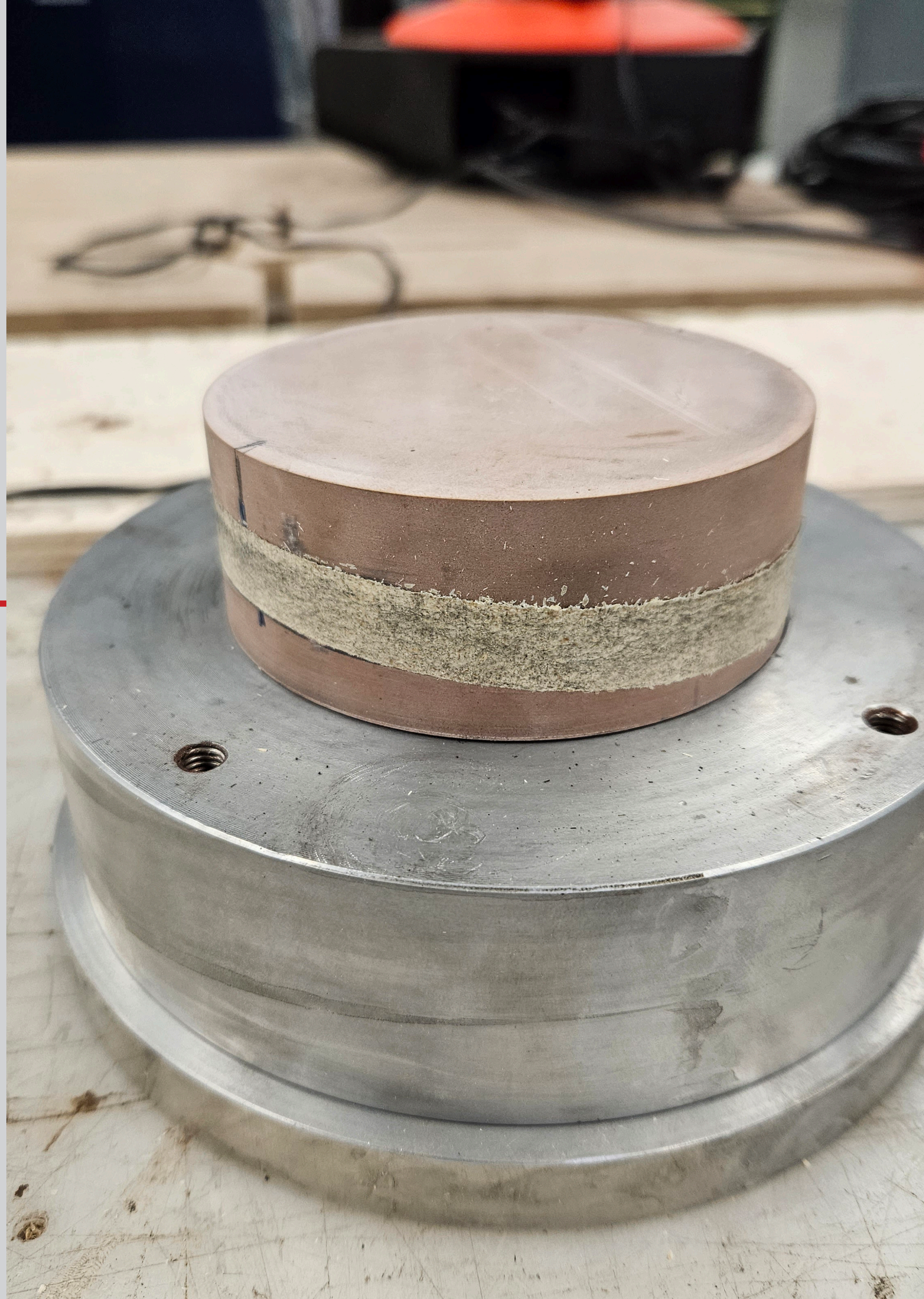
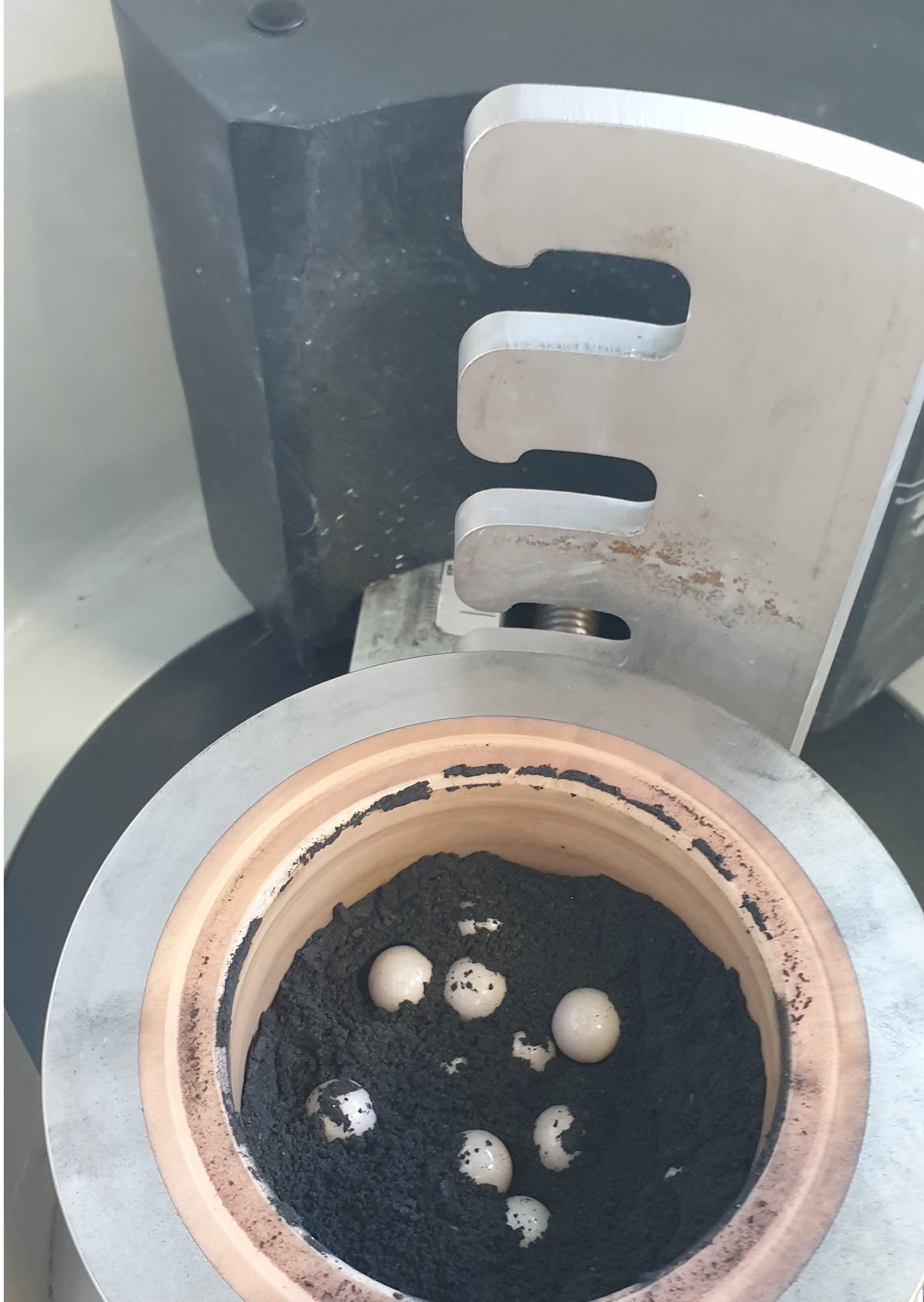
ABSTRACT



ii ABSTRACT

In contemporary architecture free-form buildings play an important role. The materials used, for example fibre reinforced composites or concrete, are not sustainable. Because the built environment is responsible for a significant part of the global resource usage and because it is one of the most polluting industries it is important to make every effort to reduce its environmental impact. In more conventional architecture renewable and more sustainable materials like timber are among the oldest building materials and are now being rediscovered. In curved façades however it is much less common because curved surfaces and the material properties of renewable and sustainable materials cause complexities in the production and assembly processes. Whether curved façade panels, made from a bio-composite, can be fabricated using an industrial fabrication process has not been extensively researched. The goal of this thesis is to explore the possibilities of making curved façades more sustainable by using a bio-composite and by using an industrial production process. This is done by conducting literature research and by designing a bio-composite façade panel and production process. This process has been supported by experimenting, prototyping and a case study of the Depot Boijmans van Beuningen designed by MVRDV.

Because the bio-composite façade panel is produced using a hot press and an aluminium mould it is best suited for façades of which all panels are identical or for panels with a lot of repetition. One of the advantages of the material, design and production method is that the panels consist of very few parts. The water resistance is something that needs to be improved ether by changing the composition of the material or by applying a bio-based coating.



CHAPTER
ONE

INTRODUCTION

FIGURE 1.1
Depot Bijmans van Beuningen (Waalboer, 2023)

INTRODUCTION

This master thesis titled "Fabrication of sustainable free form façades" has been written as the final part of the curriculum of the Master Track Building Technology at the Faculty of Architecture and the Built Environment to obtain the degree of Master of Science at the Delft University of Technology. The first mentor is Dr. -Ing. M. Bilow of the Chair of Building Product Innovation and the second mentor is ir. P. de Ruiter of the Chair of Design Informatics. The board of examiners is represented by ir. G. Coumans of the department of Architecture / Form and Modelling studies. This introductory chapter gives an overview of the thesis by formulating the Problem Statement followed by the Main Research Question, Sub Research Questions and the Methodology used for this research. The chapter will be concluded by stating the Design Assignment which gives insight in the desired outcome of this thesis.

SCOPE

In-Scope: Material, fabrication process, design options

Out-of Scope: structural assesment, quantification of the sustainability

PROBLEM STATEMENT

The problem addressed in this research is twofold; although bio-composites are being considered a realistic alternative for wood and less sustainable building materials it is not yet widely used in free form architecture. Secondly the level of automation and industrialization of the construction industry is low compared to other sectors.

WOOD IN FREE FORM ARCHITECTURE

Wood is and always has been widely used in buildings but became less common with the rise of new building materials like concrete and steel during the industrial revolution. These materials helped to enable the design and construction of larger and taller buildings. This led, in the United States of America (USA), around 1885 to the first modern skyscrapers. These buildings should not be considered free-form because they do not fit the definition as formulated by (Veltkamp, 2007) as building shapes that are double curved, which do not feature repetition of elements and of which the shape is not structurally optimized. For the introduction of free-form architecture other advancements in technology were needed. Through developments in computer aided design (CAD) andcomputer aided manufacturing (CAM) techniques in the second half of the 20th century it became much easier to design and fabricate complex free-form shapes in architecture (Kolarevic, 2004). These freeform buildings mostly rely on concrete, steel, glass and aluminium for their structure and façades. In the design and construction of family housing timber however remains widely used in countries like the USA because of its availability, design flexibility and the short construction times. In Germany the choice for timber as a construction material is obstructed by classical prejudices such as low value stability, the poor overall quality of timber frame houses, respectively, their high combustibility and extensive maintenance, and their relatively high price (Gold and Rubik, 2009). The interest in wood as a sustainable alternative building material for high-rise buildings increased with the growing awareness that the threats of climate change and the scarcity of non-renewable resources are real and need to be dealt with. Using wood instead of steel and concrete for tall, super-tall and even mega-tall buildings is being researched (Li et al., 2019,Foster et al., 2017) and the first timber high rise buildings have been built (figure: 1.2 on page 16).

The use of wood in free-form architecture however is rare even though it could contribute to a more sustainable built environment and construction industry as long as it is sourced in a sustainable way (Dangel, 2016). Because of this the first part of problem statement is about using bio-composites) as an alternative building material for free-form architecture.

LEVEL OF AUTOMATION AND IDUSTRIALIZATION OF THE CONSTRUCTION INDUSTRY

In the traditional construction industry, the level of automation and industrialization is low compared to other industries (McKinsey Global Institute, 2017). There are exceptions. For example in classical timber frame construction. Companies operating in this area mostly limit themselvesto the design and fabrication of orthogonal buildings and incorporate multiple façade functionsinto their building components. For example, insulation. The fabrication process they use have a relatively high degree of automation and industrialization compared to the traditional on-site construction methods(figure 1.1).

FIGURE 1.2
Traditional Timber Construction (Roe, 2023)

Contemporary architecture however does not limit itself to orthogonal shapes. A lot of academic research is being done by, for example, ETH Zurich's Chair of Architecture and Digital Fabrication and the University of Stuttgart's Institute for Computational Design and Construction into the industrial fabrication of free-form timber architecture. .

GOAL

The goal of this thesis is to explore the manufacturing process for curved façade panels made from a lignocellulosic bio composite.

RESEARCH QUESTIONS

MAIN RESEARCH QUESTION

Can curved façade panels made from bio-composite be fabricated using an industrial fabrication process?

SUB RESEARCH QUESTIONS (SQR)

The curved bio-composite façade panel

SQR 1a: What are the conventional ways to build a curved wooden façade?

SQR 1b: What are the requirements for a façade made of bio-composite?

Theindustrial production process

SQR 2a: What is the state of the art regarding the industrial fabrication of wooden façades?

SQR b: What is the state of the art of the fabrication of curved surfaces?

SQR 2c: What is the influence of curved surfaces on the industrial fabrication process?

DESIGN ASSIGNMENT

Design a curved wooden façade panel and an industrial production process to fabricate it.

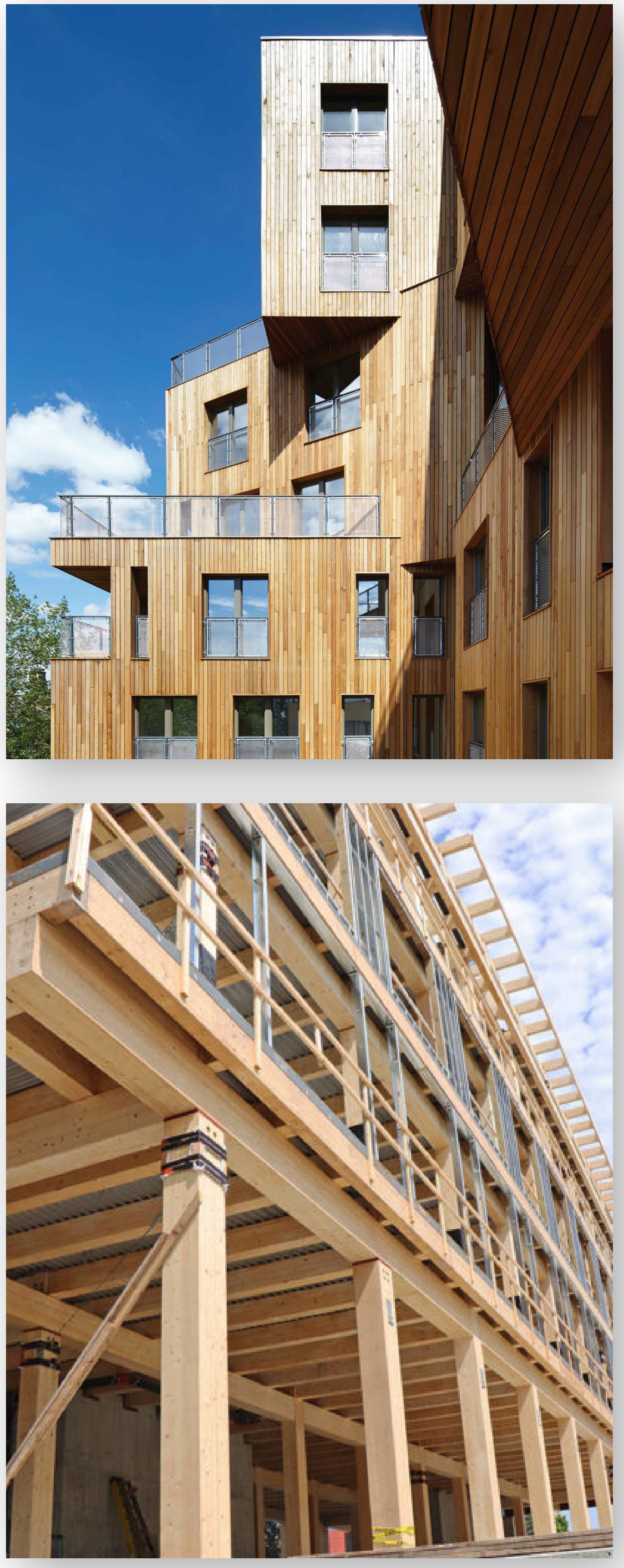


FIGURE 1.3
Examples of tall timber architecture (top,Hobhouse , 2023)
(bottom, Black Press Media file photo, 2022)

FIGURE 1.3
Façade panel Depot Boijmans van Beuningen

CURVED SUSTAINABLE FAÇADE PANEL

The first design goal of this thesis is to design a curved façade panel made from bio-composite for free form architecture. In order to do this the Depot Boijmans van Beuningen in Rotterdam (figure: 1 on page 14 and 1.3 on this page) designed by MVRDV Architects will be used as a case study. This building has been chosen not because it should be redesigned but because the double curved panalised façade makes it well suited for the goal of this research.

