Design of a Demountable Bio-Receptive Living Concrete Façade Element

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TU Delft

HOLCIM

front page: Green façade ([1])

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Preface

This thesis presents my research on a demountable design for a living concrete façade element. It is written as a final requirement for obtaining the degree of Master of Science in Civil Engineering at Delft University of Technology. During this thesis I had the opportunity to combine my love for plants and nature with my studies in structural engineering, which I am incredibly grateful for. This journey has been both challenging and fulfilling, and I owe much of its success to the support and guidance of several individuals.

First, I want to express my gratitude to Dr. ir. Marc Ottelé for his invaluable help and expertise regarding the topic. His extensive knowledge on the subject of living concrete, has been inspiring to my work. During our meetings there was always room for moments of laughter and humor, making the process besides productive also enjoyable.
I am especially thankful to Dr. Florentia Kavoura for her support throughout the structural aspects of this thesis and my journey with working with the software Abaqus. Her patience and encouragement helped me navigate the numerous errors and frustrations that came with learning the software. After each meeting or question, she would always conclude with a positive comment, such as, "Very good work, Joost! Do not stop now, we have momentum!" Those words consistently left me feeling more confident and motivated after each meeting.
Additionally, I want to thank Prof.dr. Henk Jonkers. Although our personal meetings were limited, his feedback during progress meetings was always insightful and pointed me in the right direction to advance my work.

I am also grateful to the company, Holcim, where I had the privilege of conducting this project. In particular, I want to thank Ir. Tom van Rijswijk and Martijn Graafmans for their continuous guidance. While the process was of course not without challenges, their support was always very helpful. Tom's expertise in sustainability provided me with valuable knowledge, for which I am very thankful. Special thanks to Martijn, whose kind presence during each meeting stood out. Even at moments of critical feedback, he always concluded with encouraging words and a compliment.

Besides my committee, several others individuals have been of great help during my thesis. I want to thank Yufei Zhang for her expertise in Abaqus, who on several occasions, besides performing her own PhD study, took the time to help me with some errors in my model. A special thank you to Maiko van Leeuwen, who helped me with determining the correct approach to every practical experiment I performed. Ton Blom, Fred Schilperoort and Ake Blom have been of great help with their guidance and expertise regarding the testing equipment.

Finally, I would like to dedicate a special section to my family, who have supported me not only during this academic journey but throughout my entire life. My mother who has always been there for me, whenever I needed something. I could always call her, if I needed someone to listen to my struggles or to give me some motivational support. My father who literally supports me in anything I do, no matter what. Who is so eager to help, that I think every time we talked about my thesis, he asked me if he could be of any help, in any way, which has always felt as great support. Then of course my brother Stefan, who has always been my biggest motivation, because as being his little brother it has always been my goal to achieve great things to make him proud. Besides that he has been there my whole life for me, through fun times and through harder times where I needed some non-parental support. I also want to thank my girlfriend, Fernanda, for her patience and love during this, sometimes frustrating, process. She always had faith in me to bring this journey to a successful end.

J.J.A.F. Kraaijvanger
Delft, January 2025

Summary

Urbanization has significantly altered the built environment, leading to increased urban heat and the loss of green spaces, which are being replaced by buildings, which in its turn retain more heat inside the city. Climate change causes extremer weather, resulting in heavier rainfall and urban floodings, for which cities are often unprepared. Incorporation of nature into the vertical buildings surfaces has the potential to address these challenges. A promising solution for creating these vertical green areas are porous concrete façades. Although research into this application has been performed for several years, a widespread implementation remains limited. A demountable, quick-to-install solution could assist the broader implementation of green solutions in urban areas. This research investigates the feasibility of such a demountable system.

Porous concrete façade systems typically consist of two layers: one structurally back layer made of conventional concrete and a porous concrete front layer. These layers are usually cast together. A demountable connection is potentially installed at the back of this structural layer, however this study also explores the possibility of a demountable connection attached directly on the porous layer, omitting the structural layer.

Several design options for a demountable porous concrete system are introduced and compared to each other by a multi-criteria analysis. The evaluation considers criteria regarding physical boundaries, economic and technical aspects, aesthetics and the connection. This analysis results in one final solution which is further developed and structurally analyzed with Finite Element software. This final design is analyzed in two applications: as a bi-layered design and as a single layered porous design.

As reduction of the weight positively impacts the demountability of the system, the possibility of a porous concrete system without a structurally layer is of high interest. However, the structural analysis of this option requires knowledge of its material properties. As much about this material is unknown, experimental tests were conducted to determine the Young's modulus of the porous concrete and the pull-out strength of the combination of porous concrete and bolts. Results regarding the Young's modulus of three samples ranged from 12948 MPa to 15231 MPa. Pull-out strengths obtained ranged from 8.74 kN to 15.69 kN for 5 tested samples.

Finite element analysis results regarding the bi-layered system demonstrated the potential of the system with a corresponding steel rail connection. Results showed that the connection could sustain a load of 140 kN before yielding starts, where the proposed application only requires to withstand a load of 0.4 kN. Tensile stress limits of the C20/25 structural layer were reached at a load of 5.1 kN resulting in a unity check of 0.079. An optimized connection design was proposed, as the first analysis demonstrated it was over-dimensioned. Dimensions of the connection were halved, resulting in a maximum load allowed of 62 kN leading to a unity check of 0.146. Similar results regarding the façade are observed, as no adjustments were made there.

Finally the performance of the single porous layered system was analyzed. Here the tensile strength is the governing limit of the material, reached at a load of 1.17 kN, with a safety check of 0.317. Pull-out forces occurring at the bolts are compared to the experimental obtained results. Where wind loads and a self-weight of 1.17 kN of the system are applied, a resulting bolt force of 5.46 kN is measured. Concluding that the pull-out forces are the critical area with a safety check of 0.625. This demonstrates the feasibility of the single layered system, however several material properties of the porous concrete are still unknown, therefore definitive conclusions regarding the single layered design remain challenging.

This research successfully demonstrates the possibility of a bi-layered demountable green façade system, evaluating the structural behavior and bio-receptivity. It shows the potential of a single layered design, however further research regarding that topic is recommended.

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1 Introduction

1.1. Motivation for this research

The percentage of urban areas worldwide is rapidly increasing. In 2018, 55.3% of the global population resided in urban areas, and by 2050, this percentage is expected to rise to 68.4% [2]. This trend of urban expansion brings with it numerous environmental challenges, one of which is the Urban Heat Island (UHI) effect. The UHI phenomenon occurs when urban areas experience significantly higher temperatures than surrounding rural areas. This is primarily caused by the replacement of natural land cover with heat-absorbing materials such as concrete and asphalt, which trap heat during the day and release it at night. The lack of vegetation, which could otherwise provide cooling through evaporation, intensifies this effect. As urban areas expand, the UHI effect becomes more noticeable, contributing to increased energy consumption, higher emissions, and harmful impacts on human health [3].

This increase in urbanization is often accompanied by a reduction in green spaces, both in terms of overall coverage and within urban environments. The decrease in urban greenery has led to an increase in negative environmental impacts and effects on the health of city inhabitants [4]. Furthermore, recent observations indicate a trend of intensified rainfall during winter periods due to climate change, thereby causing congestion in water drainage systems [5]. In addition to this, increased human activities in urban areas have resulted in the daily inhalation of elevated levels of CO_2 and fine particle matter [6]. Rising global temperatures, a direct consequence of climate change, require for improved insulation to protect against extreme heat conditions, particularly in densely populated areas.

One proposed solution to these urban challenges is the implementation of green walls, which can mitigate environmental damage by improving insulation, delaying peak water drainage, and filtering and absorbing CO_2 and fine particles. Green walls also contribute to recuding the Urban Heat Island effect by providing additional cooling through increased vegetation coverage [7]. These systems can be implemented through various methods, such as living wall systems (LWS) or green façades (GF) that utilize climbing plants. Typically, these systems are built in front of existing façades, though they require additional maintenance and are limited in terms of building height and plant selection. LWS are frequently implemented as non-structural cladding systems, constructed from materials that typically have a shorter lifespan than the buildings to which they are applied. In addition, these systems often result in significant financial and environmental costs [8]. To address the issue of mismatch in lifespan, a potential solution lies in designing living wall systems where plant life is integrated into the building's structural elements, rather than existing as an independent layer [9].

This solution involves the use of bio-receptive materials or porous concrete, which can be integrated directly into a building's structure. These materials provide a more sustainable and long-term solution by supporting the growth of non-vascular plants, which offer superior thermal insulation compared to traditional green façades. Bio-receptive green walls not only contribute to energy efficiency but also expand the potential selection of plant species that can be cultivated in urban environments [10].

1.2. Problem statement & research questions

Although the development of the aforementioned green concrete panels has been successfully achieved, a suitable system for attaching these green walls to structures has yet to be implemented [10]. Most panels are characterized by their heavy construction, which presents a significant disadvantage compared to existing living wall systems. Furthermore, their application is primarily limited to new constructions, restricting their use. The significant weight of the panels poses an additional challenge, particularly when considering their installation on existing structures [9]. Additionally, repairing damaged sections of the wall presents difficulties, as replacing parts can be both complex and costly. A demountable design could address this issue, offering a more practical solution. However, this solution comes with certain challenges. These challenges are related to the limitations of porous concrete. Due to its voids and reduced structural strength, it is assumably not feasible to install connections directly onto its surface. Consequently, to accommodate demountable connections, several modifications are to be considered, either in the composition of the material or in the design of the elements. It is required that these adjustments are implemented in a manner that does not compromise the bio-receptive properties of the system, maintaining both its functional and structural integrity.

Following the previous mentioned problem, this thesis aims to design a demountable Living Concrete wall element, comprising a demountable connection, a porous layer and, if necessary, a structural layer. To achieve this, both layers are addressed. With respect to the structural layer, considerations include reducing its weight and size to increase efficiency during the (de)mounting process or leaving out the structural layer completely. However, the primary focus is on the porous layer and the connection between the two layers. While reducing the dimensions of the porous layer is a potential strategy, it is important to maintain its bio-receptive properties.

These considerations result in the following research question:

To what extent can a Layered Living Concrete element, for the application as a green façade to Dutch low-rise buildings, be designed in such a way that it can be easily demounted and replaced while maintaining the level of bio-receptivity and considering efficient production and installation?

To answer this question, the following sub-questions are defined:

Sub-question 1: *How can modifications to the shape, dimensions and weight of the individual layers of the Layered Living Concrete element improve its (de)mountability while maintaining its bio-receptive properties and structural integrity?*

Sub-question 2: *What is the optimal size of the wall element to ensure its suitability as a demountable green wall component, in such a way that individual elements are easy to replace, while considering efficient production and installation?*

Sub-question 3: *To what extent can the porous front layer achieve sufficient strength without relying on a structural back layer, in order to enable the front layer to be demountable?*

Sub-question 4: *Which type of connections are suitable for the attachment of a vertical green wall element to a building structure?*

1.3. Delimitations & scope

The proposed designs focus on residential buildings or low-rise industrial buildings situated in the Netherlands. According to Eurocode standards, the Consequence Class CC1 is applied, as these structures fall within the category of buildings with low risk to human safety in the event of failure. To ensure structural integrity, wind loads are based on the most unfavorable wind conditions typical of the Netherlands. For simplicity, the maximum height of the buildings is set at 10 meters, and the building is assumed to be a square with dimensions of 10 x 10 meters.

In the design phase, it is assumed that the structure supporting the green wall is rigid, allowing the material properties of this supporting structure to be excluded from the analysis at this stage.
For designs that use a structural layer within the green façade element, it is assumed that the porous layer does not contribute to the structural strength of the panel. In this case, all loads are supported by the structural layer, while the porous layer is treated as dead load, contributing only to the weight of the panel without providing additional strength.

The scope of this research is defined by the design of an element suitable for a non-insulated façade of a low-rise building in the Netherlands. The existing design provided by Holcim is used as the starting point for design. It is assumed that the panel is bio-receptive, maintaining the focus on achieving demountability. However, for each proposed modification it is important to analyze the consequences for the bio-receptivity.

Various demountable design options are explored, including the possibility of making either the entire panel or only the front layer demountable. To ensure demountability, the dimensions, weight, shape, and concrete mixture of the panel are analyzed. Additionally, the connection between the two layers is addressed.

1.4. Approach and reading guide

The approach to this thesis is described with the following 8 steps:

Theory

step 1: Literature review: The first step of this research involves a review of existing literature on the properties of porous concrete, its current applications, several connection types used across different industries, and the associated material properties. This literature review aims to identify limitations in the existing literature, thereby forming the foundation for the next steps of this research. The conclusions of this step helps with the development of design strategies and requirements.

step 2: Design requirements: The second step involves the identification of requirements for the designs based on the literature review in the previous step.

Method

Step 3: Material properties: Step 3 presents the necessary method needed to determine two important material properties of the porous concrete. It clearly explains the steps taken to set up tests to determine the Young's modulus and the pull-out strength of a combined sample of porous concrete and a bolt.

step 4: Designs & MCA: Step 4 aims to develop several different design options for the green façade element and its demountable connection, where the element designs are divided into two layers: the porous and a potential structural layer. Combinations of different element and connection designs are combined into conceptual designs for the green façade. Each of the proposed designs, is evaluated using a Multi-Criteria Analysis (MCA).

step 5: Finite Element Analysis: In this step the proposed method is presented to analyzed the final design through Finite Element Analysis (FEM). The structural behaviour of the design is assessed to determine whether it meets the material requirements. This identifies any necessary adjustments to optimize the design.