FABRICATION PROCESS

The second design goal is to design a manufacturing process for the curved wooden façade panel.

METHODOLOGY

The research for this thesis has been divided into four phases. These are not perfectly sequential as can been seen in figure 1.4 Methodology on page 18.

Phase 1: Literature research and plan analsis case study.

This phase focuses on understanding the two main research topics. Sustainable curved facades and industrial production processes. A plan analysis of the Depot Boijmans van Beuningen (Depot) in Rotterdam designed by MVRDV will also be executed to be able to validate the research and the design assignment. This case study will be on going, roughly, between P1 and p4.

Phase 2: Design phase façade panel

In this phase a bio-composite facade panel will be designed for free form buildings using the Depot as validation. The design should be able to be fabricated in an industrial process. This process will be designed in phase 3.

Phase 3: Design phase fabrication process

In this phase the facade design produced in phase 2 will be used as input and the production process for the bio composite façade panel will be designed.

Phase 4: Modelling and experimentation

The facade panel design produced in phase 2 will be modelled on a small scale. This scale depends on the design. The production process will be researched by experimentation.

Phase 5: Final Design

The findings gathered during the design phase and the validation cycles as shown in the process scheme will be incorporated in the final design. This design will be presented during P4. Feedback received during P4 will be evaluated and if feasible in the given time frame applied.

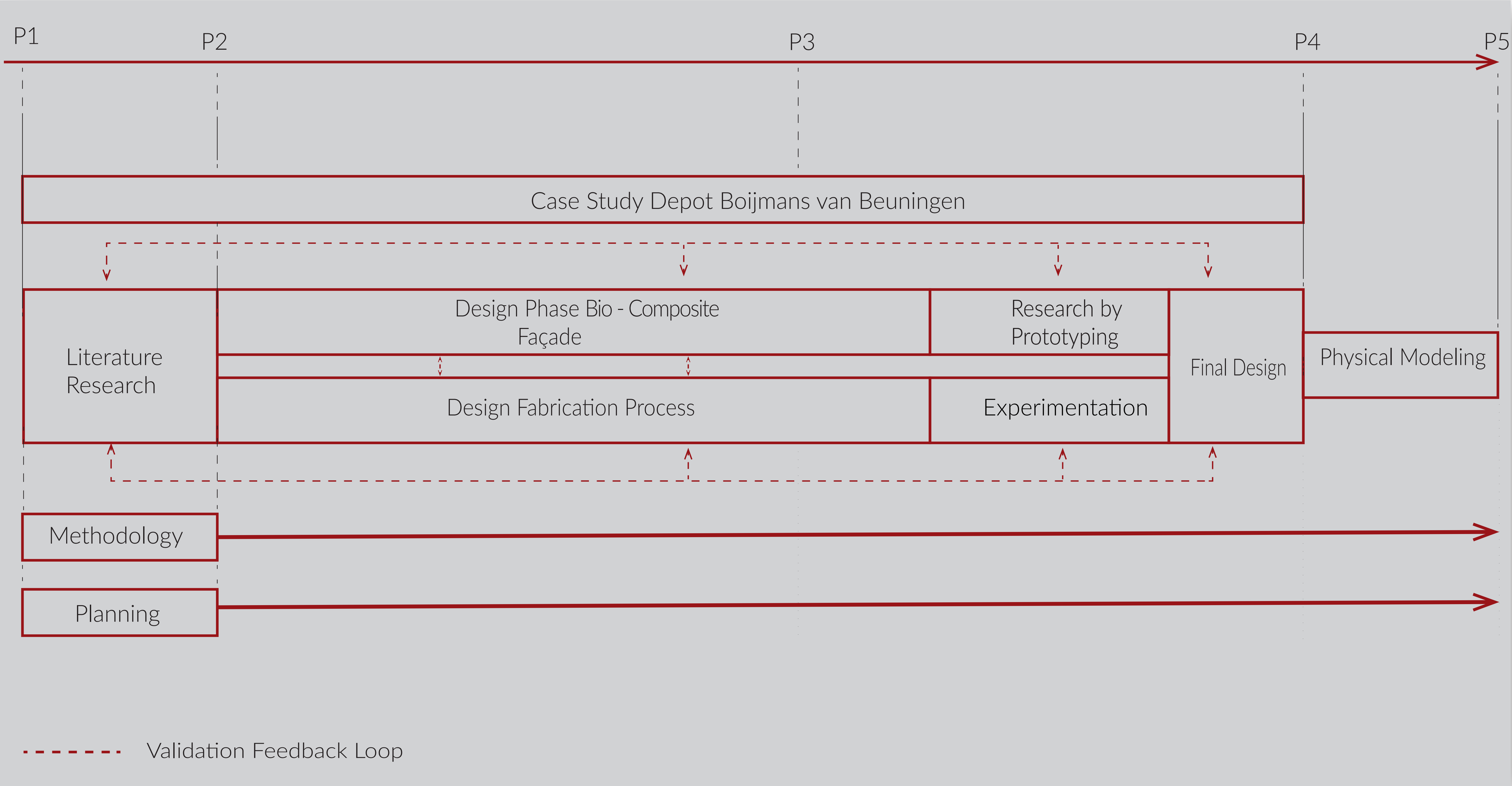
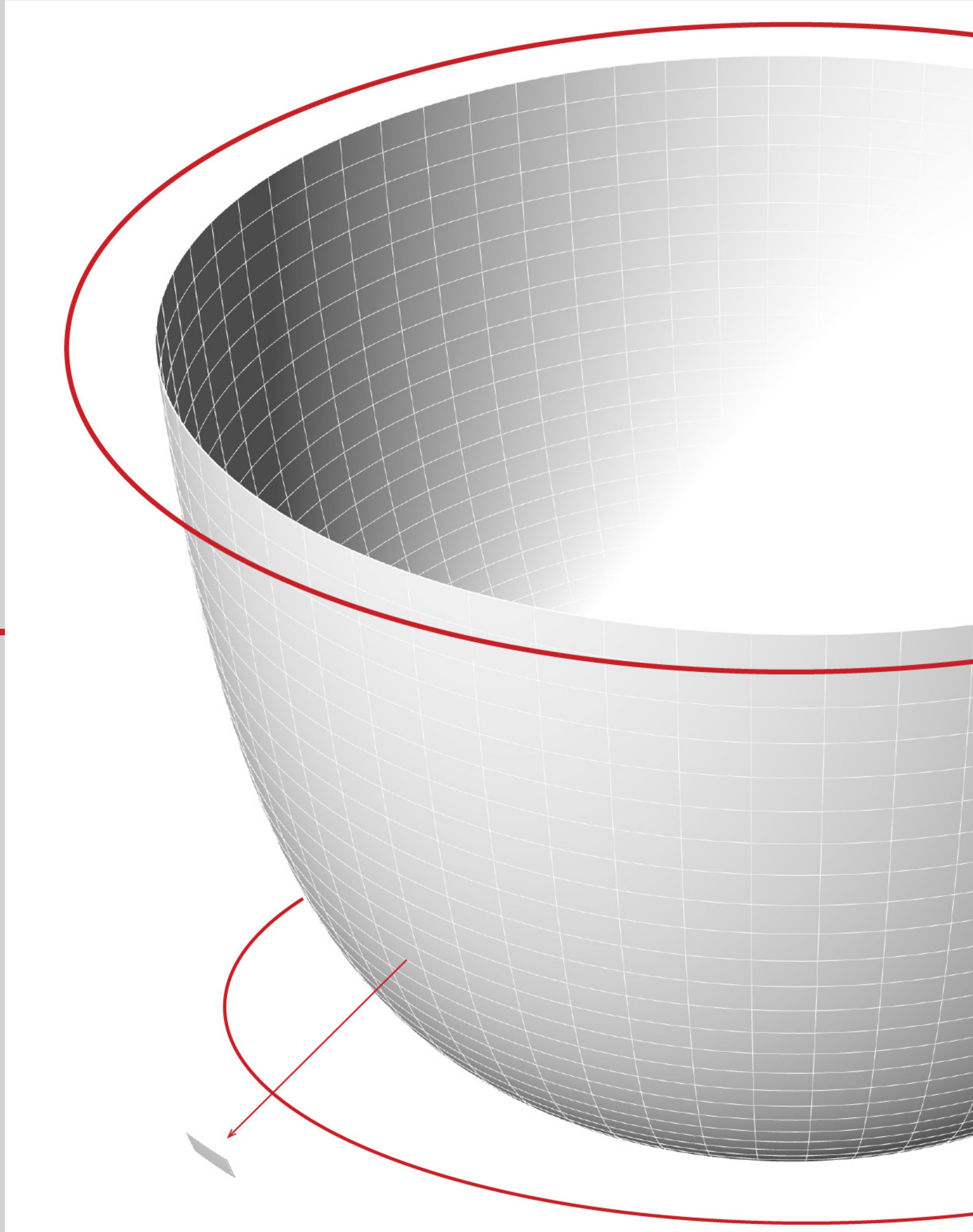


FIGURE 1.4
Methodology

CHAPTER
TWO

RESEARCH



GOOD LORD!' SAID HENDERSON. 'FALLEN METEORITE! THAT'S GOOD.' 'BUT IT'S SOMETHING MORE THAN A METEORITE. IT'S A CYLINDER – AN ARTIFICIAL CYLINDER, MAN! AND THERE'S SOMETHING INSIDE.'

G. WELLS, THE WAR OF THE WORLDS (1898)

Analysis Depot Boijmans van Beuningen

BUILDING DATA

Location: The Netherlands
City: Rotterdam
Architect: MVRDV, Rotterdam
Interior: John Körmeling, Marieke van Diemen, Pipilotti Rist
Landscape: MTD Landscape Architects
Year: 2020
Client: Museum Boijmans Van Beuningen, De Verre Bergen Foundation, Municipality of Rotterdam
Floor Area: 15.000 m2
Height: 40 m
Footprint: 1.257 m2
Budget: € 94.000.000,-
Programme: Offices, Retail, Cultural, Bar-Restaurant

STRUCTURE

General

The Depot might look like a relatively simple building but appearances are deceiving. It consists of six stacked storage depots with a required floor load of 1.250 kg/m^2 The architect also envisioned a roof garden with full grown trees. To complete the puzzle, the building has a ground level footprint with a diameter of 40 m and a top level diameter of 60 m. This results in a overhang of 10 m in all directions. Because of this the occurring loads in the structure are very high and comparable to high-rise buildings (Peters and Loosjes, 2019).

	Column Structure	Mega Structure	Steel Structure
Construction Height Floor 390 mm,	390 mm, 450 mm	390 mm, 450 mm	710 mm
Construction Roof	++	++	-
Vibrations Floor	+	++	+
Mezzanine	++	++	+
Stability	Core walls	Load bearing façade	Core walls
Design Flexibility	-	++	+
Future Flexibility	Fully adaptable	(Internally) adaptable	Fully adaptable
Construction Speed Shell	+	-	++
Construction Cost Shell	++	+	-

TABLE 2.1
Design options structure Depot Boijmans van Beuningen(Peters and Loosjes, 2019

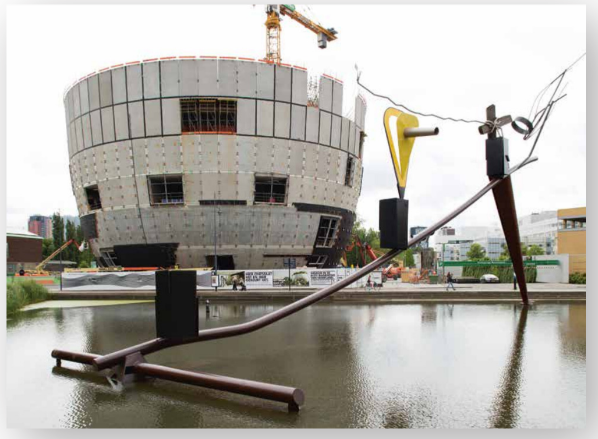


FIGURE 2.2 A
Shell (Stieber Fotografie, 2023)

FIGURE 2.2 B
Reinforcement in-situ concrete shell (Stieber Fotografie, 2023)

MAIN STRUCTURE

A concrete load bearing shell construction has been chosen from three alternatives as shown in table 2.1 below..

The load bearing shell consists of two parts. The lower part is an in-situ poured High strength self--compacted concrete (HSSCC) plinth while the top part consists of prefabricated concrete segments divided over four rings with 65 segments each (figure 2.2a). This is necessary because the strong curvature on the lower levels of the building causes high bending moments and normal forces. These have to absorbed by the HSSCC plinth. To do this massive amounts of reinforcement steel had be applied as can be seen in figure 2.2b.

FAÇADE OPENINGS

For each floor of the building the maximum number of segments that could be left out, from astructural point of view, have been calculated. This has been used as a starting point for façadedesign. The openings in the façade cause a concentration of ring forces in the remaining parts of the façade as well as a large diversity in compression forces in the different concrete segments in the façade. The thickness of the concrete C55/67 shell varies between 350 mm on the 1st floor to 500 mm locally on the ground floor. These variations are largely caused by the openings in the façade and the variations in curvature.

FLOORS

The horizontal forces (Dutch: spatkrachten) originating from the shell cause omnidirectional ten-sion forces that have to be absorbed by the floors in the building.

COLUMNS

Both the location and the number of columns are optimized in order to share the loads as equally as possible over all the columns. Because of this balanced load transfer a reduction in reinforcement was achieved. The columns have a square steel tube (S460) core and C80/95 concrete.

FOUNDATION

The load bearing shell has a concrete ring beam foundation. The ring has been thickened by a number of foundation blocks.

PREFABRICATED CONCRETE SHELL

From a structural point of view it made sense to pour the first part of the shell in-situ. To make the building more cost efficient the 2nd part has been assembled out of prefabricated concrete elements. Because all elements in the same horizontal plane are the same only one mould per floor is needed. The concrete segments are flat on the outside to make the fabrication process more efficient and to make it easier to assemble the glass façade.

FAÇADE

The Depot has a number of striking characteristics. The round shape, the fact that it is a crossove between a museum and a depot, the roof garden with

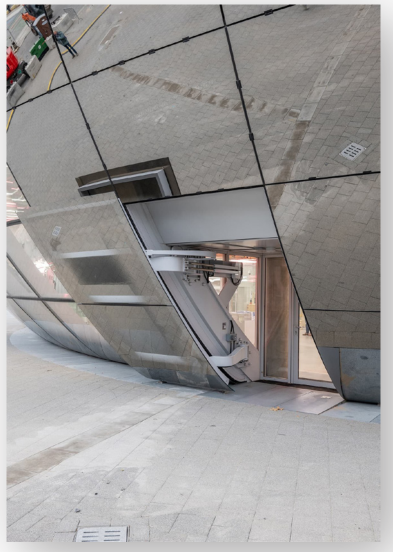


FIGURE 2.3
Mirror Façade Panels (Swagerman, 2023)

full grown trees and last but not least the reflective façade. The 6.609 square meters of reflective glass is subdivided into 1.664 individual double curved panels (figure: 2.3). This curvature decreases with the height at which the panel is mounted. "The mirroring panels ensure the integration of the design with its surroundings, by reflecting and thus honouring the activity and the nature of the Museumpark, designed by landscape architect Yves Brunier with OMA in the nineties." (MVRDV, n.d.)