Results

Step 6: Material properties results: Here all the results taken from the experimental test regarding the material properties are presented.

step 7 : FEM results: In this step the FEM results are presented. A next step after obtaining the results is optimization. The design should be adjusted according to the results of the previous steps. This involves adjustments to either the weight, dimensions, shape or thickness. The conclusion of this step is a detailed optimized design that meets the functional and technical requirements.

Step 8: Design results: This step presents the final design proposal for both the element and the connection. Which are combined into a complete final design for the green façade element.

Step 9: Discussion, conclusion & recommendations This last step reflects back on all the obtained results, drawing its conclusions and presents the necessary recommendations. In the discussion, the process is reviewed.

The complete approach to this research is schematized in Figure 1.1

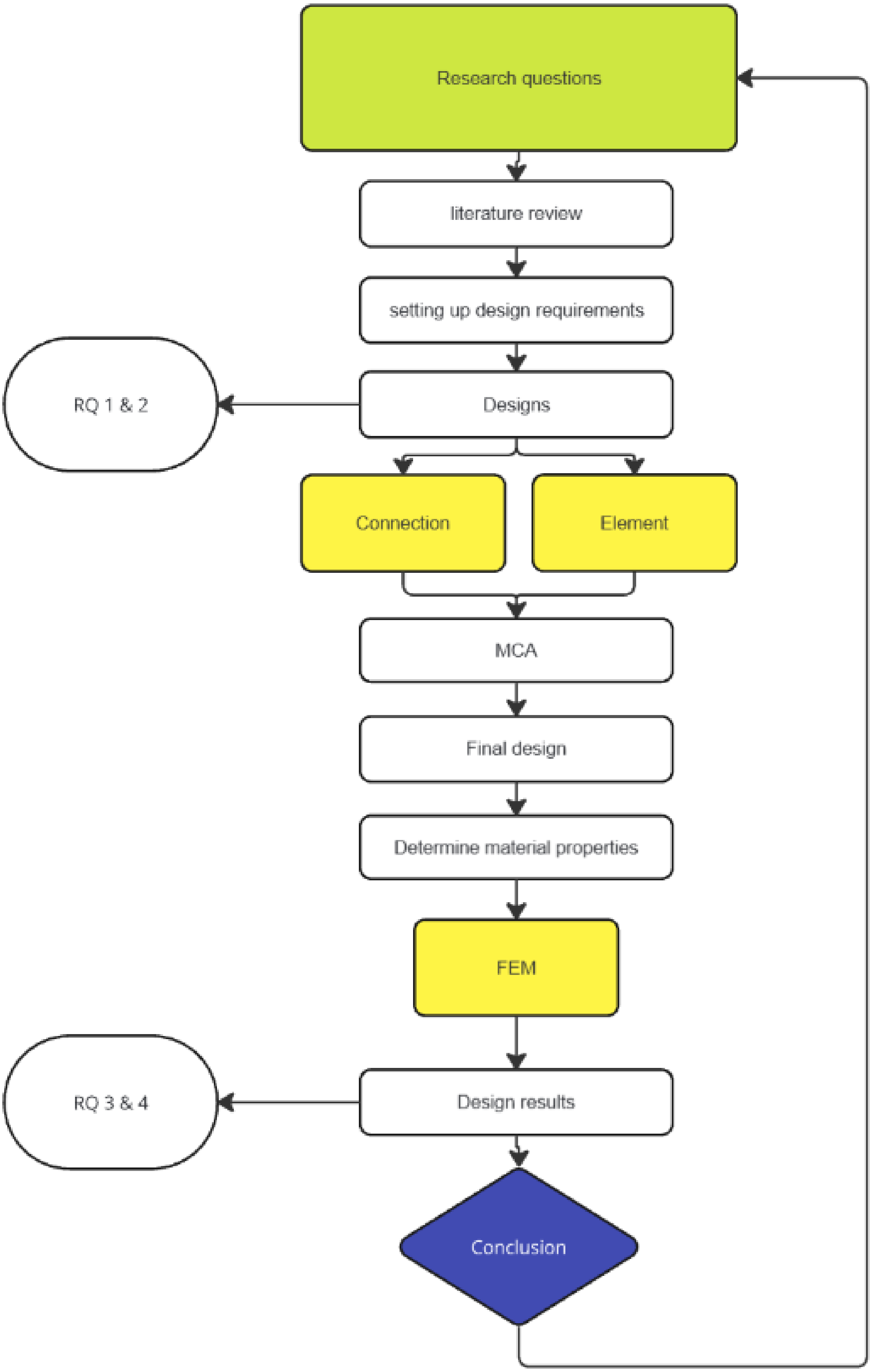


Figure 1.1: Research steps

I

Theory

2

Literature review

2.1. Porous concrete properties

Many researchers have investigated similar topics regarding living concrete, living wall systems and the bio-receptivity of concrete. Different types of design for living concrete walls are made and tested. There is a variation of multiple-layer concrete walls, single-layer concrete walls, walls that are solely bio-receptive to non-vascular plants such as algae and mosses and walls that do accept rooted plants. All of these designs make use of different concrete mixtures, some are very porous and others make use of conventional types of concrete. On top of that, they all have a different methodology on how to measure the results. This section provides a short summary of the interesting aspects found in several papers and their relation to the proposed research. It demonstrates several different concrete mixtures exist for various applications.

Each paper has its own interesting way of addressing the bio-receptive wall, one case for example introduced an interesting aspect, the bio booster. This paper made use of the same type of layers as mentioned before, a structural back layer and pervious front layer. However the back layer here is constructed of high-performance fiber-reinforced concrete(HPC), making it possible to reduce its thickness. The bio booster ensures a natural bio-colonization of the wall and a good moisture distribution. This paper shows a great testing setup for bending tests of the HPC layer. In table 2.1 the material proportions of sample PC-4 can be found, this results in a compressive strength of around 2.6 MPa where PC-4 scores best and thus is picked for continuance of the research. In table 2.2 the HPC-12.0 is selected for its high strength and ductile behavior. [10].

Table 2.1: Material proportions of pervious concrete with a compressive strength of 2.6 MPa and a water-to-binder ratio of 0.35. 0.2% of super-plasticizer is added to the mix. [wt%] [10]

No.	Material	PC-4
1.	Binder:	31
	- Cement OPC (89.9%)	-
	- Spent catalyst (10%)	-
	- Nano-silica (0.1%)	-
2.	Expanded clay, 2-4 mm	4
3.	Expanded clay, 4-8 mm	52
4.	Expanded clay, 8-16 mm	13

Table 2.2: Material proportions of HPC-12 mix [kg/m3] [10]

No.	Material	HPC-12
1.	Quartz Sand (0/0.2 mm)	1230
2.	Silica fume (purity 76.5%)	231
3.	Cement (CEM I, 42.5 R)	712
4.	Water	217
5.	Superplasticizer (Sika Viscocrete 3)	31
6.	Macro-fibers (□ 0.7 x 40 mm)	12

This paper has a follow up report, where it recommends new designs. These new designs are necessary to solve some observed issues. For example the thickness of the HPC back layer is reduced from 30 mm to 20 mm to reduce weight, whereas the panel dimensions are increased from 400 x 600 mm to 600 x 1200 mm. The pervious front layer thickness is reduced from 50 to 30 mm, where in the first paper the bio booster was 30 mm thick and placed on top of 20 mm of pervious concrete, now it is placed directly on the HPC concrete and has the same thickness as the pervious front layer. The design has a river shaped bio booster to optimize the use of irrigation water. It is also stated that the design is almost maintenance free, which can be considered an advantage. However it is noted that these systems are solely for non-vascular plants, which is possibly a explanation for the relatively small thickness of its front layer compared to the Holcim design. [11].

Another shows how to measure the chemical and physical substrate properties, which potentially have an impact on the bio-receptivity of a panel. Which they apply to their porous concrete design mixture, creating a void content of 30% [12]. The results of their concrete substrate properties can be found in table 2.3. The average compressive strength of the porous concrete substrate was 4.38 ± 0.66 MPa. The materials used are: blast furnace slag binder, two proprietary alkali activators (ISOACTIVE 950: 3.67% of dry binder mass and ISOACTIVE 930: 5.4 %), quartz aggregates (2.0-3.2 mm) and a water to binder ratio of 0.295.

Table 2.3: Chemical and physical properties of porous concrete [12]

Property	Value
Chemical	
EC [mS/cm]	1.32
pH [-]	9.58
Physical	
Compressive strength [MPa]	4.38
Mass [g]	91.19
Bulk volume [cm^3]	51.11
Water saturation [g]	14.18
Water holding [g]	6.76

One research is very similar to the proposed research, the concrete mixtures used here are patented by Holcim. This research does work with vascular plants. It verifies the constructability and it studies growing plants from seed. The methodology of this research consists of 8 steps:
1. Create new concrete to support plant life
2. Verifies constructability
3. Validates plant growth
4. Verifies new construction methodology
5. Analyses the new concrete's chemical effect on plants and irrigation
6. Tests mechanical properties
7. Validates outdoor germination and perenniality
8. Analyses costs

The testing element sizes used are ''A1'' size (50 cm x 88 cm x 24 cm with 16 cm thick steel reinforced C25 and 8 cm pervious concrete). This results in a compressive strength of around 10 MPa of the pervious concrete at 28 days which shows it is self-supporting. However it is not sufficiently strong enough to be used as a load bearing wall without the supporting back layer. In Table 2.4 the two different pervious concrete formulas are shown, unfortunately it is not completely clear which of these two mixtures result in the mentioned compressive strength, but it can be assumed to be mixture F2. Other characteristics are, porosity of 32% and density of 1.7 and it is noticed that the connection between the two layers is not a point of weakness. Later full size (2.7m high x 2.0 m wide) elements are tested. It mentioned that seeding is less expensive than planting, but it may take a long time before the seeds germinate. The whole system proves to be functional and survived for a long time, even through winter and regrew after winter [9].

Table 2.4: Pervious formulas of the new concrete.
F1 = cement formula, F2 = formula with cement, metakaolin, and limestone filler [9].

Component	**F1 (kg/m^3)**	**F2 (kg/m^3)**
Cement	333.6	179.5
Aggregates 6–10 mm	1570.8	1570.9
Metakaolin	-	82.5
Limestone filler	-	41.2
Superplasticizer	3.3	3.9
Viscosity modifying agent	0.011	-
Water	90.0	91.0

A similar research provides an approach where the voids in the pervious concrete are filled with a compost soil mixture. It uses coarse aggregates of 20mm with Ordinary Portland cement, class F fly ash and 25% or 30% void content where the choice was made to continue with the 25% mixture. The limitation to this approach is that the compost needs to be fed with nutrients, which is extra maintenance compared to the design proposed by Riley. It uses a slab size of 500 x 500 x 100 mm and cubes of 100 mm to determine the compressive strength. All mixtures shown in Table 2.5 except SL were sufficient for non-loadbearing application with a compressive strength of about 4.5 MPa [13].

Table 2.5: Several porous concrete mix proportion details [13]

Mix ID	**Void content (%)**	**Coarse aggregate (kg/m^3)**	**Fly ash (kg/m^3)**	**Cement (kg/m^3)**	**Water (kg/m^3)**
SL	30	1612.47	0	81.30	33.59
SL1	25	1612.47	0	162.60	57.98
SL2	25	1612.47	40.65	121.95	57.98
SL3	25	1612.47	81.30	81.30	57.98

A master research thesis conducted at TU Delft, also working together with Holcim provides more insight. This research performed tests on several different concrete mixtures. A specific mixture was found that has a particularly high compressive strength (around 7.9 MPa where 6 MPa is required according to the study), while maintaining the level of bio-receptivity and a porosity level of around 22%. Stated in the research is that other ways to improve the strength have a negative effect on the porosity, concluding that it seems impossible to further increase the strength or porosity. The characteristics of this mixture C2.1 are shown in table 2.6 [14].

Table 2.6: Mix proportion details of porous concrete mix of master thesis TU Delft. [14]

Series No.	Aggregate type	Aggregate fraction	WCR	Stabilizer	Admixture
C2.1	Lava stone	8/16	0.4	No	Cugla Colloidaal 100
C2.2	Lava stone	8/16	0.6	Yes	Cugla Colloidaal 100
C2.3	Lava stone	8/16	0.8	Yes	Cugla Colloidaal 100

2.1.1. Young's modulus

As the modulus of elasticity was not determined in [14], it was found in other literature. Different pervious concrete mixtures with porosity varying between 17 and 31 % and compressive strength varying between 8.4 and 23.2 MPa the modulus of elasticity varies between 16200 and 22300 MPa [15]. Other literature shows a range of modulus of elasticity from 4000 - 16000 MPa at porosity levels of 32 - 16 %, respectively [16]. Another approach is using Equation 2.1 [17], which is determined by practical testing and the equation is almost identical to the equation of the American Concrete Institute for normal-weight concrete.

$$E = 0.0426(2491 - 2550p)^{1.5} * \sqrt{f'_{\mathrm{co}}(1 - 2.1p)} \quad (2.1)$$

Where p is the porosity [%] and f'_{co} is the compressive strength [MPa]. According to this equation the E modulus of the mixture provided by [14] is around 7500. Eurocode EN-1992-1-1:2005 provides the following equation for conventional concrete:

$$E = 22 * (f_{\mathrm{cm}}/10)^{0.3} \quad (2.2)$$

Where f_{cm} is in MPa and related to the characteristic compressive strength. Using interpolation the corresponding value for E is 23746 MPa. However it is unsure if the same relations of conventional concrete are valid for the porous concrete. As all these values vary significantly it seems that a correct value is hard to determine with high certainty.