CHAPTER
THREE

DESIGN ASSIGNMENT

Production

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FIGURE 3.1
Process

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FIGURE 3.2
Non-homogenous sample

FIGURE 3.3
Homogenous sample

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Removing the mould

The mould is made of three parts. An 8 mm base plate which is bolted onto the hollow chamber with eight Allen head bolts. Four dowel pins are used to align the parts and four threaded holes are added

FIGURE 3.4
Hot pressing process (M. Bilow)

it sometimes happened that the die became stuck. The most likely cause for this is material leakage between the die and the hollow chamber or, because of uneven distribution of the material during filling, a pressure difference occurred which caused the die to rotate slightly inside the mould. Because it is impossible in this case to remove the die by hand the press was used to force the die out. In one case, after a malfunction of the Joos 100 LAB press, another press was needed to release the die. Usually removing the sample from the mould was straightforward (figure 3.5).

The bio composite used in this research is produced by hot pressing the ingredients in a mould. There are several ways to design and construct moulds. In this section the two moulds that were used in this research will be discussed separately.

MOULDS

Rectangular mould

Any mould used for this process must be able to withstand the pressures and temperature needed to produce the bio composite. This, however, is not the only criterion. The following should also be considered.

- Ease of use. For example, it should be easy to add and remove the material.
- Easy to assemble and disassemble. A mould consists of several parts which are bolted together. The number of these parts should be as low as possible, and it should be easy to assemble and disassem ble to keep the setup costs as low as possible.
- Due to the temperatures used expansion of the materials must be considered.
- The mould must be able to deliver the required tolerances and surface quality.
- The material used should be easy to machine. Machining cost is greatly influen ced by the choice of material. The easier a material is to machine the lower the cost because the machines needed are cheaper and it takes less time to fabricate the mould.
- The mould should be durable. Machining a mould is expensive which means the more parts can be produced with it the lower the unit cost of the parts.
- The material cost of the mould should be considered.

FIGURE 3.5
Removing mould (Photo: M. Bilow)

A well-designed mould is a balancing act between all these criteria. It is not a question of choosing the cheapest material or the strongest, but it should be the material that meets all criteria as well as possible. One of the moulds used is shown below. The mould itself has been designed and built by Thomas Liebrand and the inlays by the author. (figure 3.7 Rectangular mould on page 33) The interior dimensions are 150 x 300 x 60 mm with 10 mm radii in the corners. The weight of the mould, including die and without inlays is, approximately 7,3 kg. With inlays 9,7 kg.

The rounded corners of the mould increase the strength of the mould because it increases the material in the casing of the mould at the corners with around 30% (Figure 3.6 Rounded corners mould). It also improves the filling of the mould as well as the removing of the sample.

The rounded corners of the mould increase the strength of the mould because it increases the material in the casing of the mould at the corners with around 30% (Figure 3.6 Rounded corners mould). It also improves the filling of the mould as well as the removing of the sample.

To control the temperature during pressing a slot has been added into the die to insert a thermocouple as close to the centre of the mould as possible. This is connected to the Joos press to control the temperature cycle either by hand or automatically. The die is a solid block of 7075 aluminium machined to the desired dimensions by the Electronic and Mechanical Support Division of TU Delft (DEMO). The properties of this aluminium alloy can be found in table 1 Mechanical properties of Aluminium 7075 on page 34. The casing is made from the same material and designed to withstand the pressures used.

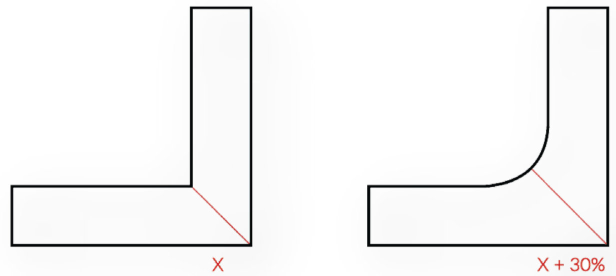

FIGURE 3.6
Rounded corners mould

Because the material of the casing and die are the same there are no differences in thermal expansion that could cause the die to get stuck in the casing. The base plate of the mould is 8 mm thick aluminium. The plate is guided onto the casing by 4 10 mm dowel pins and fastened by 8 M6 Allen head bolts. After pressing the bolts and dowel pins are sometimes hard to remove. To make this easier the holes in casing for the dowel pins and the bolts are sprayed with copper grease to make them easier to remove. When needed the M4 push bolts can be used to separate the base plate from the casing. The tolerances for this mould are quite strict because the material used flows during pressing which causes it to creep into cavities. This causes imperfections at the edges of the samples and makes the mould harder to disassemble. These tolerances have not been quantified.

Inlays for the rectangular mould

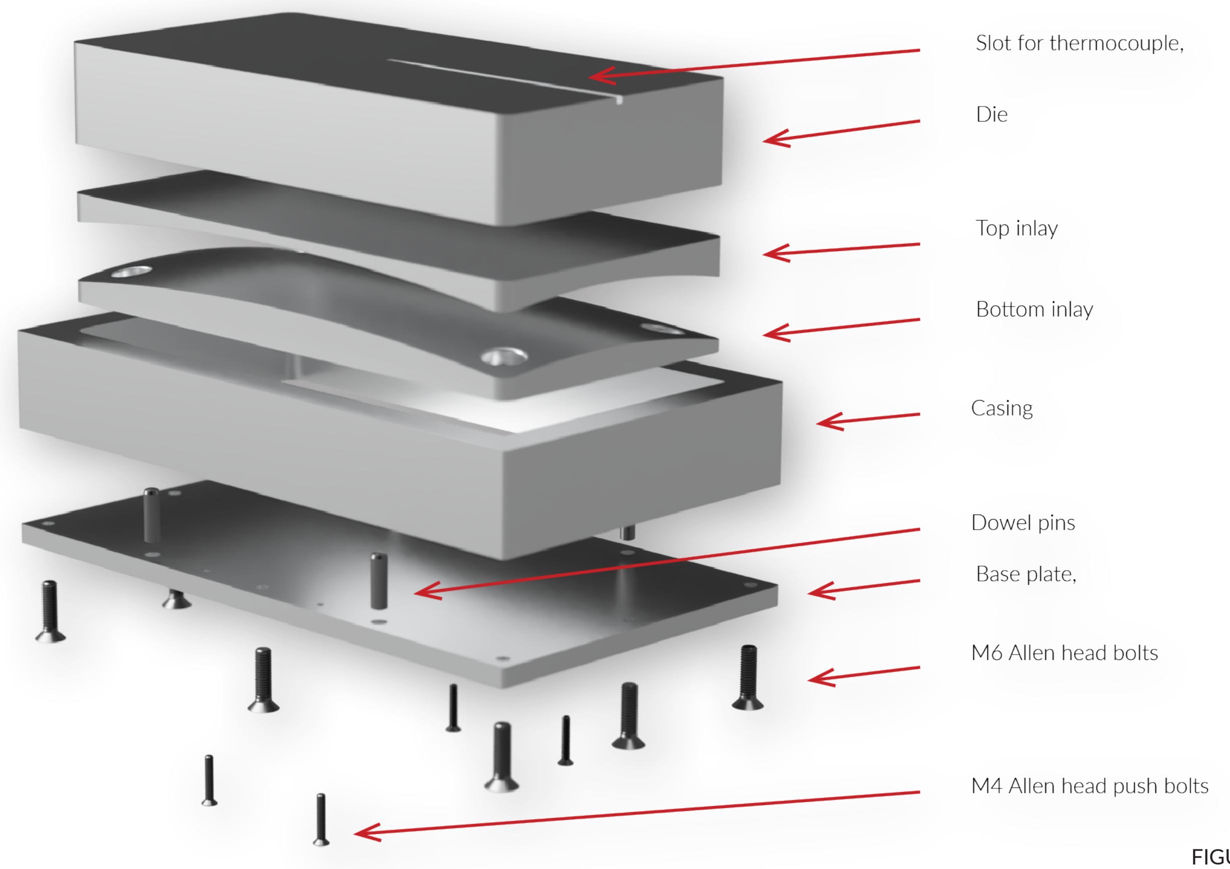

FIGURE 3.7
Rectangular mould

The inlays have been made to produce curved surfaces. These are a model of the top row of façade panels of the Depot Boijmans van Beuningen as they are designed by the architect (MVRDV).

The inlays have been machined out of aluminium 2024 (table 2 Mechanical properties of Aluminium 2024 on page 33) by the Model Making and Machine Lab (PMB) of the Faculty Industrial Design and Engineering (IDE) and further refined by the Student Walk-in Workshop (SWW) of the Faculty of Mechanical, Maritime and Materials Engineering (3ME). The dimensions are 150 x 300 x 20 mm with 10 mm radii in the corners. Near the corners of the bottom inlay (Figure 3.9 Bottom inlay curved surfaces) indentations in the inlay cause a built-up of material during pressing, This has been done to give the material enough thickness in order to be able to make threaded holes in the panels so double-ended-stud--bolt can be attached. These indentation have been designed to be self-releasing to be able to remove the material after fabrication.

Material selection

The materials used to produce the moulds and inlays were not thoroughly researched before they were produced. The reason for this is that, because there was no budget, we had to use whatever was available. In this case 7075 aluminium for the mould and 2024 aluminium for the inlays. The description of material selection in this section is meant as a 'retrospective validation' and as information for further research.
The most obvious materials to research are steel and aluminum given the fact that the mould is used under high pressure and temperature. However, diverse material characteristics in these groups make some more suitable and than others. Criteria for the mould have been formulated and Granta Edupack 2022 has been used to find the material best suited to use for a mould.

Mechanical Properties	Aluminium 7075	90.0% Al, 5.6% Zn, 2.5%Mg, 0.23%Cr, and 1.6% Cu
Density	kg/m^3	28.100
Thermal Expansion Coefficient	$10^{-6}K^{-1}$	24
Compressive Yield Strength	MPa	607.9
Tensile Yield Strength	MPa	503
Shear Strength	MPa	331
Modulus of Elasticity	GPa	71.7
Shear Modulus	GPa	26.9
Milling Speed (V_c)	m/min	395

TABLE 3.1
Mechanical properties AL 7075

Mechanical Properties	Aluminium 2024	93.5 % Al, 4.4% Cu, 1.5% Mg, and 0.6% Mn
Density	kg/m^3	27.800
Thermal Expansion Coefficient	$10^{-6}K^{-1}$	23.2
Compressive Yield Strength	MPa	607.9
Tensile Yield Strength	MPa	324
Shear Strength	MPa	283
Modulus of Elasticity	GPa	73.1
Shear Modulus	GPa	28
Milling Speed (V_c)	m/min	395

TABLE 3.2
Mechanical properties AL 2024

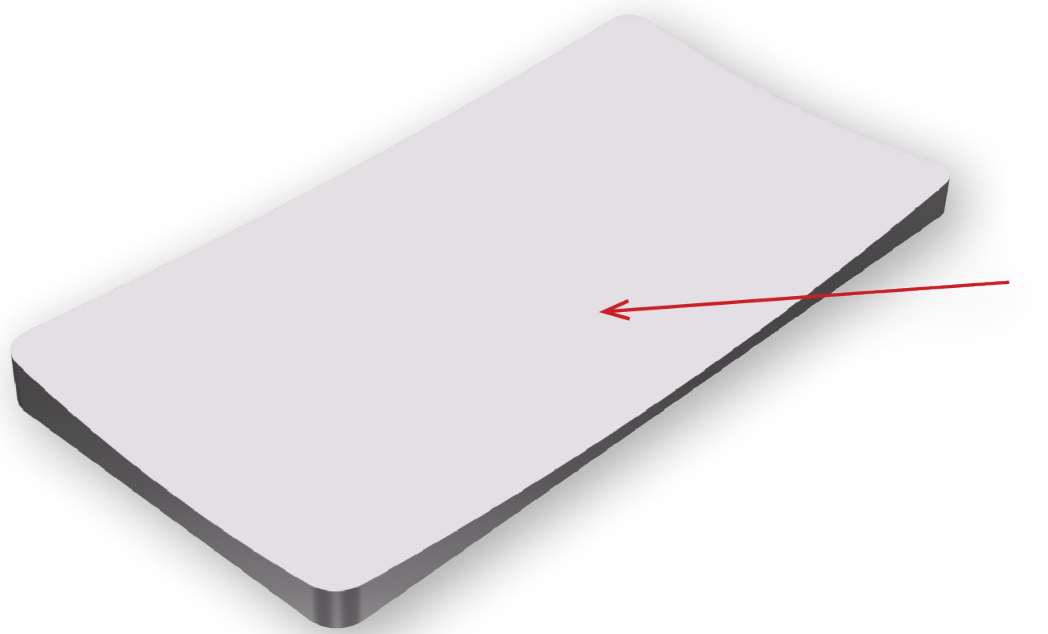

FIGURE 3.8
Top inl;ay curved surfaces

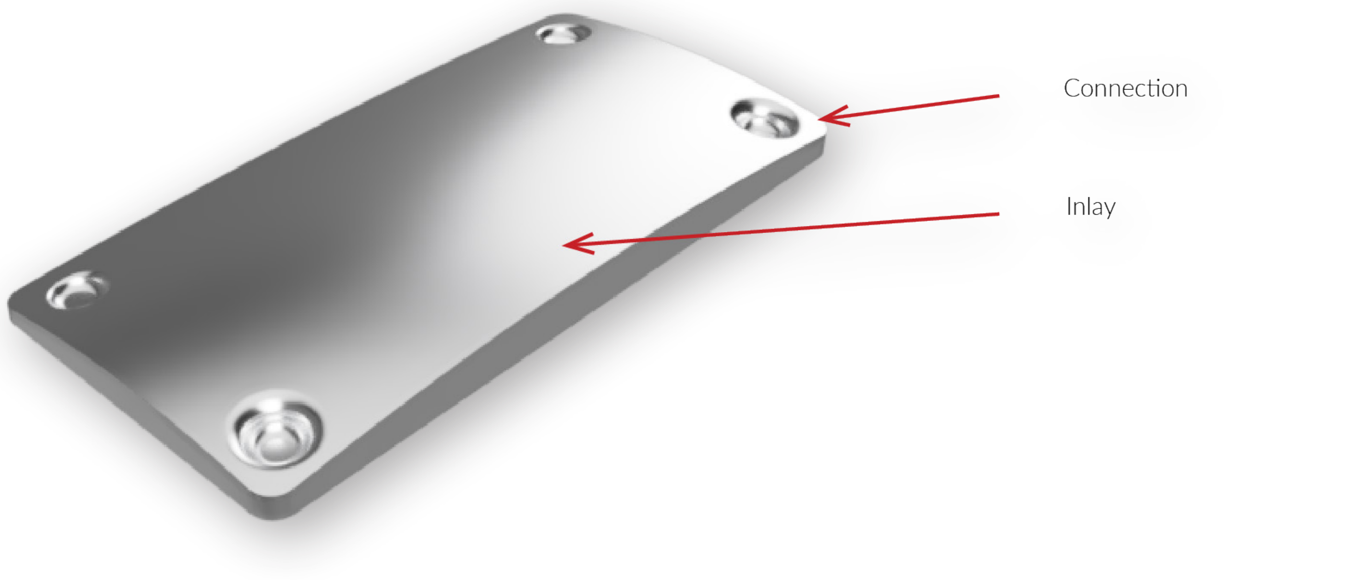

FIGURE 3.9
Bottom inlay curved surfaces

All mechanical properties of both aluminium 7075 and aluminium 2024 are above the temperatures and pressures used during the production of the bio composite. It should be noted that if the pressure inside the cavity of the mould is between 10 and 20 MPa the tensions in the material of the mould are the not necessarily the same or even in the same range. To manufacture an efficient and economical mould this, among other things, should be analysed and optimised. This however is not in scope for this thesis.
A first material selection has been made using common sense. Because of the criteria mentioned in table 3 steel and aluminium are logical materials to research for the moulds.
A filter has been applied in Granta Edupack 2022 based on the production process of the bio composite. This is shown in table 3.4.

The outcome of the filter has been plotted with the price of material on the y-axis (€/kg) and the machining speed (m/min) on the x-axis. This graph is shown below.
This shows that there is a clear distinction between steel alloys on the left side of the graph and aluminium alloys on the right. In general, the aluminium alloys in this selection have a higher machining speed than the steel alloys. Beacuse of the relatively high machining speed of aluminium, the lower average price, and because steel is more corrosion sensitive aluminium seems to be more suitable for constructing the mould.
But this is only part of the story. A distinction must be made between low and high-volume production of parts. If the volume is low aluminium can be the best solution because it is generally less expensive and can reduce cycle times during production because of shorter cooling period. Another advantage of using aluminium, especially in low volume or prototyping situations, is the higher machining speed during mould production. A disadvantage of aluminium is that it is less wear-resistant than steel. This effect could be reduced by applying a wear resistant coating. But in general, it causes the material to be less suitable for larger series.
For high volume production tool steel is a more logical choice because of its wear-resistance. Disadvantages of steel are that it must be protected from corrosion by applying a coating, the higher price and that it is harder to machine than aluminium.

Graph 3.11 (page 36) shows that aluminium 2024 in not only the alloy with the highest compressive strength but also a low price per kg. Because Al 2024 is available in blocks of 300 x 2.600 x 16.000 mm (H x W x L) it is the most suitable candidate for creating moulds in a large variety of sizes.

Material criteria mould
The temperature range needed is between 100°C and 200°C.
Pressure in the mould: 10 – 20 MPa
Machine speed: + /++
Durability: ++
Corrosion resistant: ++
Price: ++

TABLE 3.3
Material criteria mould

	Minimum	Maximum
Compressive Strength	20 MPa	
Maximum Service Temperature	150 °C	
Minimum Service Temperature	15 °C	
Durability	Acceptable	Excellent
Weak Acids	Acceptable	Excellent
Weak Alkalis	Acceptable	Excellent
Organic Solvents	Acceptable	Excellent

TABLE 3.4
Material filter Granta Edupack

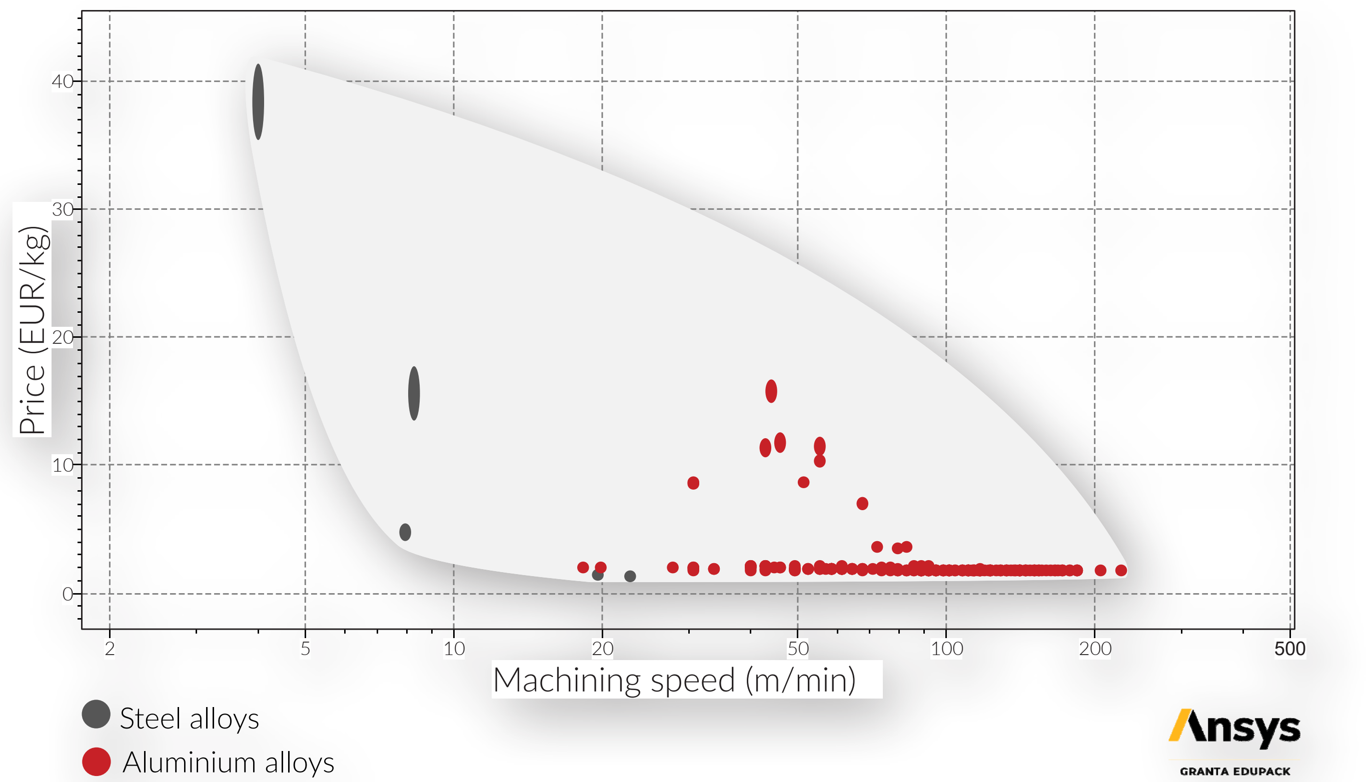

FIGURE 3.10
Graph Machining speed and Price / kg

Round mould

Because the production of the samples in laboratory conditions is time intensive a smaller round mould has been created which needs less material. This increased the production speed of samples significantly. This is not only caused by a shorter pressing process but by a shorter set-up time per sample because it takes less time to produce the material needed to fill the mould.

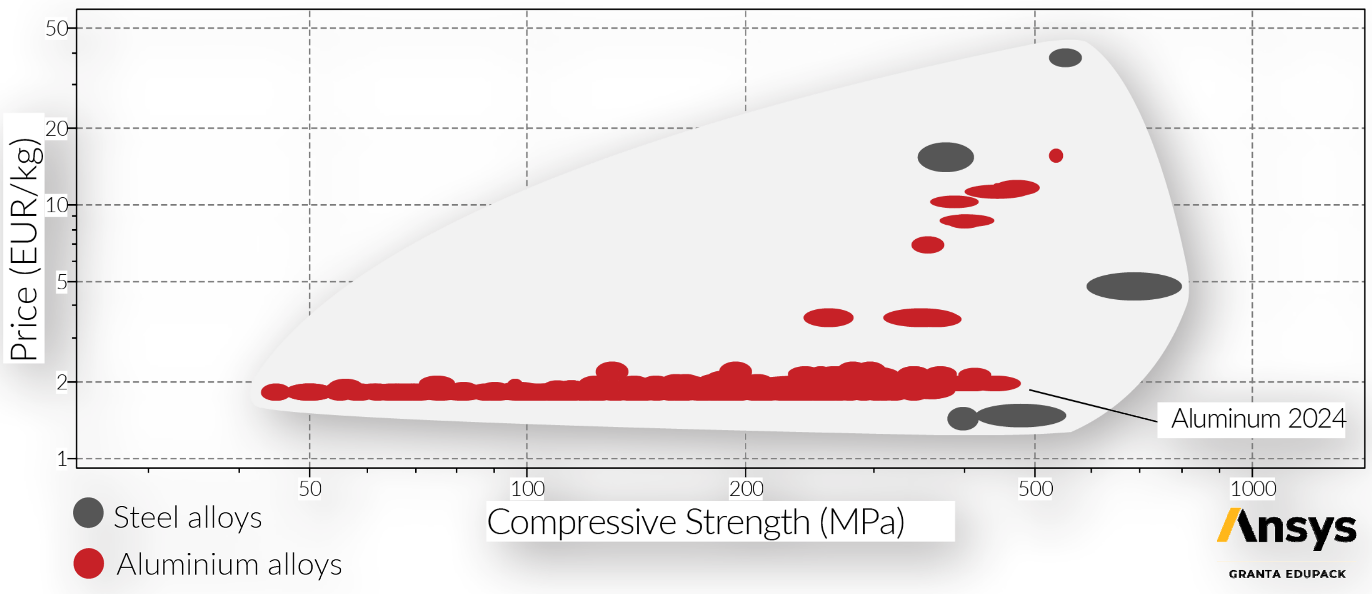

FIGURE 3.11
Graph Price per kg and compressive strength

Because the die of this mould consists of three separate parts it is easier and cheaper to machine different profiles for it. The profiles are easily changed because they are bolted on with four Allen head bolts.

The manufacturing of the shaper dies has been done on a lathe (figure 3.12) with the help of DARE (Delft Aerospace Rocket Engineering) of the Faculty of Aerospace Engineering. These profiles are pressed into the material. The round mould is shown in exploded view in figure 3.14 on page 37 and the die with several profiles in figure 3.17 on page 38. The inner dimensions are 90 mm Ø and a height of 40 mm. The outer dimensions are 150 mm Ø with a height of 60 mm. Both the top and bottom plate are 150 mm Ø and 10 mm thick. The spacer and shaper dies are both 90 mm Ø and 20 mm thick.

Because aluminium has very good machining characteristics the surface quality of the samples is quite good without special treatment of the mould. The sample on the left in figure 3.15 on page 38 is made with an unpolished shaper die directly from the lathe. The sample on the right is made after the die has been polished. This was done at the Surface Treatment Laboratory at Delft Aerospace Structures and Materials Laboratory (DASML) at the Faculty of Aerospace Engineering by using a sanding machine (figure 3.13 page 37) with ultra fine grits up to 4000. After this the surface has been finished using a polishing machine and polishing paste. This removes al the machining marks and leaves the surface of the material very smooth. The same surface treatment has been done on the rectangular mould (die and base plate). This results in a surface quality shown in figure 3.3 on page 29.Ox moris senatium con hoccibem ubis til ve, ut resuli publintili potis pare me terehem dis. Maris, Cato virideni publis, untelabista rei publiusquam rem publiu cuperi ipios ocaesimus,

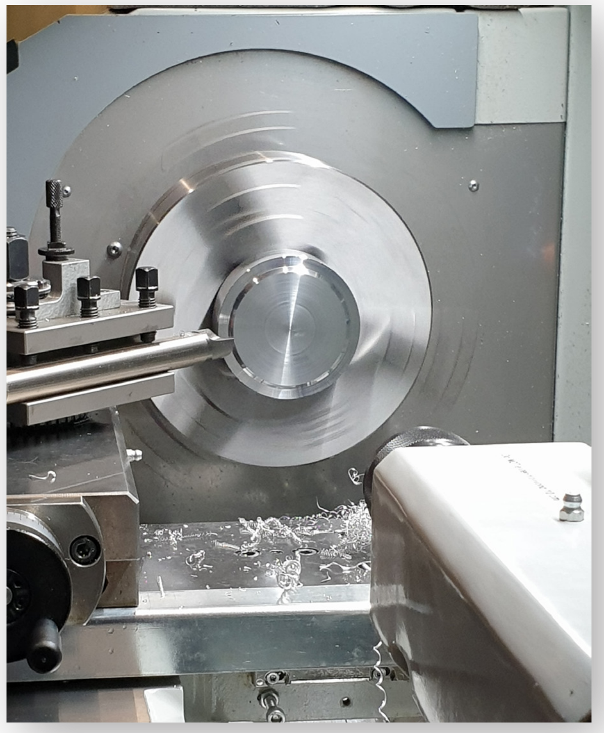

FIGURE 3.12
Machining the inlays for the round mould

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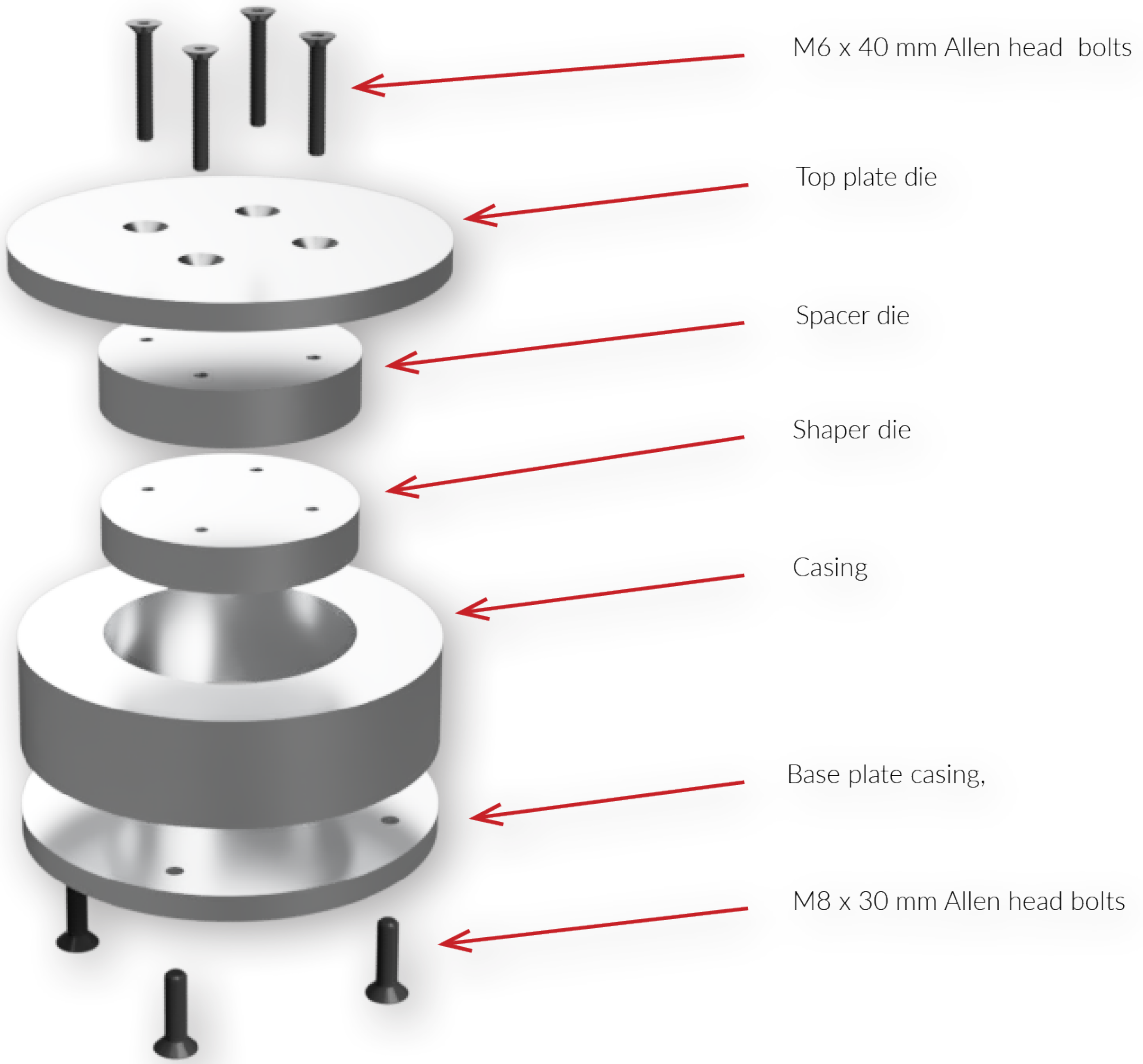

FIGURE 3.14
Round mould exploded view

FIGURE 3.13
Polished contact surfaces round mould

FIGURE 3.15
Polished contact surfaces round mould

FIGURE 3.16
Left sample polished , right not polished

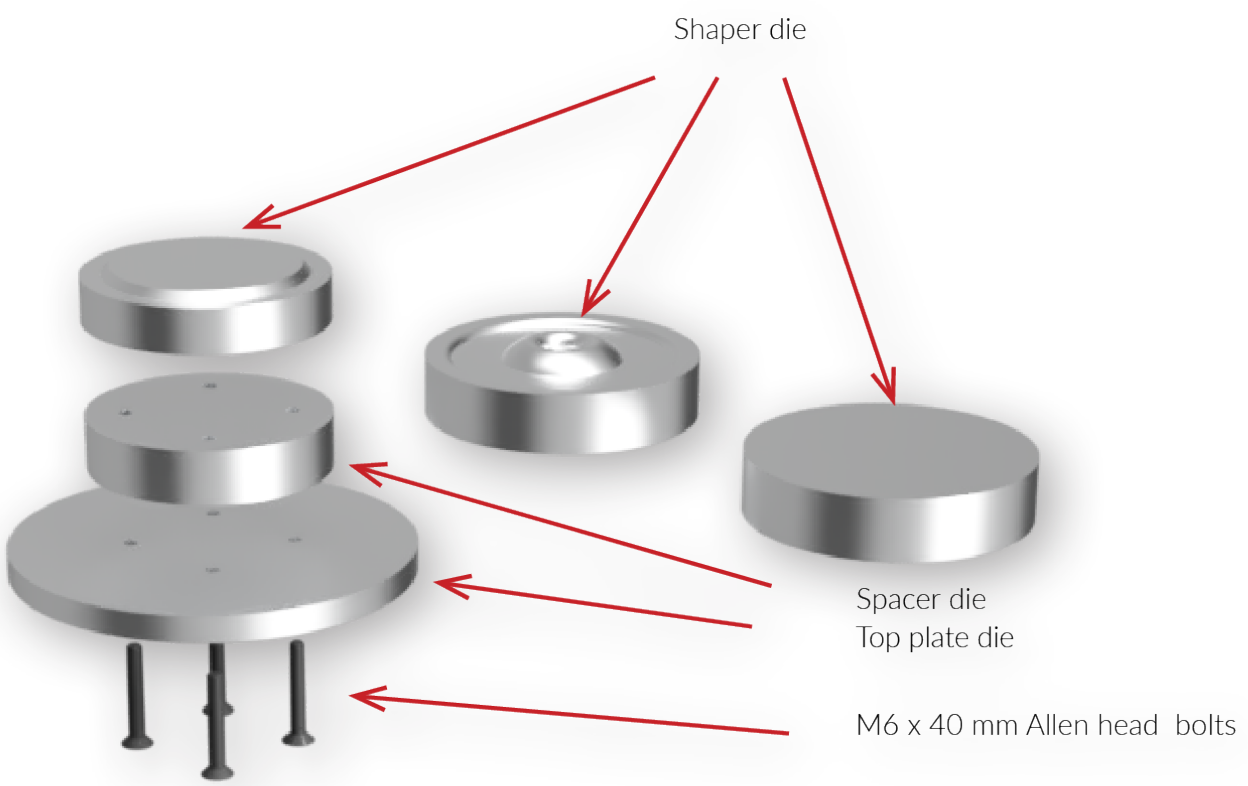

FIGURE 3.17
Different shapers for the round die

ALERNATIVE MATERIALS FOR MOULDS

A significant contribution to the cost of curved façade panels are the material and machining cost of the moulds and inlays. Because of this it makes sense to research alernative materials that are either cheaper or easier to machine. This will be discussed in this section.