This literature review provides insight into many different pervious concrete mixtures, showing the requirements regarding their characteristics such as, compressive strength, dimensions, irrigation system, porosity and water to cement ratio.

2.2. Current systems for porous concrete

Porous concrete is currently being applied in several fields, the most common areas of application are as a pavement material [18] and as a bio-receptive material in the application of vegetation porous concrete [19]. Although both applications are interesting, for this literature review solely the application of several vegetation porous concrete systems is reviewed.

2.2.1. Slope stability

One specific application of vegetated porous concrete is as slope stability and greening of the slope. This can provide a solution to slope instability due to landslides in certain areas. It protects the slope immediately while ensuring the growth of vegetation. The advantage of porous concrete over conventional impermeable concrete is the fact that it is suitable for both vegetation growth and surface drainage, providing a solution to both problems at the same time. In addition, it is suitable for very steep slopes. The application of the porous concrete is as a sub-layer on top of a soil layer, with another layer of soil on top of the porous concrete. Therefore, as the vegetation starts to grow, the porous layer will be partially or completely covered. [20] [21].

2.2.2. Vegetated walls

Another way of applying porous concrete is for use as a vegetated green wall for building façades or for sound insulation walls, as a benefit of the vegetated wall is the high noise reduction performance [13].

An effective way to apply porous concrete as vertical greening systems is to make use of a layered system: a structural layer behind the porous layer [10]. Living walls can increase the aesthetics of buildings and have a positive effect on biodiversity in the city. In addition, it assists in energy savings for heating and cooling of buildings, due to the reduced surface temperature of building façades.

2.3. Connection types of other industries

In literature, no demountable connections related to porous concrete can be found, clearly demonstrating a research gap. On top of that, demountable connections between a non-load bearing wall element and a structural wall are limited in literature as well. Therefore it is necessary to review the literature for connections to different materials and in different applications that are possibly suitable. This section discusses several useful types of connection from other industries found in literature.

2.3.1. Demountable bolted connections

One notable design is explored by [22] in their investigation of shear connections between laminated veneer lumber (LVL) plates and HEB steel profiles. Among the three connections they examined, two used screws and Geka connectors, which would not be suitable for concrete structures. However, the third design presents a promising concept for demountable connections in concrete walls. This design consists of a steel tube with a round plate welded to one end, incorporated into the floor element. A bolt can be inserted through the tube and secured with rings and a nut (Figure 2.1). This configuration can potentially be applied to connect a concrete wall element to a steel column, demonstrating the adaptability of timber connection designs to concrete applications.

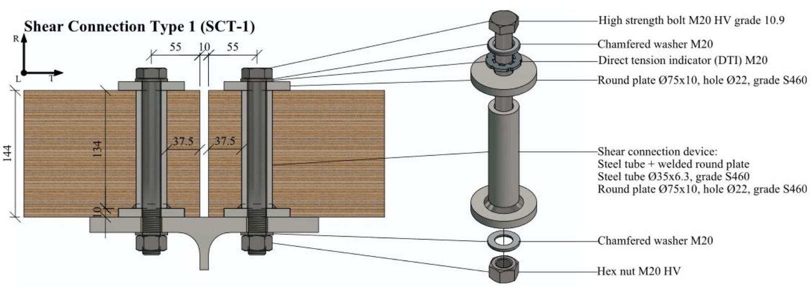


Figure 2.1: Demountable connection by [22]

Another reviewed connection consists of a dry connection system for assembling shear wall panels, featuring an H-connector that connects two concrete walls or a wall to a base. This connection is assembled using high-strength bolts, with the H-connector placed between the concrete panels. An important consideration in this design is the need for bolt holes to be pre-installed in the concrete walls, with reinforcement placed around these openings to maintain structural integrity (Figure 2.2). The system's performance was validated through strength tests, showing that the connection was not a weak link in the overall structure. This method highlights the potential for pre-fabricated elements and dry connections in modular construction, a technique that can be adapted to a variety of materials, including porous concrete [23].

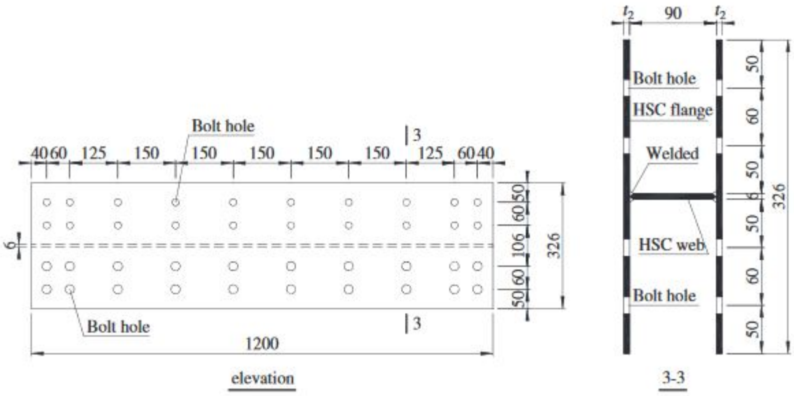
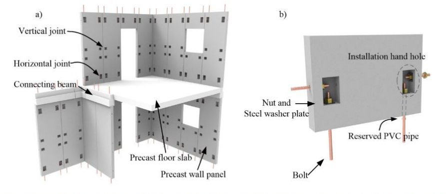


Figure 2.2: H-connector by [23]

A different approach is a bolted connection integrated directly into wall elements. In this system, bolts extend from the wall panel below and are secured to the upper wall with washers and nuts, allowing for vertical assembly of wall panels. A similar concept has been proposed in the European Commission's guidelines for wall panel connections [24] , as seen in Figure 2.3. Both designs are modular, however disassembly of one specific panel can be tedious, as other panels would have to be removed first. [25].

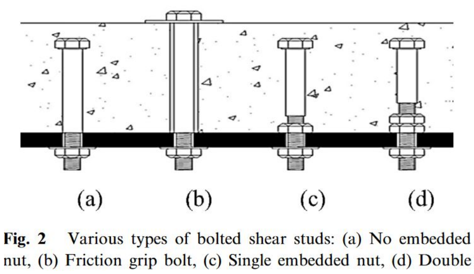


(a) Demountable connection by [25]

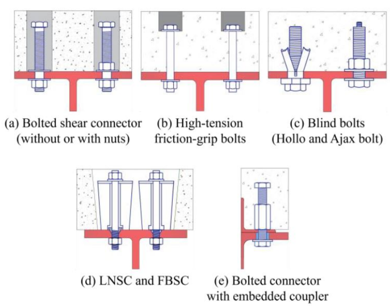
(b) Demountable connection by [24]

Figure 2.3: Two integrated bolted connections

Several bolted connections in concrete are possible. They vary from bolts which are casted inside the concrete, meaning they can not be accessed after installation, to connections that are visible from the outer part of the concrete and therefore can be accessed after assembly. Besides incorporated bolts, there is a possibility to cast in anchors where bolts can be screwed into. This provides the possibility of fastening another connection onto the concrete in a later stadium. The variation of concrete bolted connections can be found in Figure 2.4.



(a) Demountable connection by [26]



(b) Demountable connection by [27]

Figure 2.4: Variation of concrete bolted connections

Both connections (b) are the ones that provide access for demounting from the exterior side of the structure. This is an important consideration in many building types where interior access for maintenance or disassembly is restricted, such as in industrial or commercial applications. Exterior access to connections can enhance the flexibility of modular building systems, making this design an attractive option for non-load-bearing wall systems [26] [27] .

2.3.2. Demountable Plug-and-Play connections

Another common type of demountable connection is the Plug-and-Play connection. These type of connections are suitable for application to structures that might require disassembly in the future. Also for these type of connections it is necessary to look into the application in different industries. Many useful references are found in the area of ventilation façade modules which are added to existing façades. The following section reviews these Plug-and-Play connections which provide useful insights for creating adaptable and easily (dis)assembled connections in other applications.

One of the reviewed systems is the E2VENT project, a EU initiative focused on the development of adaptive ventilation façade modules for refurbishment of existing buildings. While the overall system is innovative, the connection mechanism is of particular interest for this research. The base of the connection are L-shaped aluminum profiles bolted into the existing façade. The ventilation module, or other plate elements, can be hung from these profiles and fastened with nuts, allowing for easy installation and removal. As shown in Figure 2.5 , the modular element is slotted into the profile in a simple manner. This approach allows for a high degree of flexibility and could potentially be adapted for other façade materials or structural systems [28].

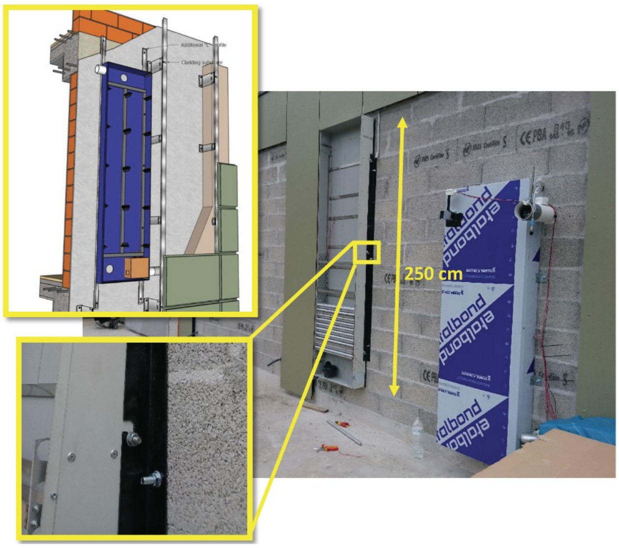


Figure 2.5: Demountable connection by [28]

A similar system is produced by ETEM, a producing company of aluminum profiles and façades. Their Bravo W ventilated façade system connection is very similar to the design of E2VENT, though with a reversed connection system. In this system, the panels themselves feature sliding slots that fit over a horizontal bar mounted onto the existing structure, as illustrated in Figure 2.6. This also allows the panels to be easily hung and removed as needed. The Bravo W system in this situation is constructed with aluminum, however different materials are potentially used [29].

Figure 2.6: Demountable connection Bravo W by [29]

RenoZEB offers another perspective on modular façade systems with its focus on energy-efficient building renovations. The RenoZEB system involves installing modular façade panels over existing structures, improving insulation, airtightness, and integrating solar and ventilation systems. Unlike the rail-based systems of E2VENT and Bravo W, RenoZEB uses individual anchor points, allowing panels to be hung from specific attachment points rather than a continuous rail. The bottom panels are supported by four anchors, while upper panels are hung from two anchors, creating a robust yet flexible system. The use of singular anchor points simplifies installation while maintaining the necessary structural integrity. This connection method could be particularly useful in scenarios where the space for a continuous rail system is limited. Several interesting anchor points are shown in Figure 2.7 [30].

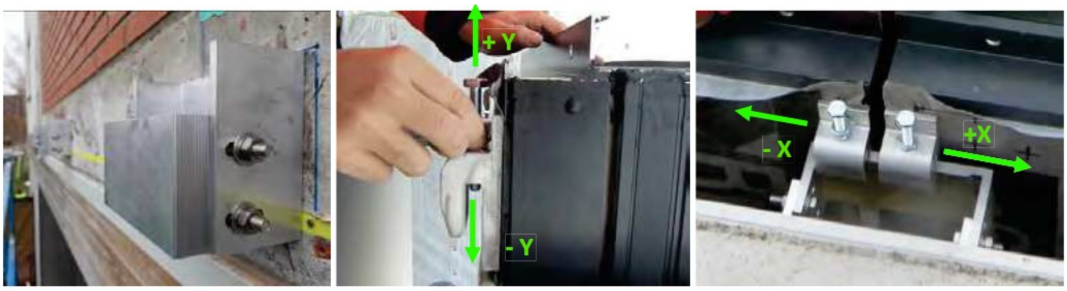


Figure 2.7: Demountable connection by RenoZEB ([30])

A different type of connection is found in the area of wall decoration hanging systems, the GeckoTeq Z bar rail. This connection is therefore applicable to lightweight material compared to conventional weights known in the industry of structural engineering. However, the connection could be modified to increase its strength by, for example, increasing the thickness or applying a stronger material. It consists of two identical aluminum Z-shaped profiles. Firstly one of the profiles will be bolted to the existing structure, the other one should be bolted to the panel. They can then be hung onto each other, providing a clean connection close to the existing wall. Extra benefit of such rail connection is the even distribution of the forces over the length of the rail. Figure 2.8 provides a visualization of the connection

[31].