RAKU TOOL WB-0950

Another material that has been used to machine the inlays for curved surfaces is an epoxy board material called raku tool wb-0950. This material has been chosen because the recommended machining speed is much higher than for aluminium which means the machining time is significantly shorter. Which makes it more suitable for smaller series and prototyping. The inlay made has not been tested full-size because of a machining accident and another sample of material was not available. However, in this section a theoretical exploration of the material will be presented and discussed. It is a high temperature Epoxy Board used for tools and moulds and is marketed by Rampf Tooling Solutions GmbH & Co KG, Grafenberg, Germany. The key properties of this material are heat resistance up to 200°C, a closed surface structure, good machinability, and dimensional stability. A more complete list of properties can be found in table 3.4.

The most important properties when making a mould are the shore hardness D, thermal expansion coefficient, deflection temperature (HDT) and compressive strength. Here it should also be noted, that as with aluminium, that the pressures inside the cavity of the mould might not be representative for the tensions inside the material.

Shore hardness

The shore hardness scale has been introduced so that the hardness of different materials can be compared. This scale has several categories ranging from Shore 00 for very soft gels and rubbers to Shore D for hard rubbers, semi-rigid and hard plastics. The Raku tool wb-0950 board has a Shore D hardness between 75 and 80 which means its very hard and comparable to a hard hat.

FIGURE 3.18
Rounded corners mould

Mechanical Properties		RAKU TOOL - WB0950
Color		Brown
Density	kg/m^3	950
Shore Hardness D		75 – 80
Thermal Expansion Coefficient	$10^{-6}K^{-1}$	30 - 35
Deflection Temperature (HDT)	°C	190 - 200
Compressive Yield Strength	MPa	70 - 80
Flexural Strength	MPa	40 - 50
Milling Speed (V_c)	m/min	940

TABLE 3.4
Mechanical properties of Raku tool wb-0950 (Rampf ToolingSolutions GmbH & Co KG)

Thermal expansion coefficient

The thermal expansion coefficient is a measure for how much a material expands or shrinks with a change in temperature. And is calculated with the formula:

$$\alpha_V = \Delta V / V.\ \Delta T$$

α_V = volumetric expansion coefficient
ΔV = change in volume V (m^3)
ΔT = change in temperature (K)
V = volume (m^3)

The thermal expansion of aluminium is approximately 23.2 10-6K-1 and of Raku tool wb-0950 between 30 – 35 10-6K-1. This means that epoxy board has a 51% higher expansion coefficient than aluminium 7075 and will therefore expand more (ΔV) with the same temperature change (ΔT). The material wants to expand in all directions but because it is trapped inside the mould it cannot. This causes the tensions

FIGURE 3.19
Raku Tool WB-0950 Inlay

in the material to rise.

MORE SUSTAINABLE FAÇADE PANELS

This research is about exploring the possibilities of a sustainable façade panel made of bio-composite for free-form architecture. As a case-study the Depot Boijmans van Beuningen has been chosen not because it needs redesigning but because it is an iconic building and although it has been open for less than two years has become one of the most prominent landmarks in the city of Rotterdam.
The façade of the building is made of 1.664 curved panels divided into 26 rows of 64 identical panels. This means the panels are made in small series rather than each panel individually. The panels are approximately 3.5 x 1.5 m in size. These two facts cause an equal number of challenges to manufacture these panels in the size they are originally designed.

The production method used for the bio-composite require moulds able to withstand pressure (between 10 and 20 MPa) and temperatures (between 100 and 200 °C) which makes the moulds relatively expensive and less suitable for small series. The smaller the series the bigger the contribution of the cost of the mould to the cost of the panels.
The sizes of the panels, in this case study, are quite large. This makes for heavy, bulky, and expensive moulds.

Several techniques and designs are possible and will be discussed in this chapter.

SAME CONCEPT DIFFERENT MATERIALS

One way to make the façade of a different more sustainable material is to keep the design of the panels the same as they are now and just change the materials. To do this the first step is to look at the way the façade of the depot has been designed by MVRDV. The façade panels are made of a black aluminium frame onto which the curved glass has been attached using an adhesive sealant. Because an adhesive is used instead of mechanical connections regulations state that the glass must be secured by secondary means. In this case black stainless-steel failsafe support brackets connected to the frame to prevent the glass to fall in case of an adhesion failure. Figure 3.20 Connection detail (MVRDV).

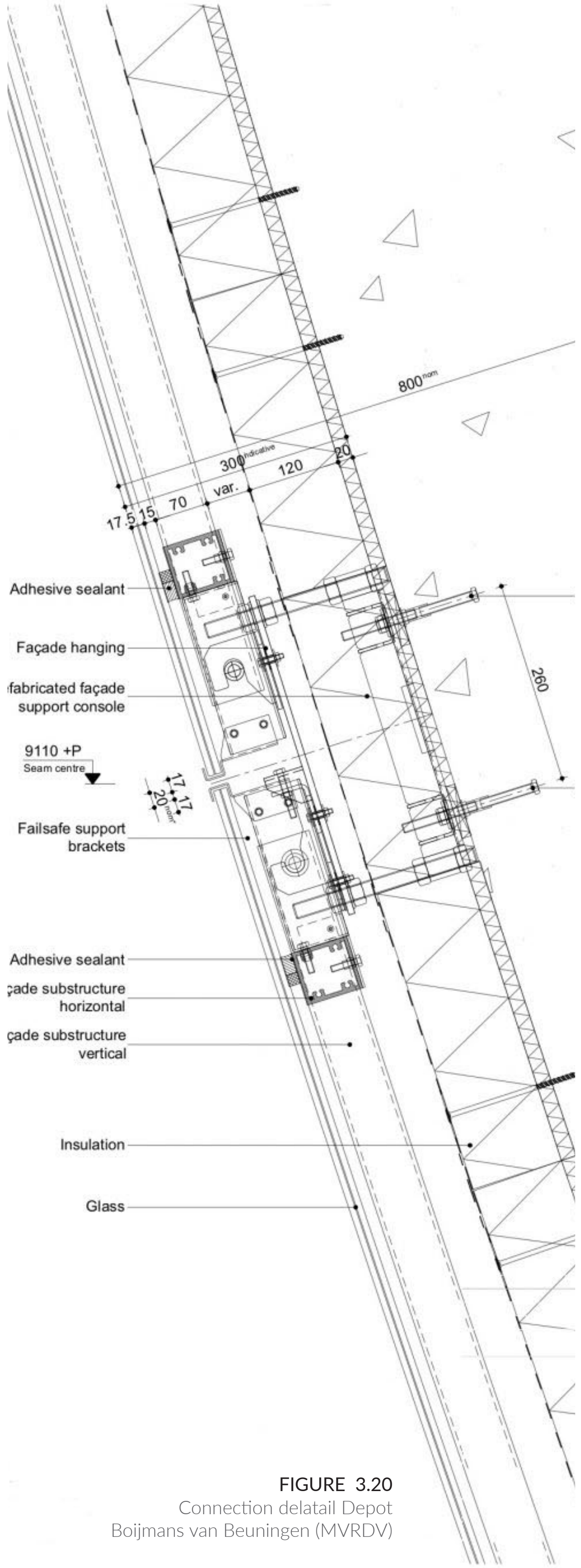

FIGURE 3.20
Connection delatail Depot
Boijmans van Beuningen (MVRDV)

The frames currently used for the façade panels of the Depot are rectangular and made of aluminium. A more sustainable alternative would be to make them of wood. This wood needs to be sustainably sourced timber, it should be resistant to moisture, and it should meet the structural conditions set by a façade of this type.

1. Design and construct a mould for the curved skin panels: base plate, casing and die.
2. The actual curved shape of the panels is created using inlays. The inlays for the mould need to be designed and machined. These will determine the shape of the panels.

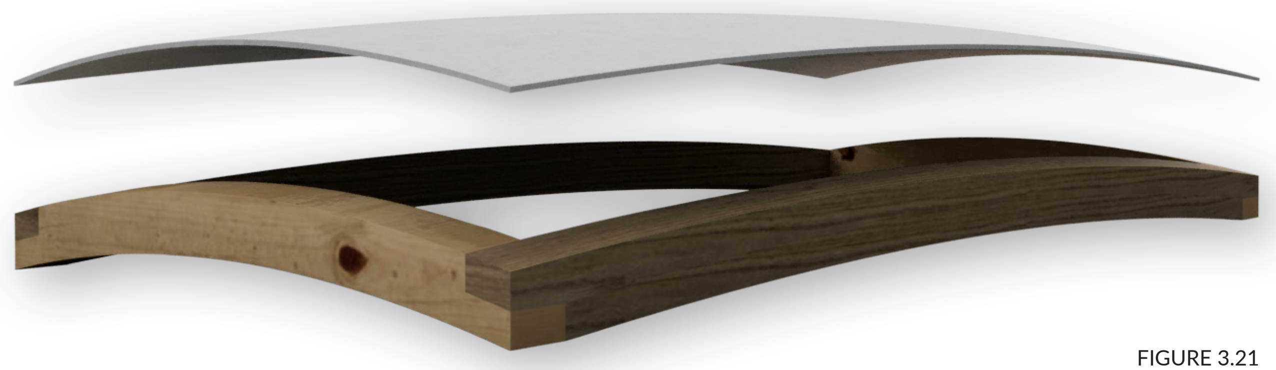

FIGURE 3.21
Bio- composite panel with wooden frame

Since the original design of the façade is followed the insulation and the vapour-permeable water barrier will be attached directly onto the structure (the concrete "bowl"). As are the connections between the frame and the structure. To complete the panel the double curved surface is mounted to the frame. These panels of bio-composite will be attached to the frame using an adhesive. The adhesive is necessary because it will also function as a water barrier between the panel and the wooden frame. On the back of the panel, invisible from the outside, the panel is secured by a mechanical connection. Both the chemical and mechanical connection can be applied off-site in the factory.
To manufacture these façade panels several steps are needed.

The Depot is divided into 26 horizontal layers with each 64 identical panels. Each vertical column contains all variations of panels. In figure 3.22 Paneling of the Depot Boijmans van Beuningen and figure 3.23 Different panels Depot Boijmans van Beuningen on page 43 this has been visualised schematically.