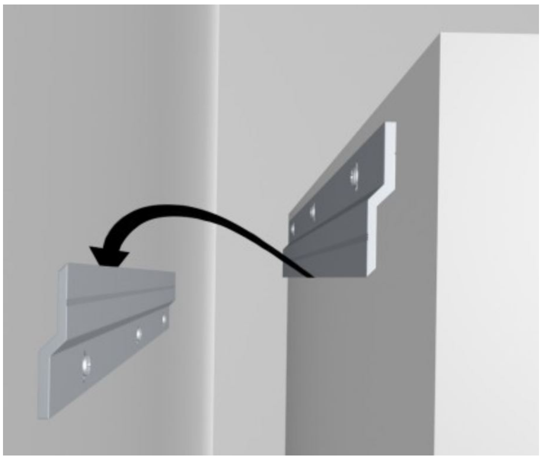
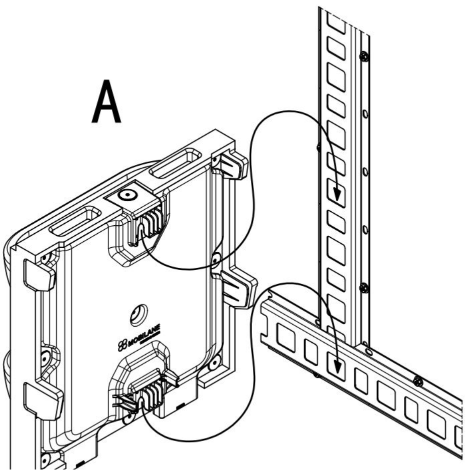


Figure 2.8: Demountable connection GeckoTeq ([31])

Lastly a relevant connection can be found in the exact same application as a living wall façade element, the Mobipanel. However this system makes use of a lightweight Expanded Polypropylene (EPP) material in the front and polypropyleen (PP) for the backside. This results in a maximum total weight of 40 kg/m^2, including plants and soil. These elements are then hung onto Omega profiles of Magnelis steel, which are bolted to the existing structure, providing a quick and simple installation of the elements. Figure 2.9 shows the connection and assembled result of the system [32].



(a) Mobipanel connection

(b) Mobipanel assembled

Figure 2.9: Mobipanel [32]

3 Design requirements

In this chapter the design requirements according to existing literature is presented. A general overview of overall design requirements is translated to specific requirements regarding three sections, First the structural requirements are mentioned, secondly the production requirements and lastly the requirements regarding transportation and installation. Where the element dimensions are related to the transportability and producibility, the structural requirements are related to the strength and weight which are depending on the thickness and overall design of the element.

3.1. Overall design requirements

Several requirements have been determined for the overall design. These requirements are mentioned shortly in this section and are used to setup the final requirements. The overall design requirements are as follows:

- The product must have a demountable connection (Installation)
- The product must have a irrigation system, which is preferably not incorporated in the concrete due to maintenance difficulties. (Installation)
- The product must meet the safety regulation requirements according to the Eurocode (structural)
- The product must be producible on a larger scale (production)
- The product must be transportable by the standard sized trucks, meaning it should meet the maximum size and weight limits of these type of trucks (transportation)
- The product must be able to be installed by a maximum of two people, meaning the weight of the product falls in the safety limits of the Arbowet. (Installation)
- Each panel must be individually demountable, meaning that no other panels have to be removed prior to demounting a specific panel. (Installation)
- The size of each panel should match with standard sizes used in existing structures. (Installation)

3.2. Structural requirements

3.2.1. Strength

In the case of a design which is added to an existing structure, the design can be considered as a non-load bearing wall. There are no specific values mentioned in the standards, therefore a minimum value has to be found in literature. According to the reviewed literature a compressive strength of at least 6 MPa is required for a non-load bearing wall [33].

3.2.2. Thickness

As determinated in previous research, the necessary thickness of the porous layer has a minimal value of 30 mm. This is due to how deep the soil will infiltrate in the voids of the layer [34]. The structural layer requires a minimal thickness of at least 20 mm, this limit is determined because of the required material necessary to install a connection into the layer. Where the shortest existing sleeve anchor is being used as a reference which needs a embedment depth of minimal 7/8 inch which converts to 19.05 mm, therefore 20 mm is chosen [11] [35].

3.2.3. Wind load

The porous concrete façade is considered as impermeable regarding the wind. This because the voids are filled with soil and is therefore permeable for water, however not for wind. Due to this, the façade is regarded as a wall with one skin, thus the according values in the Eurocode standard EN-1991-1-4 should be considered [36].

In order to ensure the possibility of a wide implementation of the system, the most challenging situation is assumed, therefore the worst terrain category 0 in wind area I in Netherlands is used. For the green façade the wind load is determined only by the external pressure as the internal pressure is not in direct contact with the green façade. Therefore, the resulting governing wind load is equal to -2.21 kN/m^2. Which is applied in the most unfavorable direction, out of plane of the façade as the main structure is less able to contribute to the force distribution in that situation. Meaning that most of the load is carried by the connection. Complete calculations regarding wind loads are provide in Appendix A.

3.3. Production requirements

Regarding the production requirements, not many constraints are found. However it is important that the amount of production steps is kept at a minimum to reduce costs. On top of that it is important that, if possible, standard sizes are used. For a specific production line in the factory of Holcim, it is known that sizes are limited to squares of 1.2 meter by 1.2 meter and they are adjustable with multiplications of 0.3 or 0.4 m. Furthermore all the steps needed to produce an element have the requirement to poses the ability to be automated in a factory. Besides that, to optimize the production process, ideally several panels are produced at the same moment. This means that within the aforementioned limits, several panels are produced. However, a space between the panels of minimally 10 mm is required for demoulding. This adds a limitation to the size of the panels, as not the complete 1.2 meters are available for panel production. Therefore, regarding the production, the most important boundary condition is related to the maximum sizes for the production line, within the limits of 1.2 by 1.2 meter.

3.4. Transportation and installation

This section starts with analyzing the transportation details for both a bi-layer as a single layer panel. It continues with the requirements regarding the installation, taking into account the lifting weight limits, connection and irrigation system.

3.4.1. Transportation of bi-layer panel

Regarding transportability, several assumptions must be made. First, the mode of transportation needs to be determined. Given that building façade elements are typically transported from the factory to the construction site, it is most likely that trucks are used for this purpose. Furthermore, in order to minimize disruptions to other traffic, adherence to the maximum load dimensions permitted for trucks is essential. If these dimensions are exceeded, escort vehicles are required. Specifically, escorting is mandatory when load dimensions exceed 3.50 meters in width and 27.50 meters in length on provincial roads, and 4.00 meters in width on highways within the Netherlands. Consequently, a maximum width of 3.50 meters has been assumed, as provincial roads are likely to be used to access construction sites. A standard flat trailer, commonly used for the transportation of wall and façade elements, has a length of 13.60 meters and a load capacity of 30,000 kg [37].

Trailer dimensions:

- Width: 3.50 m
- Length: 13.6 m
- Max load height: 2.85 m
- Max load weight: 30,000 kg

Concrete panel characteristics:

- C20/25 concrete density: 2600 kg/m^3
- Porous concrete density: 1770.6 kg/m^3
- Taking into account a spacing between each panel of 0.01 m.
- Length: 0.6 m (effective length: 0.61 m)
- Width: 0.6 m (effective width: 0.61 m)
- Thickness: 0.05 m (effective thickness: 0.06 m)
- Weight: 37.8 kg

It is calculated how many panels fit within the trailer dimensions based on the space, weight and orientation of the panels.

Number of Panels That Fit Based on space:

$$\text{Number of panels in length} = \frac{13.60\,\text{m}}{0.61\,\text{m}} \approx 22.29 \rightarrow 22\,\text{panels}$$

$$\text{Number of panels in width} = \frac{3.50\,\text{m}}{0.61\,\text{m}} \approx 5.73 \rightarrow 5\,\text{panels}$$

$$\text{Number of panels in height} = \frac{2.85\,\text{m}}{0.06\,\text{m}} \approx 47.5 \rightarrow 47\,\text{panels}$$

$$\text{Total panels (space)} = 22 \times 5 \times 47 = 5,170\,\text{panels}$$

Number of Panels That Fit Based on Weight:

$$\text{Max panels (weight)} = \frac{30,000\,\text{kg}}{37.8\,\text{kg}} \approx 793\,\text{panels}$$

Comparison of Space and Weight Limits

- Total panels based on space: $5,170$ panels
- Total panels based on weight: 793 panels

Conclusion

Since the trailer's weight capacity limits the number of panels to **793**, the **weight** is the limiting factor, not the available space.

3.4.2. Transportation of a single layer panel

Concrete panel dimensions:

- Taking into account a spacing between each panel of 0.01 m.
- Length: 1.20 m (effective length: 1.21 m)
- Width: 0.60 m (effective width: 0.61 m)
- Thickness: 0.03 m (effective thickness: 0.04 m)
- Weight: 38.25 kg

It is calculated how many panels fit within the trailer dimensions based on the space, weight and orientation of the panels.

Number of Panels That Fit Based on Space:

$$\text{Number of panels in length} = \frac{13.60\,\text{m}}{1.21\,\text{m}} \approx 11.24 \rightarrow 11\,\text{panels}$$

$$\text{Number of panels in width} = \frac{3.50\,\text{m}}{0.61\,\text{m}} \approx 5.73 \rightarrow 5\,\text{panels}$$

$$\text{Number of panels in height} = \frac{2.85\,\text{m}}{0.04\,\text{m}} \approx 71.25 \rightarrow 71\,\text{panels}$$

$$\text{Total panels (space)} = 11 \times 5 \times 71 = 3,905\,\text{panels}$$

Number of Panels That Fit Based on Weight:

$$\text{Max panels (weight)} = \frac{30,000\,\text{kg}}{38.25\,\text{kg}} \approx 784\,\text{panels}$$

Comparison of Space and Weight Limits

- Total panels based on space: $3,905$ panels
- Total panels based on weight: 784 panels

Conclusion

Since the trailer's weight capacity limits the number of panels to **784**, the **weight** is the limiting factor, not the available space.

3.4.3. Installation

All requirements regarding installation are separated into three different categories: the lifting weight limit of two persons, the fact that each panel requires to be individually demountable, which relates to the connection and the irrigation. Besides these three categories, a more important aspect for the installation on buildings is the match in dimension between the existing structure and the green façade. Therefore, this subsection concludes with information regarding the dimensions of buildings in the Netherlands.

Lifting weight limit

According to ISO 11228-1 a person is allowed to lift a maximum weight of 25 kg assuming ideal circumstances. In the situation that a load is lifted by 2 persons, a factor of 0.85 is used. This means that 2 persons together are allowed to lift 0.85 * 50 kg, which results in a maximum load of 42.5 kg [38].

Connection (individually demountable)
Several connection systems are suitable for façades as presented previously in the literature review section. Overall these systems are divided into the following categories:

- Bolted connections
- Plug-and-Play connections
- Stack connections
- Slide connections

As mentioned in Section 3.1 the possibility to replace a specific element in a wall is a requirement of this research. This means that several connection systems (e.g. stack or slide systems) are labeled unsuitable for the proposed application. Due to this, solely the bolted connection and Plug-and-Play connections remain applicable. Besides this constraint, it is important that the element is demountable from the outside, as the function of a building makes it difficult to demount from inside the building.

Irrigation
A requirement of the research is that a element has an irrigation system to ensure the viability of plants on the living wall. This means that the design has space for irrigation pipes and connections. Preferably this system is not cast into concrete, as this complicates possibly occurring maintenance issues. Therefore, the irrigation is possibly implemented in the front or the back of the panel. It is only realized in the back in the situation that the panel is not connected directly onto the existing structure, but a gap is kept in between. When installation in the front is required, it becomes necessary to find solutions to cover the irrigation system regarding aesthetics.

Building dimensions
According to the Bouwbesluit (Dutch Building Code), a minimum free height of 2.6 meters is required for residential buildings. This requirement results in a minimum floor-to-floor height of 3 meters. For office buildings, typical floor heights range between 3.4 and 3.7 meters [39]. Consequently, no universal standard floor height applies across different building types. However, for this study, a minimum floor height of 3 meters is considered representative and is used as a basis for determining the appropriate height of the façade element designs.

Commonly used structural grid sizes for residential buildings in the Netherlands are 4.8, 5.4, 6.0, 7.5, and 7.8 meters, most of which are multiples of 0.6 meters. For office buildings, grid sizes typically follow multiples of 1.8 meters, with observed values including 1.8, 3.6, 5.4, 7.2, 9.0, 10.8, 12.6, 14.4, and 16.2 meters [40], [41]. It is noted that all grid sizes for office buildings are multiples of 0.6. Therefore, regarding the existing building dimensions, a boundary condition for dimensions of 0.6 meter is suitable for the element design.

3.5. Conclusion

Taking into account the previously mentioned requirements, it is possible to set up several boundary conditions for the design. The maximum weight of each panel is 42.5 kg due to the lifting safety limits. This weight is influenced by the dimensions of the element, which are restricted by the production limits of 1.20 by 1.20 meter. For the calculations of the weight and dimensions it is assumed that the minimal thicknesses of both layers will be used. Resulting in a 30 mm thick porous layer with a 20 mm thick structural layer. Taking into account the by production limited dimensions of multiplications of 0.3 or 0.4 meter and the building dimensions with a suitable dimension of 0.6 meter, a maximum weight is determined for both a bi-layered design and a single porous layered design. Which are based on dimensions of 0.6 meter, as this corresponds with all the requirements. For the single layered design a height of 1.2 meter is set as boudary condition, as the height in existing structures is more variable compared to the width, furthermore 1.2 meter corresponds with the production limits. In Tables 3.1 and Figures 3.1 and 3.2 show the dimensions of the bi-layered design, where Table 3.2 and Figures 3.3 and 3.4 present the boundary conditions of the dimensions and weights of the single layered design.

Table 3.1: Weight of design with a bi-layered system

	C20/25	Porous concrete	Total
Density [kg/m^3]	2600	1770.6	
Thickness [m]	0.02	0.03	
Length [m]	0.6	0.6	
Width [m]	0.6	0.6	
Weight [kg]	**18.72**	**19.12**	**37.85**

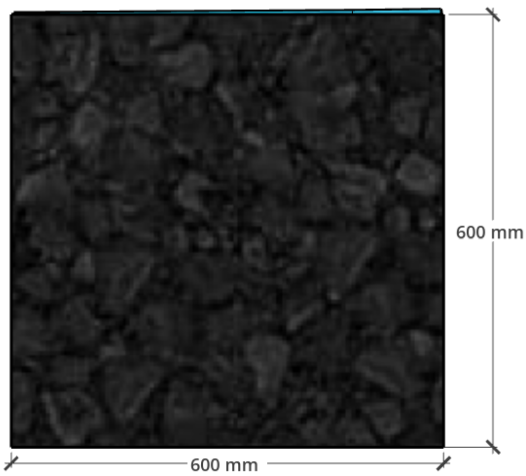


Figure 3.1: Front view of bi-layered design with dimensions in mm

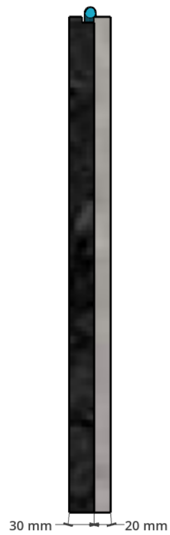


Figure 3.2: Side view of bi-layered design with dimensions in mm

Table 3.2: Weight of design with a single layered system

	Porous concrete
Density [kg/m^3]	1770.6
Thickness [m]	0.03
Length [m]	1.2
Width [m]	0.6
Weight [kg]	**38.25**

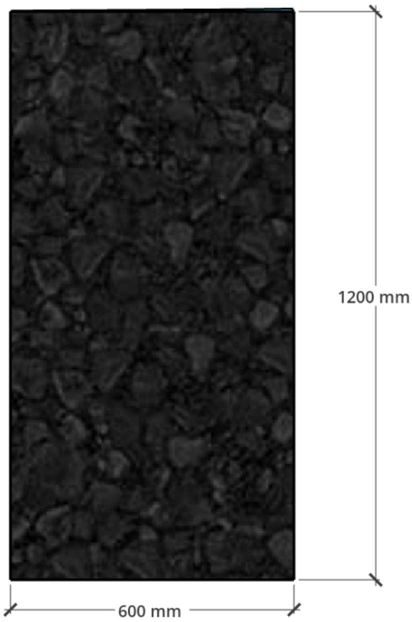


Figure 3.3: Front view of single layered design with dimensions in mm

Figure 3.4: Side view of single layered design with dimensions in mm

II

Method

4 Material properties

This chapter gives a brief explanation of the test setup that is used to determine two material properties of the porous concrete, namely the Young's modulus (modulus of elasticity) and the pull-out strength of a bolt-concrete combination.

4.1. Young's modulus

Information regarding the Young's modulus of the porous concrete is of high importance, as it helps understanding how the material deforms under various loads. A realistic and precise value, when implemented in Finite Element Analysis, positively influences the accuracy of the results. As a wide variety of values is given in literature it is hard to determine the Young's modulus of porous concrete and a realistic value is important, therefore experimental tests are required.

To determine the Young's modulus of the porous concrete material, a stress-strain diagram is used. The Young's modulus is equal to the slope of the linear (elastic) part of the diagram, and is expressed in the following equation:

$$E = \frac{\Delta\text{stress}}{\Delta\text{strain}} = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1} \tag{4.1}$$

where:

- E is Young's modulus
- σ_1 and σ_2 are the stress values at two points on the elastic line
- ϵ_1 and ϵ_2 are the corresponding strain values.

The Young's modulus can be determined using any stress-strain diagram, however in practice, it is common to use one specific methods. This method stresses a sample three times in compression by a force of 30% of the compressive strength. After three times the compressive strength of the sample is determined by compressing the sample until failure. Over the linear parts of the stress-strain diagram the Young's modulus is determined. To obtain the stress-strain diagram it is necessary to produce rectangular or cylindrical samples, with dimensions of L/d between 2 and 4.[42]. Information regarding the exact mixture for the porous concrete in this test is given in Table **??**.
As due to its low strength, demoulding of porous concrete causes complications, therefore a demountable mould is required. In the TU Delft lab a bolted rectangular mould with dimensions which are within the aforementioned required limits, is available. Therefore, for this particular test it is decided to produce three rectangular prisms with this mould with dimensions of 10 x 10 x 40 cm. The compressive strength of the porous concrete is 7.9 MPa, as previously determined in another research [43]. therefore the samples are compressed with a stress of 2.4 MPa, with a stressed surface of 10 x 10 cm this means the machine is set to a maximum force of 24 kN. Relevant information regarding stress and strain is obtained during the test by previously installed sensors on each side of the sample. A schematization

of the test setup in presented in Figure 4.1. It is expected to obtain three stress-strain diagrams with each four slopes. The final slope of each sample is expected to fail around the previously mentioned compressive strength of the porous material.

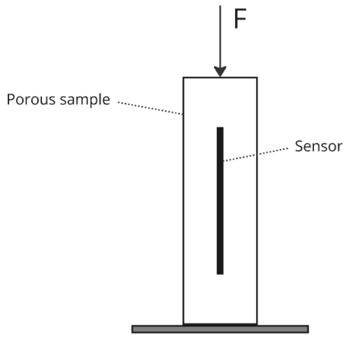


Figure 4.1: Schematization of Young's Modulus test setup

4.2. Pull-out strength

In the case of a façade element consisting solely of a porous concrete layer, it is assumed that the critical strength is located in the area where the connection is bolted to the porous layer. Therefore, the pull-out strength of these bolts is of high interest and is determined by experimental testing. It is assumed that the bolt strength is intensively higher compared to the strength of the porous concrete, thus, the concrete is expected to fail first.

Regarding the test procedure to determine the pull-out strength of a bolt and porous concrete combination, no specific test setup is available in the TU Delft lab. It is a specific situation, which is mainly of importance for this research and application, solely to determine if the concrete is able to withstand the forces that are present at the location of the bolt. Tests do exist for tensile strength of concrete, however unfortunately they do not exist in the lab for the combination of the two materials, therefore, a test setup is created for this exact purpose.

As the strength of the bolt is known and is therefore not of importance in the research, it is decided to not use real bolts. Reinforcement bars replace the bolts, which are cast into the porous concrete by a in-fill cement mixture. It is important that this cement has a strength superior of the strength of the porous concrete, to ensure the failure occurs in the porous concrete.

The test setup is as follows, porous cubes are produced with a dimension of 10 x 10 x 10 cm. Three of which are cast with a tube inside to create a hole for the reinforcement bar. The remaining three cubes, are drilled at the end of the curing time of 28 days. Reinforcement bars are placed and cast-in with previously mentioned stronger cement. In the test setup, the cubes are constrained under a steel plate where the reinforcement bar goes through the plate. On top of the steel plate, the bar is clamped in a machine that exerts a tensile force. This force gradually increases, as it is controlled by displacement, until the sample fails at the ultimate pull-out strength. A schematization of the test setup is provided in Figure 4.2.

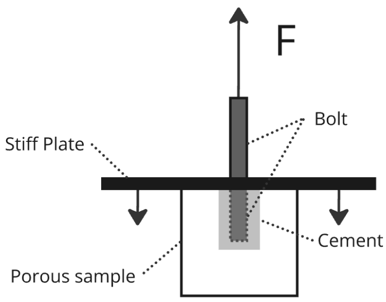


Figure 4.2: Schematization of Pull-out strength test setup

5
Design

To design several distinct options for the green façade, firstly the possible connections are reviewed and designed. For each connection a suitable design is made for the element. Lastly the irrigation system is of high importance for maintaining the plant growth. This chapter addresses the proposed designs for connection and element, combines the two and utilizes multi-criteria analysis to form a final design.

5.1. Design strategy

As discussed in Chapter 3, several connection solutions were excluded due to their incompatibility with the design requirements. Therefore, only two types of connections were identified as suitable for the proposed application. To provide a meaningful comparison between different connections within each connection type, two design options are developed for each type, resulting in a total of four designs. This number is sufficient to enable comparison while remaining manageable, allowing for detailed evaluation.

It is key to create unique designs to ensure a broad spectrum of designs is compared. Furthermore, as the designs are possibly constructed either with or without a structural layer, they are treated as two distinct design variants. Therefore, four designs are presented in the next sections, where each design is possible with or without a structural layer.

5.2. Connection design

As previously mentioned, two types of connections remain to be used: bolted and Plug-and-Play. Therefore, this section presents four distinct designs for each connection, firstly two bolted connections are discussed and the section is concluded with the two Plug-and-Play connection.

5.2.1. Bolted connections

The bolted connections found in literature are possibly combined into a suitable connection for a non-load bearing external façade, such as the green façade element. To ensure that the forces on the bolt holes are evenly distributed a steel pipe is incorporated inside the concrete element, such application has been used in the bolted connection of a timber floor system [22]. This is potentially combined with a embedded hole in the concrete such as connection (b) in 2.4b by [27]. This provides the possibility to cover the bolts after installation, for aesthetic reasons.

Bolted connection 1

The first bolted connection consists of simply a bolt which passes through the element to be hung, and connects into a bolt thread which is drilled in the existing structure. This type of connection requires a element with a structural back layer. Figure 5.1 displays a possible element with the described bolt hole. A benefit of this connection is the simple (dis)assembly, while it provides the possibility to demount each panel individually. Disadvantage is that the location of the bolt is visible from the outside, therefore a solution is necessary to cover the connection.

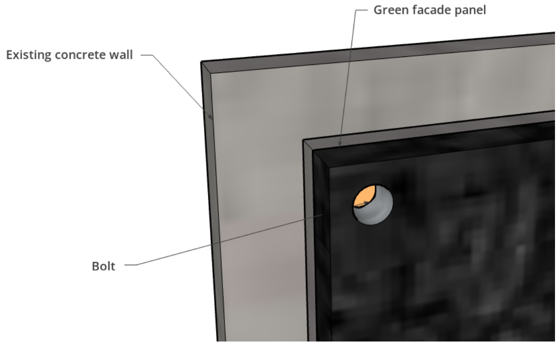


Figure 5.1: Bolted connection 1

Bolted connection 2
Another possible bolted connection is constructed at the back of a element. This Connection not only consists of bolts, it utilizes two steel corner pieces for each connection point. One of the pieces is connected by bolts to the element, another to the existing structure. In between both parts the corner pieces meet each other, where they can be connected together with another bolt. This connection is therefore reachable for disassembly from the side, top or bottom of the element, if enough space is provided for. Benefit of this connection is the location at the back of the element, the connection is covered and the panel provides a greater area of greenery. Unfortunately the mentioned reachability of this connection could become an issue. This type of connection is installed onto a structural back layer, or potentially directly onto the porous layer by bolts and anchors, however this awaits confirmation by structural analysis.

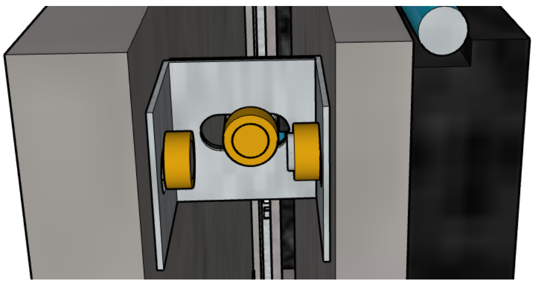


Figure 5.2: Bolted connection 2

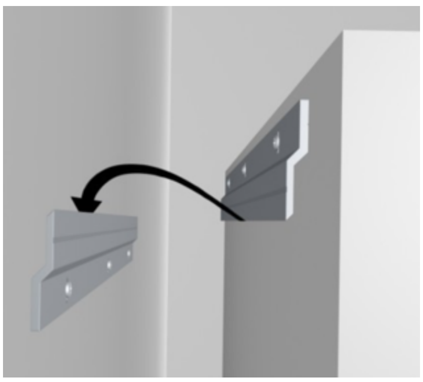
5.2.2. Plug-and-Play connection

As previously mentioned, another suitable type of connection for a façade element is the Plug-and-Play connection. The connections found in literature are all possibly applied in their own way onto an external façade panel. However, some are more convenient than others. For instance the connections by E2VENT and ETEM, these connections are very similar to each other, however the production of the connection of ETEM is more difficult, where the connection of E2VENT is easily produced by casting a screw thread inside the concrete panel frame. Thus it is preferred to make use of a connection similar to the one produced by E2VENT. Another promising connection is the GeckoTeq Rail, originally meant for hanging decoration onto an interior wall. Both of these connections ensure quick installation and each part is easily attached to the façade element or existing structure by bolts and nuts.