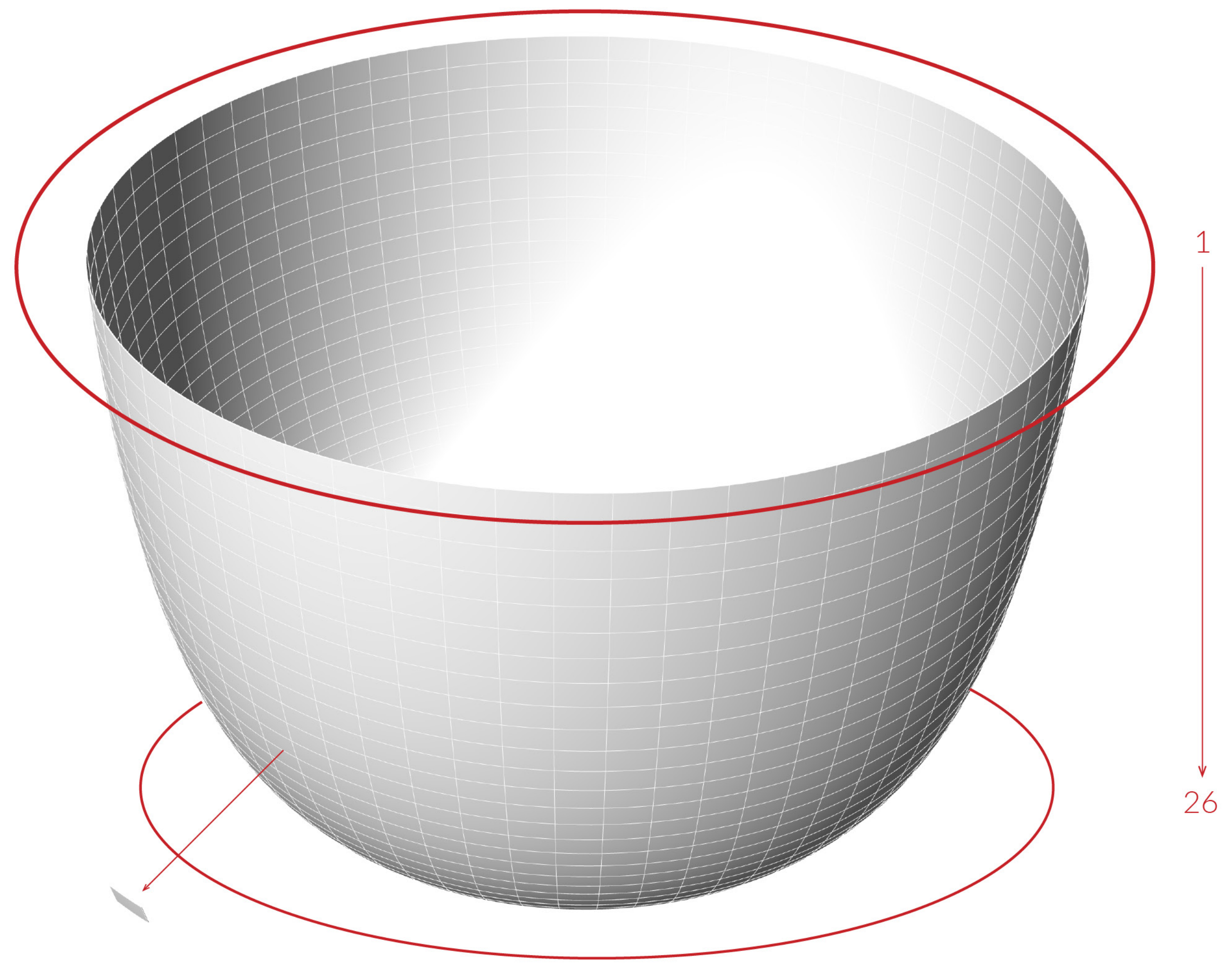

FIGURE 3.22
Paneling of the Depot Boijmans van Beuningen

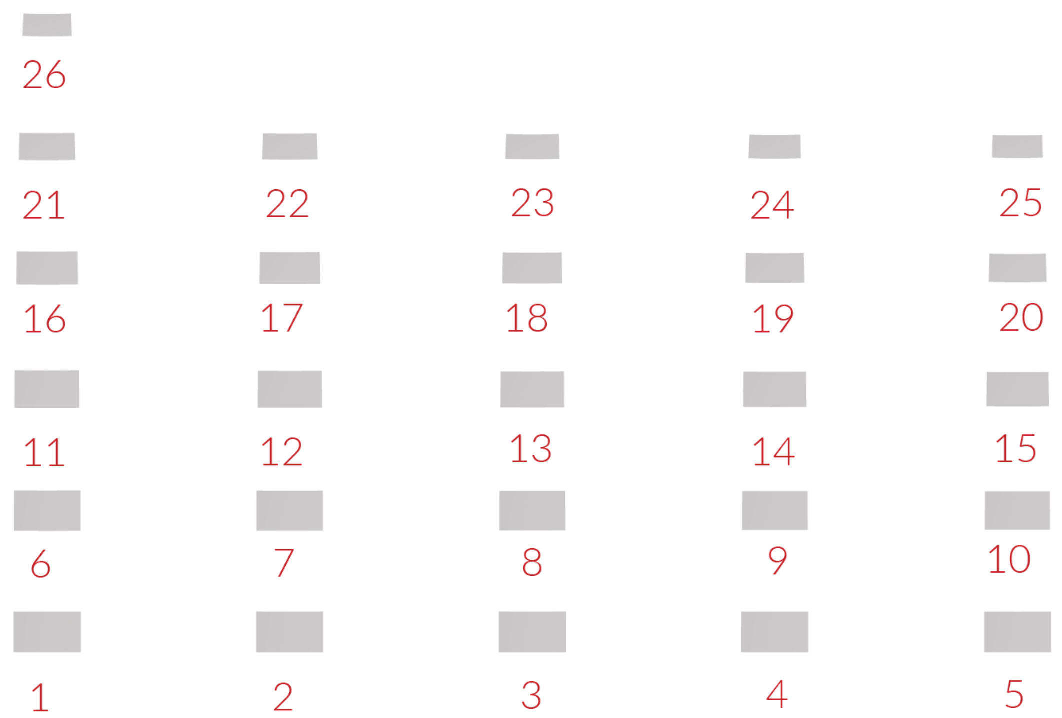

FIGURE 3.23
Different panels Depot Boijmans van Beuningen

LARGE PANELS OUT OF ONE PIECE

The way the panel is designed by MVRDV makes perfect sense when glass is being used for the façade panel. However, when bio-composite is applied it is les logical.
If frames are used, 26 different ones are needed because there are 26 types of panels. These have different dimensions but also different curvature. They must be designed, manufactured, and attached to all 1.664 individual panels. This requires labour, material, and energy. By using the bio-composite this is not necessary because the panels can be manufactured in one piece. Including the frame. Figure 3.24 and 3.25 show one of the possible designs of such a panel. The connection detail is shown in the appendix. The thicker material around the edges and along the centre lines (figure 3.24) not only makes the connections between the building and the façade panel possible but it also adds rigidity to the panel. All vertical edeges need to be slanted in order for yhe material to be removable from the mould. The thicker areas are important because the wind loads on panels approximately 3 x 1.5 m are significant and must be absorbed by the connections, the structure of the building and the panels itself.
Tests with the round mould show that it is possible to press the bio-composite with different thicknesses (figure 3.16 page 38). The samples that have been made in this way have a relatively low surface roughness even without any post processing.

SURFACE ROUGHNESS

The surface roughness is important because it determines the human perception of an object and how it interacts with its environment. For example, irregularities on a rough surface may cause cracks or corrosion. Roughness also influences the way adhesives and coatings behave. A higher surface roughness makes it easier for adhesives or coatings to stick because of the greater surface area. A higher roughness also makes it easier for dirt to accumulate on the surface.
The surface roughness of the samples has not been measured but it is expected to be in the same range as the surface roughness of the machined or polished aluminium mould components. The surface roughness is measured in Ra. This is the arithmetic average of the surface heights measured across the surface. The surface heights can be measures using a profilometer which are available in several variations. The most important ones are mechanical (figure 3.26) and optical (figure 3.27). The first has a resolution of 2 µm and the second a resolution of 0. 2 µm. Since unpolished machined aluminium has a surface roughness in the range of 25 to 0.2 µm and polished aluminium between 0.8 µm and 0.012 µm a laser profilometer is needed to measure the surface roughness of the material.

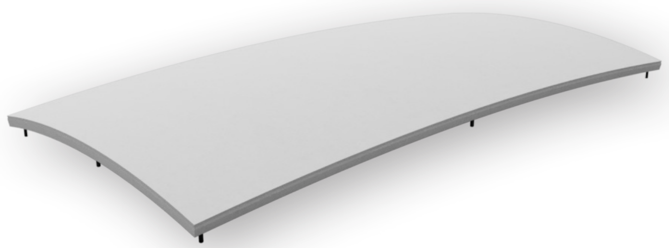

FIGURE 3.24
Scale panel 1:10

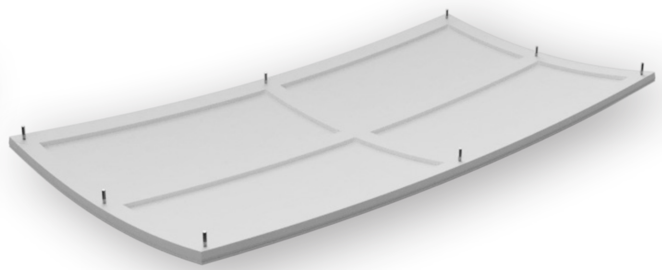

FIGURE 3.25
Scale panel 1:10

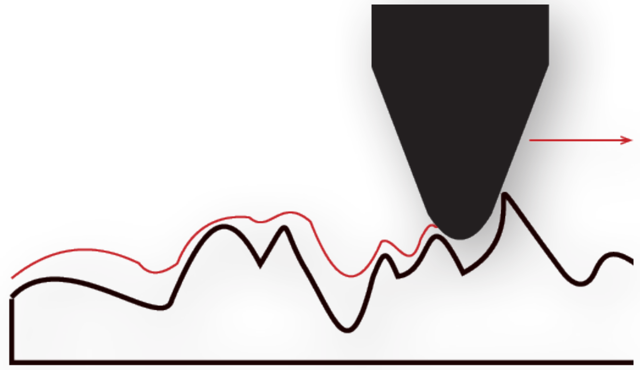

FIGURE 3.26
Mechanical measurement of surface roughness

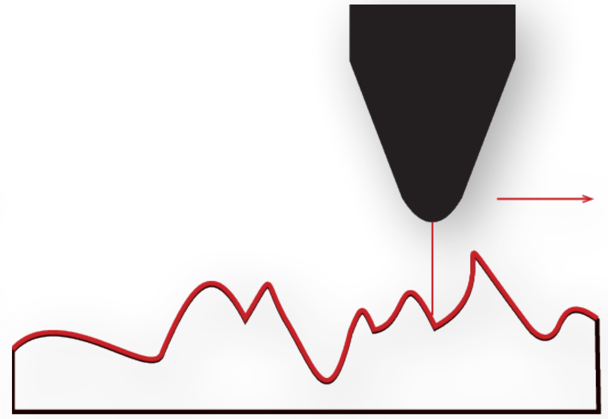

FIGURE 3.27
Optical measurement of surface roughness

COATING

For façade panels it is important to know how the proposed material responds to water. This has been looked into by measuring the water contact angle and how it reacts to being submerged for 26 hrs. The contact angle is a measure for the wettability of a solid material. This describes the way a liquid (in this case water) can maintain contact with a solid (in this the case bio-composite).
Water contact angle
The water contact angle of the bio-composite has been tested using a contact angle goniometer (figure 3.28) at the Physics Laboratory at DASML (Faculty of Aerospace Engineering). To do this a sample of the material has been placed in the machine and a drop of water (8 µl) is placed on the surface using a pipette (figure 3.29). A close-up image of this is made using a high-resolution digital camera linked to a computer. The software on the computer analyses the image and determines the contact angle. The (limited number) of tests show that the contact angle α of the samples varies between 60° and 67°. To illustrate the variation between drops four

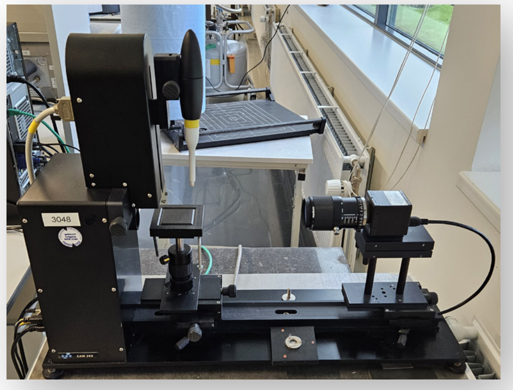

FIGURE 3.28
Contact angle goniometer

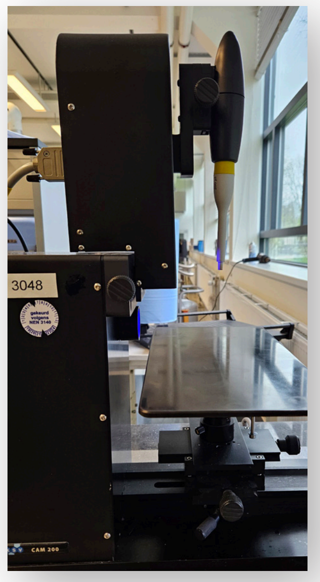

FIGURE 3.29
Pipette and sample

photos made with the contact angle goniometer are shown in figure 3.31. The angle lines are later added manually and purely illustrative.
These measurements indicate the material, as produced, to be hydrophilic because all angles are well below 90°.

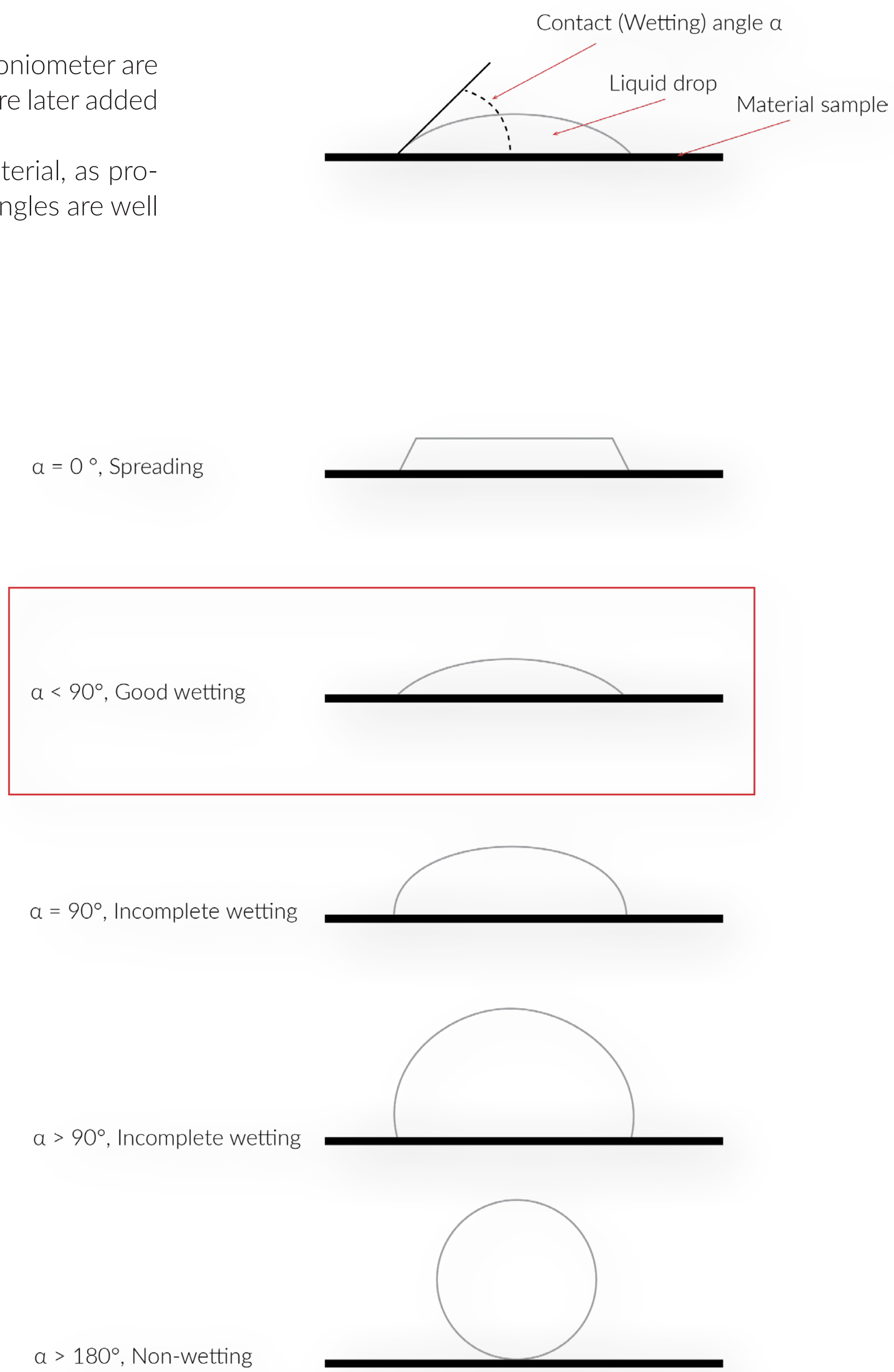

FIGURE 3.30
Water contact anglese

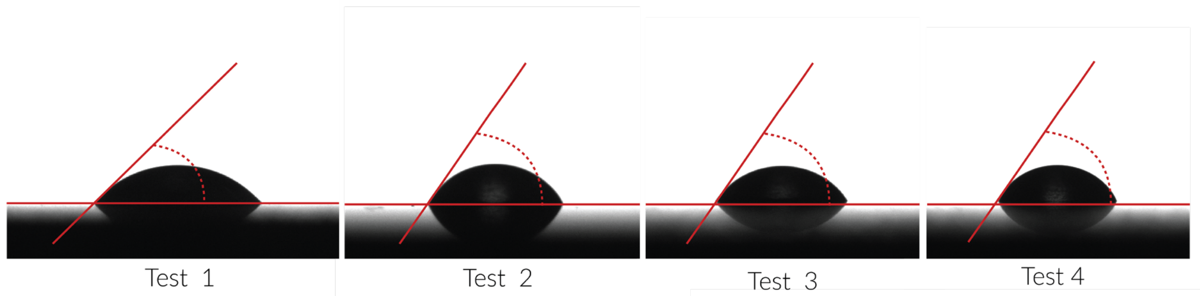

FIGURE 3.31
Illustration of the variation between drops

PRESSING SCALE MODELS PANEL

No inlays

Experimenting with the bio- composite material started with the rectangular mould without inlays. The samples created where flat rectangles 150 x 300 mm (figure 3.32 Flat sample in mould). This is roughly 1:10. The thickness of the sample pictured is 5 mm with a

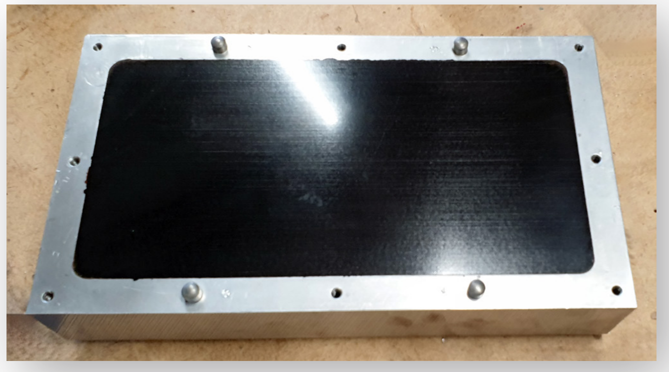

FIGURE 3.32
Flat sample in mould

FIGURE 3.33
Measuring material thickness

variation of ± 0.5 mm over the sample (figure 3.33 Material thickness). This is caused by variations in the amount of material in the mould before pressing. This causes pressure differences inside the mould and variations in thickness. On the sur-face of the sample some marks can bee seen of the production process of the raw aluminium plate used for the mould. The polishing of the base plate has not been done thoroughly enough to remove these. This leaves marks in the pressed material.
Another sample has been made using less material which results in a sample of 2.5 mm. This sample is easier to bend but it is also more prone to warping. The cause for this, apart from the thickness, is not entirely clear. The most probable causes are the cooling process and / or moisture in the air or material. This is not in scope of this research but should be investigated further. This sample also shows variations in colour in the material which are likely caused by variations in the amount of material inside the mould as well. On the laboratory scale fabrication of thin flat bendable samples bio composite is possible and they could be attached to the wooden frame using an adhesive. This also means lamination of several layers is possible. However, this would cause stresses in the material. To avoid this the curved inlays for the mould have been made. By using these the material will have the correct curvature and can be con-nected to the frame without these stresses. Another advantage of this method is that the thickness of the material is not a limiting factor because the curvature will be created during fabrication regard-less of the thickness.