Plug-and-Play connection 1 the Plug-and-Play connection of E2VENT would require a structural frame around the porous concrete instead of a structural back layer, or the connection is modified to be connectable to a back layer. This is preferable, as this ensures an extended green area in combination with improved aesthetics, as the connection is invisible. A visualization of the modified connection is given in Figure 5.3. As shown it consists of two parts, a slotted profile and a horizontal bar, each attached to either the element or the structure by bolts. These bolts function as a permanent connection and are not to be disassembled. Afterwards the Plug-and-Play connection is easily hung into the profile, being locked into the slots. In case of necessary disassembly, the panel is lifted out of the slot by two persons or with help of a small forklift. A small space above the element is necessary to provide enough room to lift the element.

Figure 5.3: Plug-and-Play connection 1

Plug-and-Play connection 2 This type of connection was originally meant for interior wall decoration, however this connection is potentially reinforced to become suitable for the installation of façade panels. Its material type and strength is changed, for instance it is constructed out of steel with steel grade S355. Another option for reinforcement is increasing the thickness of the connection. A benefit of this connection is that it consists of two identical parts, which reduces the production steps and thereby the costs. Once installed onto structure and façade panel, this connection provides quick and easy installation. One point of interest is that horizontal movement is to be restraint, in the middle of the wall this is ensured by the neighboring panels. However on the edges of the wall, it is necessary to add a plate that fixes the panels in their place.



(a) GeckoTeq Rail [31]

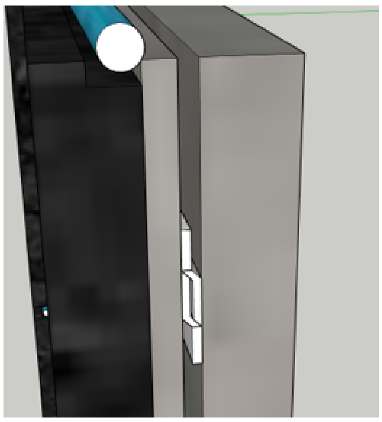


Figure 5.4: Plug-and-Play connection 2

5.3. Element design

Each of the connections mentioned in the previous section, requires its own suitable element design. In case of a bolted connection, the element requires pre-drilled holes for instance. A design with a bolted connection at the back of the element requires enough working space to dismantle the connection, therefore the element design has to be modified slightly. For the Plug-and-Play connections the main necessary requirement is a large enough free area above the element in order to lift it out of its connection. This section provides the different element designs associated to different connections. Some of the designs can be either performed in a single porous layer or a bi-layer system.

Irrigation system

Due to production and maintenance difficulties it is more appropriate if the irrigation system is not incorporated inside the concrete. Therefore it consists ideally of tubes which can be placed above the wall elements. For the water to reach the plants this way, the top of the elements can not be obstructed. Thus it is preferred to not have a structural frame at the top or this frame has to be perforated.

Element design 1

The first proposed element design is associated with the first bolted connection. This connection requires a structural back layer which is connected by bolts to the structure. Due to this requirement, the connection is visible as shown in Figure 5.5. This opening is however possibly reduced to a minimum and covered with, for example, soil or plants. The advantage of this design is the quick installation process, the easy accessible connection which ensures simple dismantling. On top of that, the production of such panel is relatively easy. On the downside, the design does not provide a full green area, which has negative impact on the aesthetics. Regarding the irrigation system, this design will be connected directly on the structure, therefore there is no additional space behind the element to install the irrigation system. This means that the irrigation system has to be installed on the front side of the panel, which again impact the aesthetics.

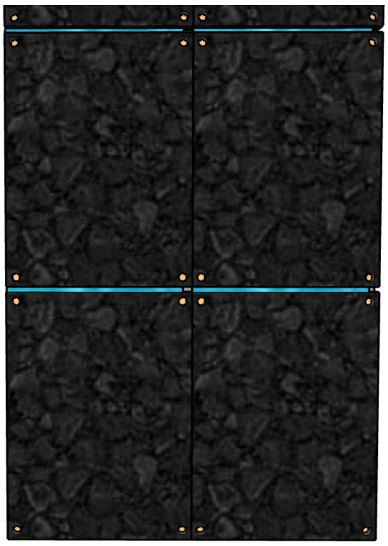


Figure 5.5: Element design 1

Element design 2

Opposed to the previous element, this design which is suitable for the second bolted connection, possess the required area behind the panel to install the irrigation system. Unfortunately, it requires extra open area around the element to make disassembly possible in a later stadium, meaning it can not provide a full green area and the main structure remains visible through the panels as shown in Figure 5.6. This design is producible with or without a structural back layer.

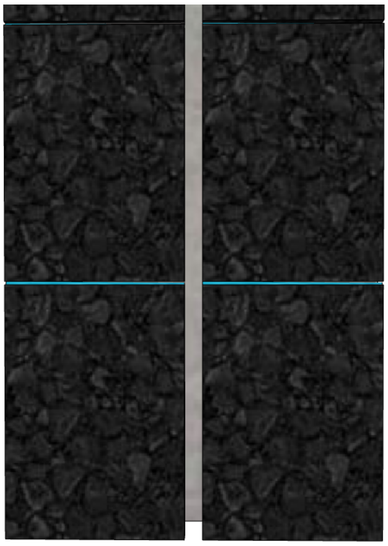


Figure 5.6: Element design 2

Element design 3 and 4

Regarding the Plug-and-Play connection, they posses the benefit of providing a greater green area. This is due the fact that no working access is necessary behind the elements, as the whole panel can be lifted out of its connection without unscrewing bolts for example. Therefore the element as in Figure 5.7 is almost completely covered and the main structure is nearly invisible. A small area above the panels is left open, for easy dismantle of the panels. Big advantage is that this design can also be implemented without a structural back, with the assumption that the porous layer is sufficiently strong enough. The only small difference between the two Plug-and-Play designs is the required area above the panels, which depends on the dimensions of the connection.

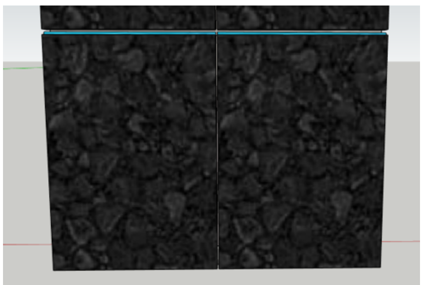


Figure 5.7: Element design 3 and 4

5.4. Multi-criteria analysis

In the previous section several combinations of connection systems and elements are proposed as a solution for the demountable green façade. In this section the criteria and weights for a multi-criteria analysis (MCA) are determined to compare the performance of each design to each other. This is done to find the best scoring design which is assessed in the next chapter. Extra information regarding the MCA can be found in Appendix B.

5.4.1. Criteria and weights

As the goal of this thesis is to research the possibilities of a *demountable* green façade, the criteria are selected regarding that goal. Therefore the specific points of interest mentioned in the research questions are taken into account. As a green façade has an aesthetic function, it is part of the criteria. As costs can become a determining factor between two high scoring designs, it is necessary for it to be part of the MCA. Although it is to be noted that no numerical values regarding costs are available, therefore assumptions are made based on production steps and material costs. Each criteria is divided into sub-criteria, as this improves the ability to score each design correctly. For the weighting technique the Weighted Additive Model is used, this model simply multiplies each criteria with each weight [44]. The main criteria and its sub-criteria are listed in Table 5.1, the main criteria are compared by ranking their importance to each other. This comparison is visualized in Table 5.2.
In this comparison, '<' means that the criteria in the most left column is considered less important than the criteria in the top row and 0 points is added to the score. '>' means it is more important and 1 point is added to the score. '=' means the criteria are equally important and 0.5 points are added. Each criteria starts with a score of 1.

Table 5.1: Main criteria with their sub-criteria which are used to rank each design to each other.

goal	**main criteria**	**sub-criteria**
Weight reduction of the element or increase of the area	[1]physical boundaries	[1a] Weight of design [1b] thickness of design [1c] dimensions of design
to produce a economical viable product	[2] economic feasibility	[2a] production costs [2b] material costs [2c] Environmental costs
to produce a technical viable product	[3] technical feasibilty	[3a] production complexity [3b] transportion complexity [3c] installation complexity
to produce a visually atractive design	[4] aesthetics	[4a] area of greenery [4b] connection visible
to optimize the demountability of the design	[5] Connection	[5a] connection complexity [5b] reachability of connection [5c] load transfer efficiency

Table 5.2: Determined priority of main criteria

	[1]	[2]	[3]	[4]	[5]	**score**
[1] Physical boundaries	-	<	<	=	<	1.5
[2] Economic feasibility	>	-	=	>	=	4
[3] Technical feasibility	>	=	-	>	=	4
[4] Aesthetics	=	<	<	-	<	1.5
[5] Connection	>	=	=	>	-	4

6

Finite Element method

To structurally analyze the design, finite Element software is utilized. This chapter provides a explanation of the method used regarding FEM with the appropriate settings and material properties that are used. For the analysis the Finite Element software Abaqus FEA is used.

6.1. Finite Element Analysis

Finite Element Analysis is a numerical technique that approximates solution to engineering problems, by splitting a structure in smaller elements (meshing). It is therefore a approximation of reality, however with a well structured model it is able to get close to reality. Performing Finite element analysis consists of the following steps:

- Define the geometry
- Assign material properties to each part
- Define the loads
- Define contraints and boundary conditions
- Assign contact interaction between each contact point
- Mesh each part
- Setup loading step and run analysis
- Obtain results in the form of graphs and visualizations

6.2. Geometry

To analyze the design, three different models are made. Firstly the bi-layered model with the original dimensions for connection and façade is modeled. Secondly the same model is optimized regarding either the connection or the façade and lastly the single porous layered design is modeled. In the final analysis the original dimension for the connection are used, as the porous layer is mainly of interest in that analysis.
All façade designs are modeled attached to a existing wall structure. This wall is not of interest during the analysis and is modeled as a very stiff material, to ensure critical areas do not occur in the wall structure. To save on computational time, the wall structure is not fully modeled. Only areas of the wall which are in contact with the other materials, connection or façade, are modeled. This is done to ensure the frictional behavior between two materials is taken into account during the analysis. The other elements representing the connection, façade and bolts are completely modeled.

6.3. Material properties

This section presents the known material properties, which are used in the analysis. The properties are regarding the materials used for the bolts, steel parts and conventional concrete. Material properties regarding porous concrete are determined in the next chapter. For all steel parts and bolts the same steel grade S355 and properties are applied regarding Young's modulus, density and Poisson ratio, namely respectively: 200000 MPa, 7850 kg/m^3 and 0.3.

6.3.1. Bolts

For the bolts, standardized bolts with strength class 8.8 are used. Plasticity behaviour is obtained from previously performed tests and given in Table 6.1. Bolts in reality are connected inside the concrete panels by anchors. For simplicity they are modeled as they go through the panels, fastened with a nut on the back.

Table 6.1: Plasticity properties bolt strength class 8.8

Yield stress [MPa]	**Plastic strain [-]**
778.8	0
888.0	0.011
944.5	0.021
985.8	0.031
1011.7	0.040
1018.5	0.045

6.3.2. Steel

The steel parts are of class S355 with the elastic properties previously mentioned. The plasticity properties are mentioned in Table 6.2. It is to be noticed that the steel fails at a plastic strain above 0.262.

Table 6.2: Plasticity properties S355

Yield stress [MPa]	**Plastic strain [-]**
355.60	0
359.90	0.012
492.27	0.045
540.50	0.138
0.1	0.262

6.3.3. Structural concrete layer

For the structural layer concrete of class c20/25 is used. Specific information is obtained in previously performed tests regarding tensile and compressive behavior and damage. The density, Young's modulus and Poisson's ratio are respectively: 2600 kg/m^3, 30000 MPa and 0.2.

Table 6.3: Concrete damaged plasticity

Parameter	**Value**
Dilation angle	35-40
Eccentricity	0.1
fb0/fc0	1.16
K	0.66667
Viscosity parameter	0.005

Table 6.4: Tensile behavior c20/25 concrete

Yield stress [Mpa]	Cracking Strain [-]
3.6	0
2.238357699	0.000107126
1.418867776	0.000186367
1.026872077	0.000251359
0.807587164	0.000310593
0.66925133	0.000367129

Table 6.5: Compressive behavior c20/25 concrete

Yield stress [Mpa]	Inelastic Strain [-]
23.11430546	0
27.49671694	0.000167974
31.22714338	0.000264745
34.24942766	0.000386806
36.5007728	0.000536401
37.91073064	0.000716045

Table 6.6: Compression damage c20/25 concrete

Damage Parameter [-]	Inelastic Strain [-]
0	0
0.075913798	0.000167974
0.101025092	0.000264745
0.12836491	0.000386806
0.158288807	0.000536401
0.191245167	0.000716045

Table 6.7: Tension damage c20/25 concrete

Damage Parameter [-]	Cracking Strain [-]
0	0
0.080103616	1.77E-05
0.115607706	2.79E-05
0.264985738	7.05E-05
0.404418445	1.16E-04
0.5	0.000154624

6.4. Loads, constraints and boundary conditions

Loads are modeled as displacements, after the analysis is completed the forces are extracted by using the reaction forces at the point of application of the displacement. Boundary conditions are used to constrain the existing wall in every direction, as this part is not to be analyzed. Displacement is placed on top of the complete surface of the green façade in Y-direction, which represents the self-weight of the structure comprising of connection, porous layer and potential structural layer. A separate model is made to analyze the wind loads on the façade, which is modeled as a displacement in X-direction on the full front area of the façade. The displacements are applied in ramp amplitude, meaning that the displace increases over time until at the end of the analysis the full displacement is applied.