Using the aluminium curved inlays

To further test the concept a small-scale model, approximately 1:10, of the curved façade panel has been made using the lignocellulosic material. The rectangular mould as shown in figure 3.7 on page 32, has been used for this. The digital model is shown of a curved façade panel is shown in figure 3.34.

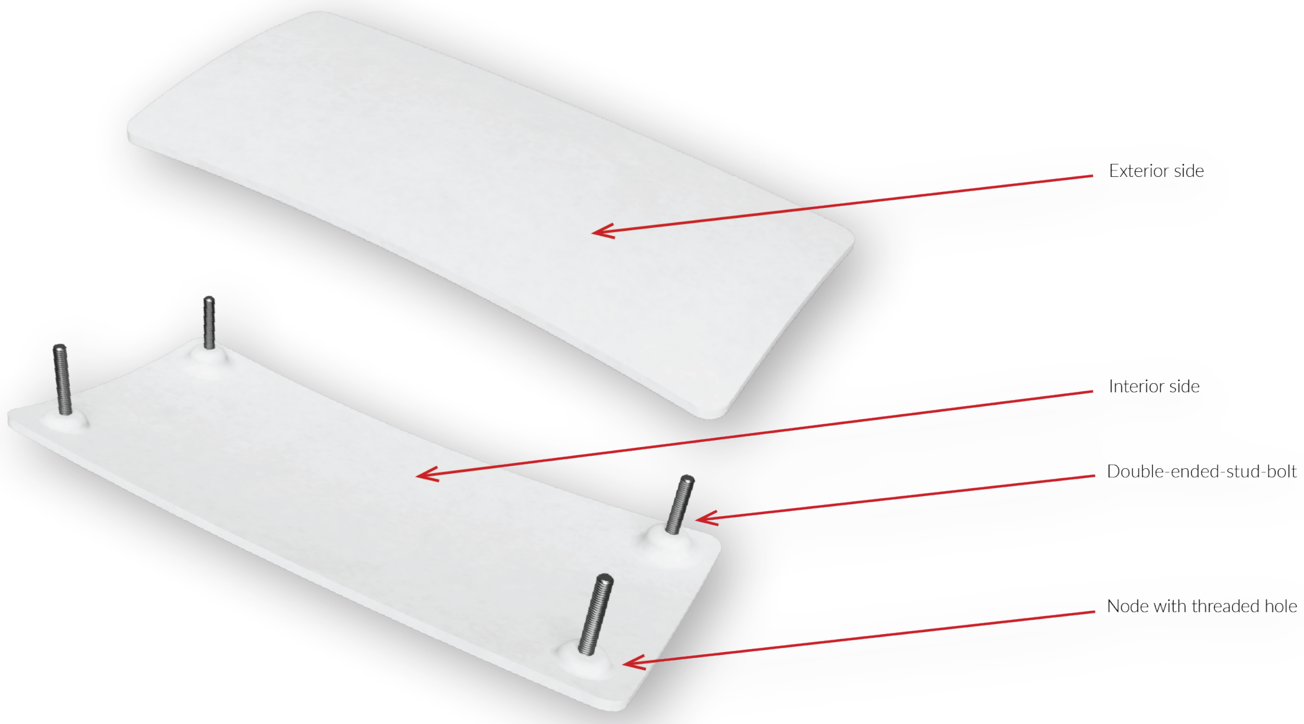

FIGURE 3.34
Scale model panel 1:10

The aluminium inlays will be tested for these aspects:

- Does the general concept of using inlays work?
- Is it possible to press the nodes of thicker material for the connections? And is the material easily removeable from the mould and the inlays?
- Is it possible to drill holes in the nodes and thread them?

CONCLUSION ALUMINIUM INLAYS

Using the aluminium inlays has been proven to be a feasible way to produce curved façade panels. This was done by pressing to panels using sawdust and the bio-composite. The results can be found in figure 3.36. The sawdust sample proved to be less solid than the bio-composite. This was expected. Adding more material locally to be able to attach the panels to the building worked but more research is needed to make the panel, including the 'nodes' more homogenous. It should be noted that the mould and the inlays should be redesigned to make it easier to remove the material from the mould.

Another important aspect is the attachment of the panels to the building. To test this holes have been drilled and these have been threaded. This made it possible to insert bolts to the panels which can be used to attach the panel. This is shown in figure 3.35.

As mentioned earlier using the almuminium inlays is possible but I don't think threading the holes in the material directly is the best option. Inserting a metal thread would give a more robust connection.

FIGURE 3.35
Connections curved façade panel

FIGURE 3.36
Scale models panel 1:10

Using the raku tool wb-0950 curved inlays

Because the machining speed of the RAKU board is much higher than aluminium it makes sense to investigate this material for the curved inlays. The board has been succesfully machined into inlays with the desired shape (figure 3.19 page 40). However the bottom one has been severly damaged during a sanding accident and is beyond repair. It was possible to test the material as an alternative for aluminium by transforming the damaged Raku board inlays into set of smaller inlays for use in the round mould. Figure 3.37 Recovered RAKU Tool WB0950 inlays.
This has several advantages. Because the rectangular mould is much bigger it is possible to tranform the inlays into three sets to be used in the round mould. Only the thicker nodes for the connections cannot be tested because they are too close to the edge to include in the round inlays.

The epoxy board inlays will be tested for these aspects.

- Will the material be able to withstand the hot press process?
- Is it possible to remove the material from the mould after pressing? Or will the material and the inlays be fused together because of the pressure and temperature used?
- Are the inlays reusable or are they one use only?
- What is the surface quality compared to using aluminium inlays?
- Are the dimensions of the sample as expected?

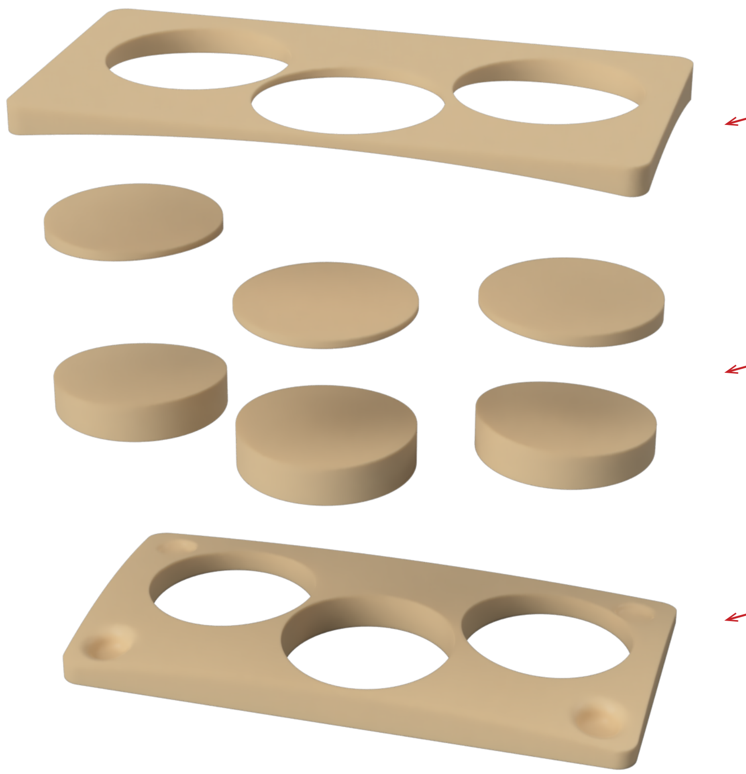

FIGURE 3.37
Recovered RAKU Tool WB0950 inlays

CONCLUSION RAKU TOOL WB-0950 INLAYS

Machining the RAKU expoxy board proved to be possible but created a lot of dust which made using PPE necessary. At first glace the surface quality was good but seemed rougher than aluminium. I used sawdust for this experiment because it requires less preparation than the bio-composite. The temperatures and pressures used were the same as for the composite. Removing the inlays and the sample was comparable to the aluminium inlays. Also the separating the inlays and the sample proved to be easy. The expoxy board inlays appear to be undamaged by the pressing process. The dimensions of the inlays haven't changed and also the surface quality is the same.

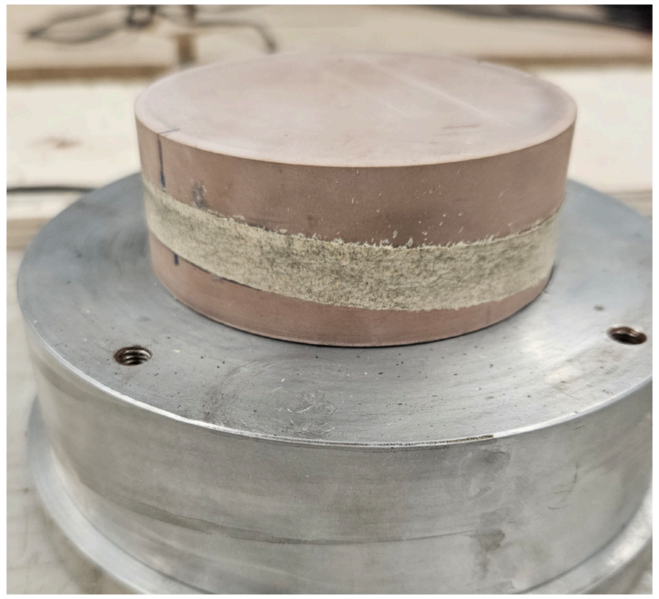

FIGURE 3.37
Recovered RAKU Tool WB0950 pressing

The same can be said about the sample itself. Using epoxy board instead of aluminium doesn't seem to have a negative impact on the samples. Both the dimensions and the surface quality are as expected.

The RAKU Tool WB0950 is an alternative material for the inlays of the moulds. There are some disadvantages however to using this material. It is relatively expensive as mentioned earlier. The machining speed is higher but can be quite messy when using a CNC-machine or a lathe. PPE is required. Another important disadvantage is that the material is hard to recycle and should be treated as chemical waste. The quality of the produced sample is good and as expected.

CHAPTER
FOUR

CONCLUSION

CONCLUSION

Is the bio-composite as used in this research a feasible material for façades? This is the question that is open for debate. Technically it is possible to fabricate façade panels, double curved or not, from this material. But does it make sense?

MOULDS

Because the machining of the alumium inlays has been delayed and the injuries sustained during the fabrication of the expoxy board inlays the experimnets with both types of inlays have been delayed. The planning is to have them both ready before the P4 presentaion. The conclusions of this research will be added to this thesis at a later date.

COST

Because the material needs to be hot pressed the process is best suited for larger series of identical panels to be cost efficient. If we look at modern free--form architecture most façades have no or very little repetition in the panelling. This makes them expensive to make with large unique panels of bio-composite.This is because the mould for each panel must machined individually. For buildings with repeating panels like the Depot Boijmans van Beuningen by MVRDV, it might be possible to be competitive with glass or composite panels but that depends on the actual cost of both solutions. A cost analysis is not in scope of this research.

For buildings with little variation in the curvature of the panels it could be a more cost-effective solution to recycle the moulds. This means that only the first mould (or inlay) needs to be machined from raw material. After all the panels with a mould are pressed it can be machined to fit the next panel. By doing so the material use and machining time would be reduced significantly. This would lower the cost of the façade.

If smaller units are used, like siding, it becomes a different story. For example, the Chesa Futura apartment building designed by Foster & Partners could be made from bio-composite in a cost-efficient way

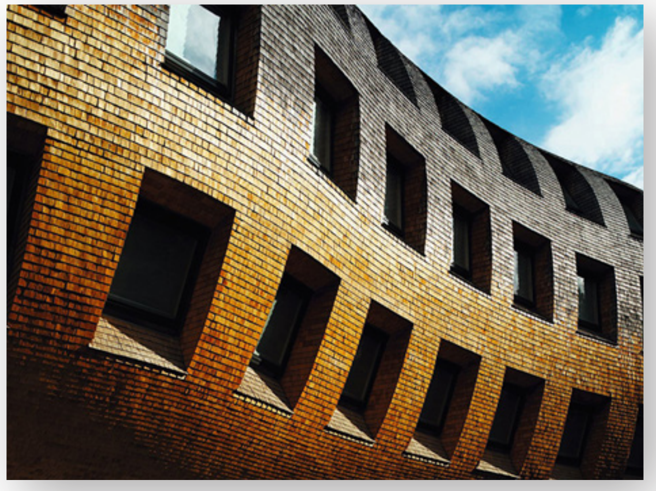

FIGURE 4.1
Chesa Futura, Foster & Partners (Chesa Futura, 2023)

because there is a large degree of repetition in the façade.

But....

The above-mentioned argument stands but is only part of the story. Sustainability goals set by for example, the Dutch government in 2016 issued a 'Sustainable procurement catalogue' for public tenders https://www.mvicriteria.nl/en). This states that 'The higher the proportion of bio-based raw materials and/or recycled raw materials in the products supplied, the higher the value of the tender'. This catalogue applies to a large variety of projects, from road building, marine projects, landscaping, construction and more (Bio-based coatings overview: Increasing activities, n.d.). By doing so the government gave sustainability a real monetary value which makes the actual production cost less relevant.

SUSTAINABILITY

Of course, sustainability is an important aspect of the solution. The material itself is completely sustainable but can the same be said for the production method of the panels?
In case large panels are used, like on the Depot, every mould must be machined out of aluminium. After a series has been completed (it might be wise to fabricate some extra in case panels need to be replaced

in the future) the mould can be sold as scrap metal and digitally saved for future use. The production of the aluminium and the machining of the mould costs energy. The same is true when another material is used. It all depends on how much energy each solution uses and how it is produced. If the moulds can be recycled, as discribed in the previous section, the environmental impact will also be a lot lower.
For the smaller sized panels, sidings, the described argument also holds but there are a few differences. Because the moulds can be used to produce large numbers of identical small panels the number of moulds that are needed is much lower. This causes the energy used per panel to be much lower.

RAKU WB-0950

Using other materials to make the mould / inlays is technically possible. This has been tested using an machinable epoxy board and the round mould filled with sawdust (figure 4.2). This is done for convenience reasons because it takes less time and effort to prepare the material. The pressure and temperature have been the same to make it a valid test. The board has some disadvantages. The tested Raku

FIGURE 4.2
Sample pressed with RAKU-Tool WB 0950 Board

Tool WB0950 is available in 1500x500x100 mm. This means 6 would be needed to make a panel of 3000 x 1500 mm. Because the epoxy board is rather costly the material cost for the mould are expected to be higher than when aluminium is used. Another disadvantage reported by the CNC-technicial is that machining the epoxy board is rather messy and airway protection had to be used.

WATER RESISTANCE

When large panels are used, made to the exact size required, the panels can be made water resistant by applying a coating. Of course, this coating must be completely bio-based to develop a consistent sustainable alternative to be used as façade panels for free form architecture. This poses no practical problem because the panels are made to size and do not need any machining which causes the coating to be damaged. For small panels this is a challenge because, as can be seen in the example in figure xx on page yy, these often have to be cut to size leaving the saw-cut unprotected. It might be possible to solve this on-site by applying the coating manually. Another solution might be possible but requires further research. Is it possible to make the material itself more water-resistant without needing any coating?

ARCHITECTURE

It needs no explanation that every choice regarding façade material has architectural consequences. A Depot designed with mirroring panels, wood, bio--composite or aluminium result in vastly different buildings. As mentioned before the goal of this research is not to redesign the Depot or any other (free form) building but to explore the technical possibilities of this material and make the built environment a bit more sustainable. The decision what material to use lies with the architects and their clients. But there are a lot of external drivers that influence this decision. An example is the Sustainable Procurement Catalogue issued by the Dutch government. Also, public relations policies of companies and institutions can be a big influence on decision making.