6.5. Interaction

Interaction definitions are necessary between each contact area of separate parts. Three different interaction properties are defined, where each interaction is defined as 'hard contact' meaning parts are not to go through each other:

- For the steel on steel interaction a friction coefficient of 0.35 is assigned.
- For the concrete on concrete interaction a friction coefficient of 0.5 is assigned.
- Lastly the interaction between concrete and steel is assigned a friction coefficient of 0.225.

6.6. Mesh

Meshing is an important aspect of Finite element analysis, as it influences the accuracy and efficiency of the analysis. The choice of mesh size takes into consideration computational time and accuracy of the results. While a fine mesh provides higher precision, potentially leading to more accurate results, it also increases the computational time. A coarse mesh may fail to capture all details of the model, leading to inaccurate results. To determine the appropriate mesh, an iterative process is used, where the mesh is constantly refined until the results stabilize as the mesh becomes finer. Particular attention is given to contact areas between different material parts, to ensure a matching mesh size to avoid inaccuracies during the analysis.

6.7. Analysis and results

After the appropriate mesh is applied, the analysis is ran. On completion of the analysis, information is taken from the results. Important results relevant to this research, which are obtained from the analysis are related to:

- Overall stresses (to verify they do not exceed the ultimate strength of the materials)
- Tensile and compressive stresses in concrete parts
- Displacements and deformations
- local stresses around bolts (to compare with porous concrete pull-out strength)

III

Results & interpretation

7

Multi-criteria analysis results

This chapter presents the results regarding the performed Multi-criteria analysis. Results consist of numerical scoring for each design, based on this scoring a conclusion regarding the best suitable design is taken. This design is further analyzed in the following sections.

7.1. Weighted scores of MCA

Each design consist of equal amounts of porous and structural concrete, therefore they are compared to each other by the impact of the addition of its connection on each sub-criteria. All the designs are scored based on the mentioned sub-criteria, more information regarding the argumentation of the scores in given in Appendix B. The results of the MCA are given in Table 7.1. The total scores are rounded to 1 decimal, as parts of the MCA are based on personal judgment and are therefore not precise up to three decimals.

Table 7.1: Weighted scores of each designs presented as the result of the MCA

		Design 1		Design 2		Design 3		Design 4	
	sub-criteria weight	score	weighted score	score	weighted score	score	weighted score	score	weighted score
[1a]	0.033	5	0.167	4	0.133	2	0.067	4	0.133
[1b]	0.033	5	0.167	2	0.067	2	0.067	4	0.133
[1c]	0.033	1	0.033	1	0.033	1	0.033	1	0.033
[2a]	0.100	1	0.100	1	0.100	1	0.100	1	0.100
[2b]	0.100	5	0.500	4	0.400	2	0.200	4	0.400
[2c]	0.067	5	0.333	4	0.267	3	0.200	4	0.267
[3a]	0.089	1	0.089	1	0.089	1	0.089	1	0.089
[3b]	0.089	5	0.444	4	0.356	3	0.267	4	0.356
[3c]	0.089	3	0.267	4	0.356	5	0.444	5	0.444
[4a]	0.067	4	0.267	4	0.267	5	0.333	5	0.333
[4b]	0.033	3	0.100	3	0.100	5	0.167	5	0.167
[5a]	0.067	5	0.333	4	0.267	3	0.200	4	0.267
[5b]	0.100	5	0.500	2	0.200	5	0.500	5	0.500
[5c]	0.100	3	0.300	3	0.300	3	0.300	5	0.500
	total score		**3.600**		**2.900**		**3.000**		**3.700**

7.1.1. Interpretation MCA results

As presented in Table 7.1, two designs are scoring much higher compared to the other two. It is also observed that their scores are relatively close to each other. This raises questions on what impacted these scores. As the determination of weights are prone to errors, it is important to evaluate what the influence of the values of those weights are on the result. Therefore, a sensitivity analysis on the weights is performed and presented in Appendix B. Based on the sensitivity analysis design 4 is considered the best scoring design. Based on this conclusion this specific design is further analyzed in the following sections of this research.

8 Material properties results

This chapter presents the results regarding the experimental test to determine the Young's modulus and the pull-out strength of the porous concrete as mentioned in Chapter 4. The chapter is concluded with a short interpretation of the results.

8.1. Young's modulus

As mentioned in Chapter 4, the porous concrete samples are compressed four times by 30 % of its compressive strength. To apply this compressive load the Green Toni machine is used. The setup is shown in Figure 8.1.

Figure 8.1: Young's modulus testing setup in Green Toni machine

On each side of the prisms, a sensor is attached to measure the strain of each side. This machine expresses its force in KN, as the area of the loaded sides of the prisms is 100 x 100, the force is set to 24 KN. At the end of the three cycles, the prisms are loaded until failure to provide an extra check of the compressive strength. It should be noted that the compressive strength can differ due to the different shapes of the samples used for this test compared to a compressive strength determination test of cubes. In addition, the absence of Cugla Colloidal 100 in the concrete mix and an adjustment in the water/cement-ratio can cause differences.

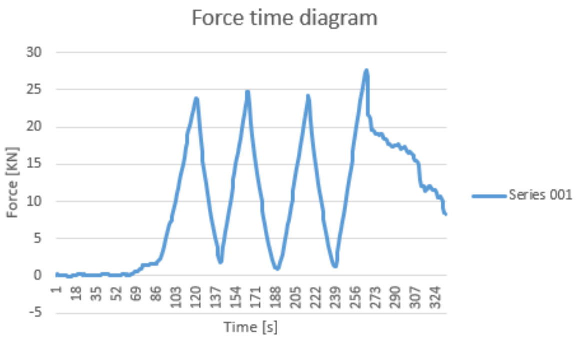


Figure 8.2: Applied load vs time diagram of sample 1

Three different samples are made and each sample is loaded four times. Therefore, twelve calculations are performed for the Young's modulus and an average is taken from this. An example of the loading cycle on the prisms is given in Figure 8.3. The average calculated Young's modulus for each sample is given in Table 8.1, more information regarding the Young's modulus tests and its calculations are presented in Appendix C.

Table 8.1: Average Young's modulus

	E [Mpa]
Series 001	12947,66
Series 002	14135,89
Series 003	15231,29
average	**14104,95**

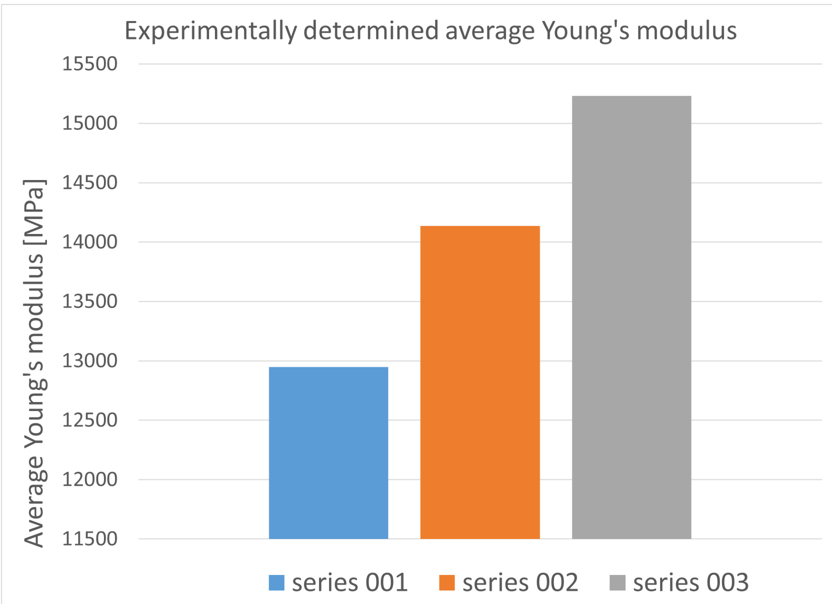


Figure 8.3: Average Young's modulus of three samples, determined by experimental testing

8.2. Pull-out strength testing

As mentioned in Chapter 4, six concrete cubes with a dimension of 10 x 10 x 10 cm are cast to determine the pull-out strength. Three of which, have a 5 cm long tube cast in to the middle, providing a hole where the bolt is cast into. The remaining three cubes are without a tube and 5 cm deep holes are drilled into them after the 28 day concrete curing time. As it is assumed that the bolt strength is not governing, and is therefore not of importance during the test, a reinforcement bar is used instead of an actual bolt. The cubes are shown in Figure 8.4.

Figure 8.4: Cubes after the reinforcement bar has been cast inside after 28 days curing time. Bolts are placed for keeping the bar in place while the concrete hardens.

In order to test the pull-out strength, the porous cube is constraint on a flat surface with a steel plate fastened on top of it. This steel plate has a hole in the middle where the reinforcement bar goes through. There the bar is clamped by 12 bolts between two steel plates, produced for this exact purpose. These two bars are connected to a machine that produces a tensile force. The connection between the machine and the two plates is realized as a hinge, to encounter for imperfections. All connected parts are pre-tensioned to ensure no slip of the test setup occurs. The complete setup is shown in Figure 8.5.

Figure 8.5: Test setup to determine the pull-out strength of a reinforcement bar cast inside porous concrete

8.2.1. Cast-in holes for reinforcement

The first test is performed on specimen Cast-in 1, which has a hole made by a cast-in tube. As there was no predefined expectation regarding the appropriate displacement rate. The displacement control settings of the tensile testing machine were set to a rate of 0.05 mm/sec. However, this rate proved to be excessive. For the remaining five tests, the displacement control was further reduced to 0.01 mm/sec, resulting in a more suitable testing condition. Consequently, the results for test sample Cast-in 1 indicate a higher failure force, likely due to the higher application rate, which raises questions regarding the validity of these results and are therefore not used in the analysis.
Results to all three Cast-in test samples are shown in Figure 8.6. Both failure force values of test 2 and 3 are around 10 kN.

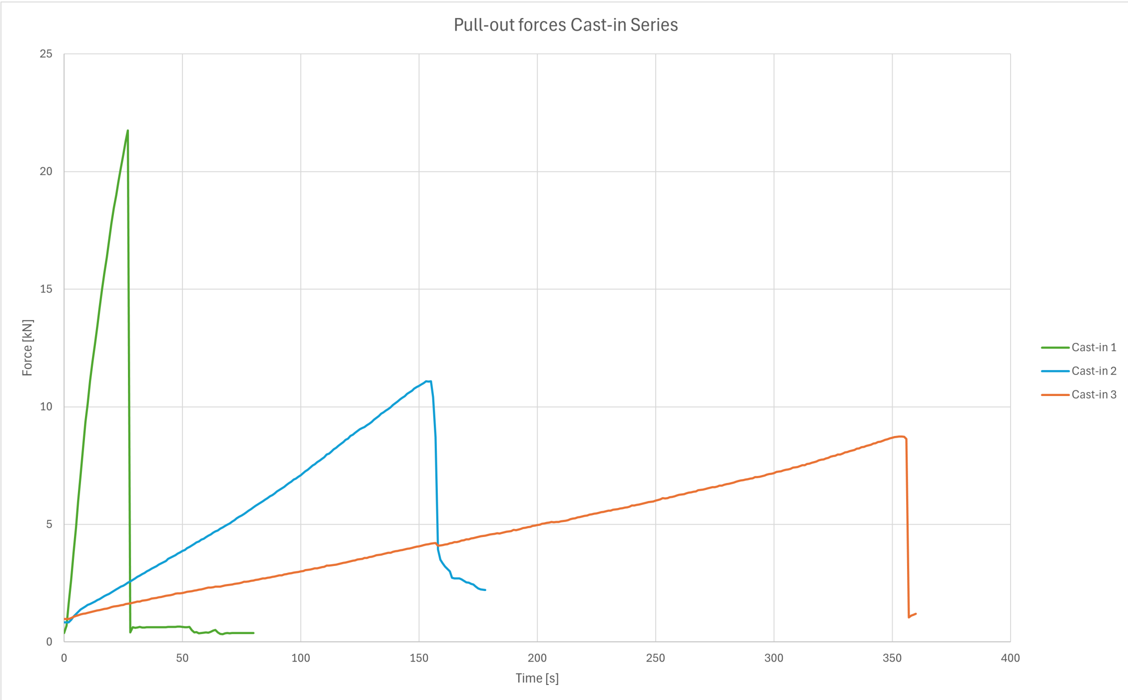


Figure 8.6: Pull-out strength test results to all three Cast-in samples. Displacement control of test Cast-in 1 was set to 0.05 mm/sec, the others to 0.01 mm/sec.

It is noticed that each sample failed due to cracking of the porous concrete, proving as expected that the strength of the porous concrete is governing over the strength of the in-fill concrete used in the holes. Difference between each graph can possibly be attributed to inconsistencies in either the samples or the test setup. After casting of the in-fill concrete, it was observed that the mixture was too liquid, causing outflow of the material, filling the voids of the porous concrete. This causes less cover of the reinforcement bar, possibly increasing the local stresses due to a decrease in loaded area. On the contrary, the in-fill concrete has a higher strength and therefore inflow into the voids possibly increases the strength of the porous concrete. Sample inconsistencies are potentially caused by this outflow. In Figure 8.7, Figure 8.8 and Figure 8.9 the significance of the inflow into the voids can be seen.