FINAL CONCLUSION

I think the bio-composite has a lot of potential, but a substantial amount of research is needed to determine its properties. This will determine for which applications it is best suited. The limiting factor right now is the water resistance. If this can be increased either by using a bio-based coating or by changing its composition the possibilities would be greatly improved. The indoor applications of the bio--composite are numerous. From kitchens to furniture but also objects like loudspeakers. Everything that can be made from standard plate material like MDF but also things that are made of plastics.

As for façade panels the answer is a little bit more complicated. As mentioned earlier the water resistance is an issue. Another is the way the material is produced. If the façade panels (curved or not) are all identical or in large series of identical panels this is not a problem. Aluminium moulds can be used many times before they need replacement. If the panels are all unique or in small series the production method is probably expensive compared to other materials.

REFLECTION

RESEARCH

Throughout my education at the Faculty of Architecture, Urbanism and Building Sciences (AUBS) at Delft University of Technology the terms sustainability, climate change and renewable resources played an important part in almost every course. Because of this I think it makes sense to try and make it also a prominent part of my graduation research. How can we, as designers and engineers, contribute to a world that is able to meet our own needs without compromising the ability of future generations to meet their own needs? This led me to the topic of my research: to examine the possibility of fabricating a more sustainable façade for free-form architecture. The results of the research show that it is possible to fabricate façade panels from a sustainable material but there are some limitations. The most important are water-resistance and the production process. For a façade water resistance, of course, is an important factor. This has been noted during the research but is not in the scope of this project to solve. More research is needed on this subject. The production method used requires a mould and a heated press to fabricate curved surfaces. This process has a large impact on the design of the façade panel. For example, if the process would have involved lower temperatures and pressures a flexible mould might have been possible, and the panel would have been designed differently to suite this production method. This makes the process most suitable to be used for larger series of elements. Most free-form architecture does not have much repetition which makes the process relatively expensive. It must be noted that this is not a technical issue but a question of cost. I have been able to fabricate a scale model of an alternative façade panel for the Depot Boijmans van Beuningen in one part. However, moulds are expensive to machine and whether it is feasible to construct the panels in an economical way depends on how the cost of the sustainable panels relate to the cost of more conventional materials.

ARCHITECTURE

Does it make sense to examine changing the façade material of an iconic free form building from an architectural point of view? Wouldn't it change the character of the building too much? The answers to these questions are, in my opinion, rather strait forward. To start with the first. Yes, it does make sense to research the possibilities of making the built environment more sustainable. The scarcity of resources and the threat of climate change prove this point. This includes free-form architecture. This type of architecture has been made possible by developments in CAD-CAM techniques and the development of new materials. Because of this it is an important reflection of the time period in which it is created and, more subjectively, can be aesthetically pleasing. The materials used are often not sustainable nor renewable. Examples of materials that are frequently used are fibre reinforced concrete, fibre reinforced composites, aluminum, and glass. These materials cost a lot of energy to produce and are hard to recycle. (Double) curved surfaces, as used in free-form architecture, are more difficult to fabricate than flat surfaces and require specific techniques and material characteristics. This becomes clear when thinking about more sustainable solutions for the façades. As argued in this thesis, the use of a bio-composite façade panel can be a feasible alternative.
Now for the second question. Wouldn't the character of the building change too much by redesigning the façade? That depends on what the original material is. In the case of the Depot Boijmans van Beuningen that material is mirrored glass. By changing to bio-composite panels the appearance of the building would indeed change dramatically. The building, as it is now, becomes part of its surroundings by reflecting it around 360°. Or the environment becomes a part of the building. This effect would disappear when using any other, non-reflective, material, this makes it not very logical to change the façade. Other free-form buildings like the Heydar Aliyev Cultural Centre in Baku by Zaha Hadid Architects would not be visually affected by fabricating the façade panels from bio-composite. In that case bio-composite could be a real sustainable alternative to fibre reinforced composite assuming the panels can meet the structural demands. As mentioned earlier more research is needed to examine this and make it possible.
There is one question remaining. How does sustainability fit in the design process? Designing is about comparing, choosing, and combining different options to come up with an aesthetically pleasing, coherent, functional / practical, and logical building that meets the needs, means and expectations of the client. These factors almost always lead to compromise. Is it possible to always choose the most sustainable option in every design decision? The consequence of this would be that every aspect of the design would be of lesser importance than sustainability. This might not always be feasible. For example, the budget might not allow the more expensive but sustainable solution. This is why I think it is important that we, as building technology engineers, take this into consideration. By technological advancements in materials and production techniques it is possible to limit the compromises needed between sustainability, design freedom, aesthetics, and costs. And thus, making sustainability more often feasible and maybe in the long run even an inevitability.

HELP

During this research process one of the most interesting things, I discovered is that it is almost impossible to graduate on your own. Before starting this journey, I thought graduating was a process between the student and his or her mentors. This is only part of the story. It is a process of acquiring of and expanding on knowledge built over time by scholars on the subject in question. This means that there is a link between the graduate and his or her predecessors. This has been brilliantly described in a well-known quote by Isaac Newton in a letter to Robert Hooke in 1675: "If I have seen further, it is by standing on the shoulders of giants." There is no way I want to compare my work to that of Newton, but it explains the way research and science work in a very clear way. We would be nowhere without our predecessors. But it is not only about a link between the past and the present. During the project I talked to a lot of people from almost all faculties on campus and with people from several companies active in the field. Sometimes I needed their insight or knowledge, but it could also be more concrete. Like needing access to facilities or materials. Or I needed their specific skills to help me with the fabrication of tooling for the research. This means there can be a multidisciplinary component to research that was not immediately obvious in the beginning. I found this one of the most enjoyable things. It is amazing to discover the breadth and depth of skills and knowledge available around campus and beyond. It is just a matter of looking for it. This can also be challenging because BT students are no chemists, physicists, or aerospace engineers. But luckily most people are willing to help.
The same is true off campus. I discovered the name TU Delft opens a lot of doors and again people and companies are willing to help with research. The list of people who helped during the process can be found on page 7 of my thesis. Many thanks to them! It can also be a humbling experience. The skills needed to make the things necessary for even the most basic research task can be very impressive. Researchers can be quite helpless without the people who have the skills to make things unless they are willing and able to learn those skills themselves. From this experience I learned that doing research and experimenting can be frustrating and that patience is a virtue. Making things takes time. Research takes time. People whose skills I needed had more to do than just helping me with my research project. It is essential to keep this in mind and be grateful for their help. One of the workshops I visited on campus had a plaque on the wall that summarised this very well: "Bad planning on your part does not constitute an emergency on mine!"

PLANNING AND FOCUS

I think one of the hardest things to do during this period was to stay focussed. It is very easy to go down your self-made rabbit hole and lose focus. This often means a risk on running behind schedule and the danger of missing deadlines. After thinking about this a lot, I am not sure how this could have been completely avoided in research like this. Research, experimenting and talking to people (often from different disciplines) leads to new insights and interesting angles to research. Sometimes these have major impact and can lead to significant changes. Some are unavoidable and must be incorporated somehow in the research and in the planning and others must be added to the "Recommendations for further research" section of the thesis.

LESSONS LEARNED

Process

Looking back, I think I should have given more attention to the challenges of keeping focus as described in the previous section. Taking the time to reflect more frequently on the process and make the necessary changes would, I think, have helped a lot in bringing structure to the process. The research topics that popped up could have been critically looked at and prioritised and their influence on the research questions would have been examined more frequently.
Did it have a negative influence on the quality of the research and the thesis? I am not sure, that depends on how you look at it. Because I kept the focus broader, I learned a lot more than I otherwise would have. That, I think, is an important facet of studying at a university. If you look at the research from a content point of view, I think the result is also better. Because I investigated the material a lot the conclusion of the research is better founded. The same is true for the recommendations for further research. It is very clear where the research gaps are regarding the bio-composite, its properties, and its applications. If you look at it from a process point of view it could have been improved. By following the process more closely the research would have been more efficient, more structured, and easier to follow for my mentors.

Planning

Research takes time. This is especially true when materials, tools or equipment must be made or ordered. It takes time to make things and suppliers often cannot deliver immediately. Working on a laboratory scale also has a big influence on lead times. Because laboratory equipment usually has a (very) limited capacity it takes time to produce the required amounts of material. I should have taken this more into consideration at the beginning of the process to make a realistic planning.

IMPACT

Academic

A lot of research has already been done on making the built environment more sustainable. For example, on production methods and on technical solutions to make building services more energy efficient. Materials also play an important part in making the built environment more sustainable by using renewable materials that are well suited to be used in a circular economy. The academic impact of the research done during my graduation is hard to estimate. The research done earlier about curved façades made from bio composite is very limited. In that respect it fills a research gap. It also made it very clear that to be a feasible alternative material for façades a lot more work must be done regarding the production methods and material properties of bio composites. Has the research added value to the academic knowledge? In a limited way the answer is yes. The research on bio composites and bio-based materials in general is very promising also for use in the built environment but a next step is needed. One of the ways to speed-up this process might be by designing an iconic free form building with a façade made from bio composite.

Societal

The societal impact of my research, although limited, is easier to answer. Both in society and in academia the urgency to lower our environmental impact and to make the energy transition a reality is broadly felt. This includes the built environment. We as engineers and academics, in the broadest sense of the words, have an important responsibility to make this transition possible. Without extensive research on many subjects durable change is impossible. As mentioned in the previous section using free form architecture to accelerate public support for alternative materials might have a positive influence.

Ethical

At first glance the ethical implications of using bio composite façades seem limited at best. It is a bit more complicated than that. The use of bio composites and bio-based materials are only acceptable when the materials are sustainably sourced. This means that the entire supply chain must be in accordance with the highest standards to avoid becoming a part of the problem instead of the solution. This is nothing new because the same is true for using wood and other natural resources. A sustainable material or product only is truly sustainable when the entire supply chain is and therefore is ethically acceptable.

TRANSFERABILITY

The design of the façade panel is completely transferrable because the digital files are available and the reasoning behind the design decisions has been described. The exact composition of the used bio composite has been intentionally kept out of this thesis to avoid intellectual property and patent complications. The same is true for the material test results.

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LIST OF FIGURES

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Figures on page 9, 11 and 58 Bilow, M. (2023)

Figure 1.1
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Figure 1.2
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Figure 1.3
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Figure 1.3
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Figure 3.20
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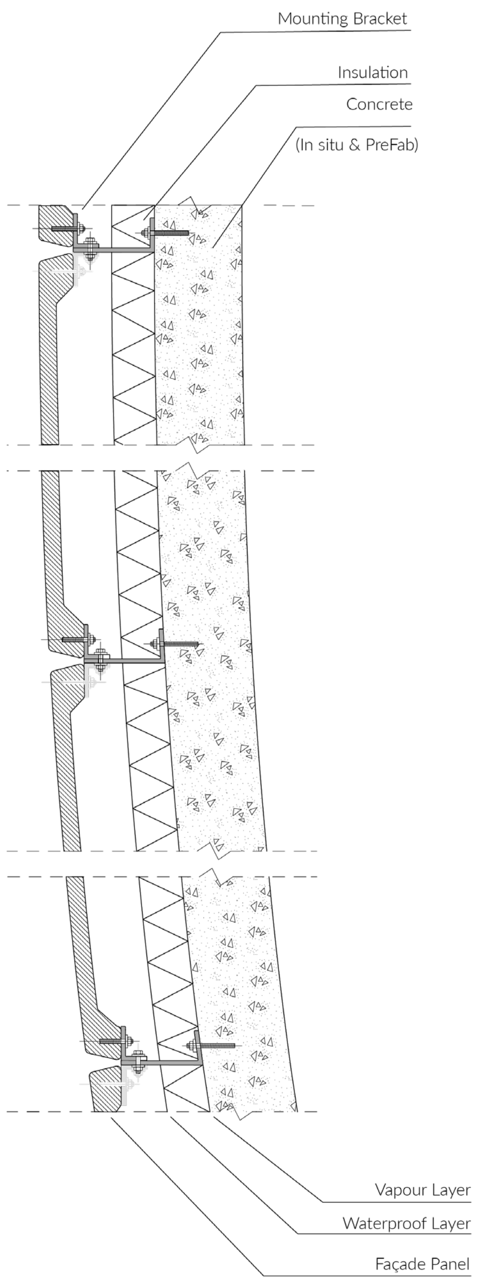
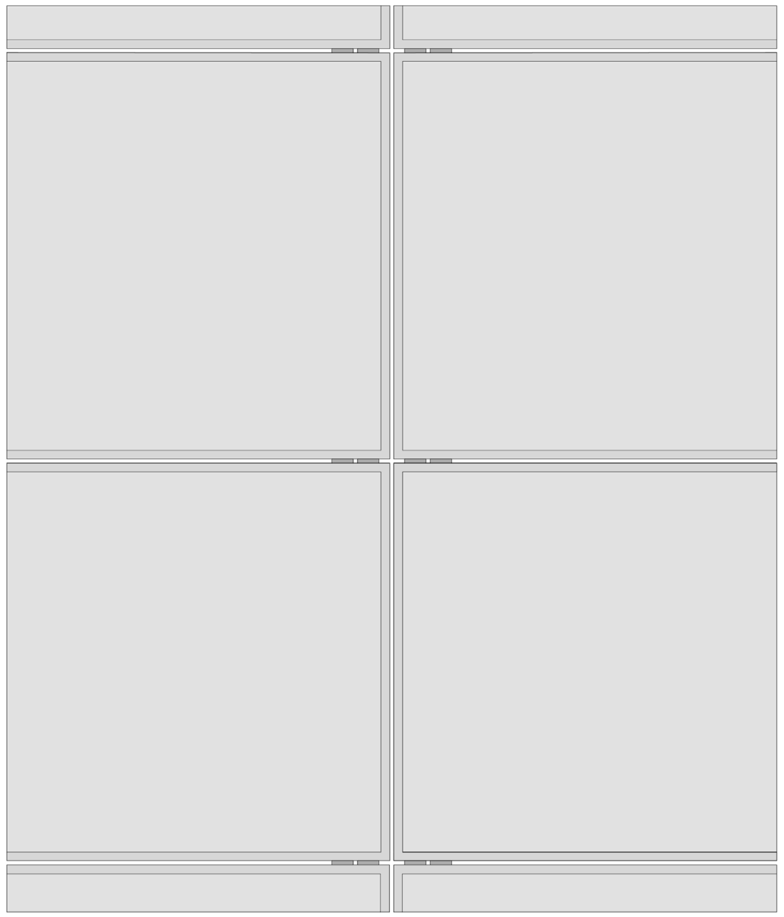
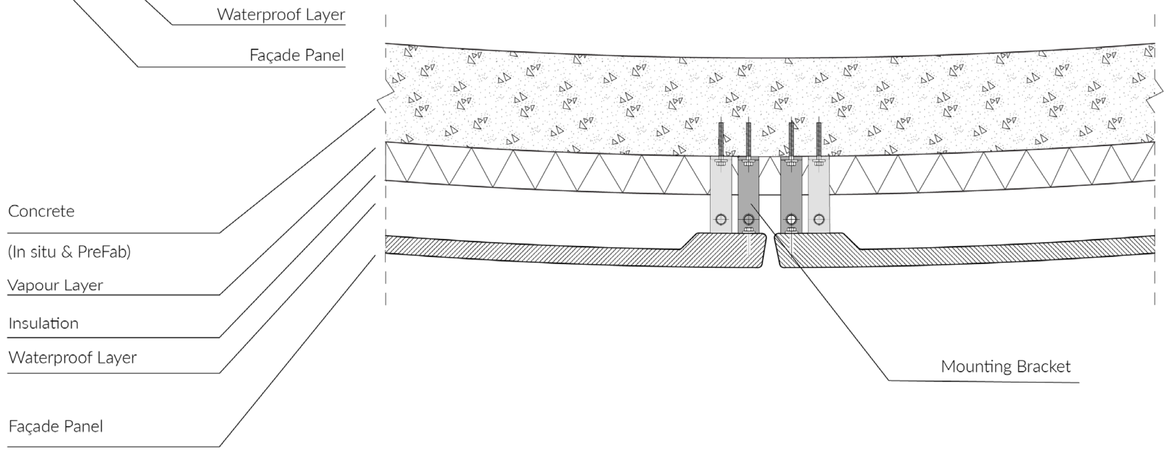
APPENDIX


Mounting Bracket
Insulation
Concrete
(In situ & PreFab)
Vapour Layer
Waterproof Layer
Façade Panel




Concrete
(In situ & PreFab)
Vapour Layer
Insulation
Waterproof Layer
Façade Panel
Mounting Bracket