Figure 8.7: Specimen Cast-in 1 after failure

Figure 8.8: Specimen Cast-in 2 after failure

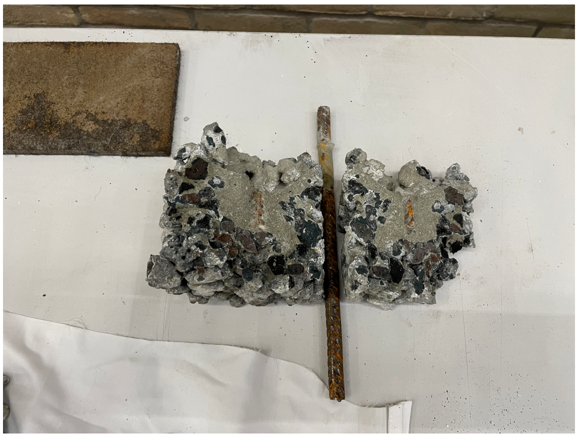


Figure 8.9: Specimen Cast-in 3 after failure

8.2.2. Drilled holes for reinforcement

For the drilled samples, the same displacement rate as for Cast-in samples 2 and 3, is applied, as this worked accordingly in the previous performed tests. Casting of the reinforcement bar in the drilled holes, is done with the same material as for the cast-in holes. However, as problems occurred in the previous cast samples, slightly less water was added to the mixture to make a less fluid mixture, to ensure against outflow of the in-fill concrete into the voids of the porous concrete. This is necessary to ensure this set provides relevant information regarding the porous concrete, however it is noted that this negatively impacts the comparability of both sets. In Figure 8.11, Figure 8.12 and Figure 8.13 it is shown that significantly less infill concrete has flowed into the porous concrete voids. Therefore, assumed is that this generates more realistic results related to the porous concrete characteristics, as it is less influenced by other materials. Figure 8.10 presents the results for all three drilled samples. It is clear that all the samples behave in a similar way, however the ultimate strength still differs notably. This suggests that achieving a homogeneous porous concrete structure is challenging. While several factors, such as material or setup inconsistencies, potentially influence the observed differences, no definitive conclusion regarding their specific causes is drawn.

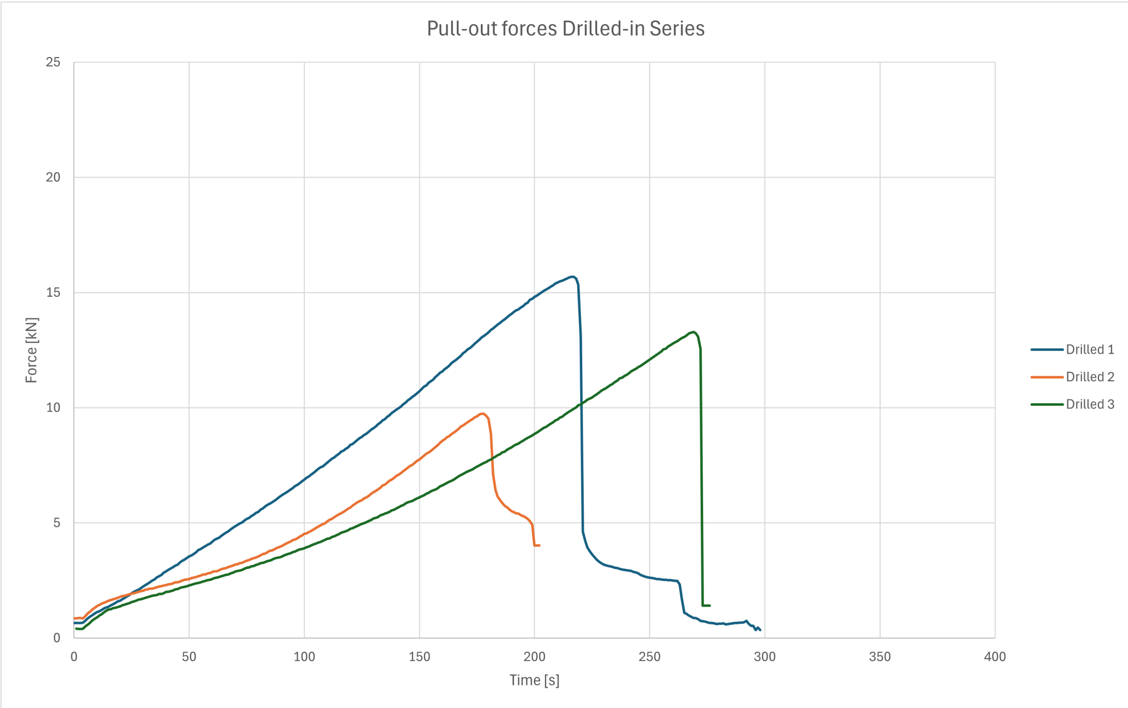


Figure 8.10: Pull-out strength test results to all three Drilled-in samples. All tests are performed with a displacement rate of 0.01 mm/sec.

Figure 8.11: Specimen Drilled-in 1 after failure

Figure 8.12: Specimen Drilled-in 2 after failure

Figure 8.13: Specimen Drilled-in 3 after failure

An overview of the determined ultimate pull-out strength for all six samples is presented in Table 8.2. Of course it is important to notice the inconsistency of test Cast-in 1 regarding the displacement rate error.

Table 8.2: Pull-out force for each specimen.
* Due to a higher displacement rate during this test compared to the other tests, this value is unreliable.

	Force [kN]
Cast-in 1	21.74*
Cast-in 2	11.08
Cast-in 3	8.74
Drilled 1	15.69
Drilled 2	9.74
Drilled 3	13.29

8.3. Interpretation results

Values determined regarding the Young's modulus are inconsistent with the values mention in Eurocode 1992-1-1:2005. This implies that the porous material behaves differently than conventional concrete types. Regarding the obtained pull-out strength of the material, it suggests that the material is capable to withstand a force of minimally 8.74 kN at each bolt location. Results associated with the drilled holes, are assumed to provide a more realistic behavior of the porous material as it is less influenced by the infill concrete, more on this is mentioned in the discussion section. It is important to use the obtained values carefully as the results are based on a limited amount of test and samples. Therefore, for further analysis it is dangerous to simply take the average of the obtained results, as this means it is likely that in reality the Young's modulus or pull-out strength is lower than the average value. Therefore, it is wise to continue with the lowest obtained value for safety reasons. In the recommendation section this is further mentioned.

9

Finite Element results

This chapter presents the obtained results from the Finite element analysis performed in Abaqus. First an analysis for the bi-layer design is performed, followed by another analysis for an optimized design for the connection. Afterwards an analysis for the single layer design is performed. Focus is on the stresses that form in the connection and façade. For the single layered design special focus is on the pull-out forces, as they are compared to the values obtained in the previous chapter.

9.1. First analysis Bi-layer design

The First analysis of the Bi-layered system consists of a 600 by 600 mm c20/25 concrete panel, connected at the top and bottom by the proposed connection to a stiff wall. Bolts of size M12 are used, however the bolts are not of interest in this analysis, focus is on the steel rail connection and the façade. The geometry of the Abaqus design is presented in Figure 9.1 and Figure 9.2. As shown here, no full existing wall is modeled. Two small wall segments are modeled at the location of the connection, this is done to save on computational time while still taking frictional behavior into consideration.

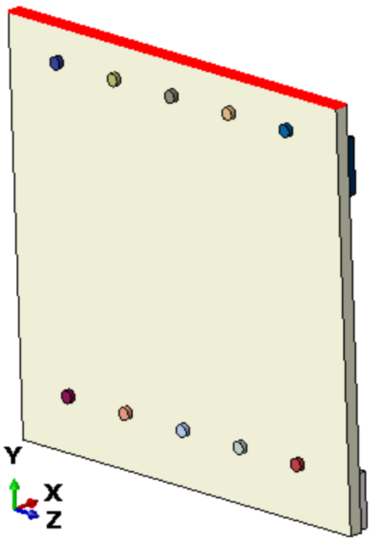


Figure 9.1: Front view of Abaqus geometry, where the displacement in negative Y-direction is applied to the red marked surface

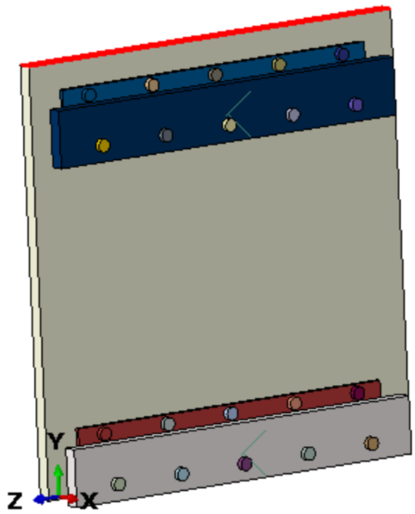


Figure 9.2: Back view of abaqus geometry

A 3 mm displacement in negative y-direction is applied to the top of the façade element. The first part of the displacement is disregarded, as the whole system needs to settle until it starts to take up forces after about 1 mm of displacement. After the analysis the reaction force of the system is taken at the point of application of the displacement. Figure 9.4 displays the force-displacement diagram of the first analysis for the bi-layered system.

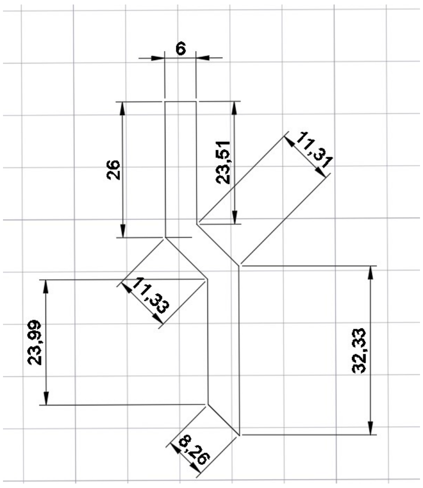


Figure 9.3: Connection dimensions in mm of first design

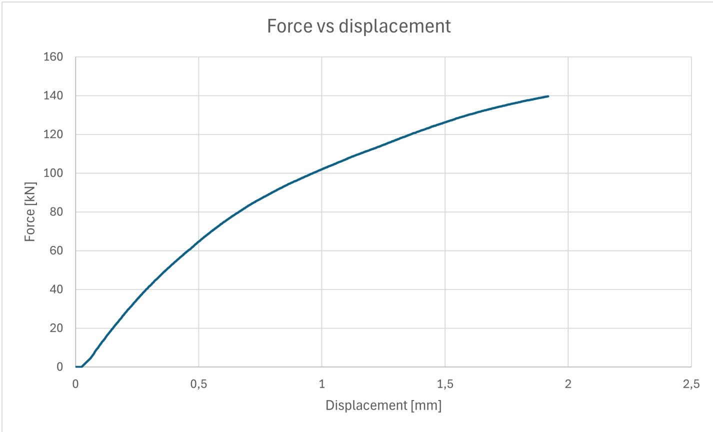


Figure 9.4: Force-displacement diagram of first analysis bi-layered system.

9.1.1. Connection

Figure 9.3 shows the dimensions of the steel rail connection, which is used for the first performed structural analysis. Figure 9.5 presents the Mises stresses at the end of the analysis, thus after the 3mm displacement with the previously showed forces. It is noted that the highest stress present is close to the 355 MPa yield strength of the material. Figure 9.6 shows the deformed shape. More information regarding the results for this first analysis is given in Appendix D. As shown in the force-displacement diagram, forces increase rapidly in the initial moments of the analysis. Due to this, the first obtained data point occurs at a load of 4.43 kN. As previously mentioned, the actual self-weight is 37.85 kg thus a force of 0.37 kN. Figure D.3 provides information of the first data point obtained, representing the lowest applied force present in the analysis. This data point shows a stress of 33.3 MPa occurs, taking into consideration that the applied force is a factor ten higher than the actual load. Stresses in the connection occurring due to the applied wind load are presented in Figure 9.7. A stress of 5.5 MPa is observed in the connection.

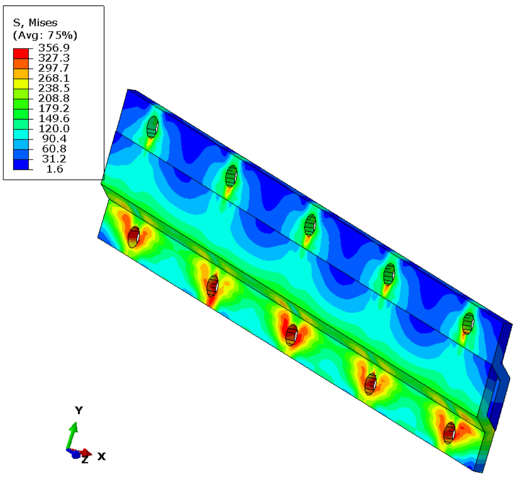


Figure 9.5: Von Mises stresses in MPa of connection for first analysis bi-layered system due to a 3 mm displacement load as self-weight

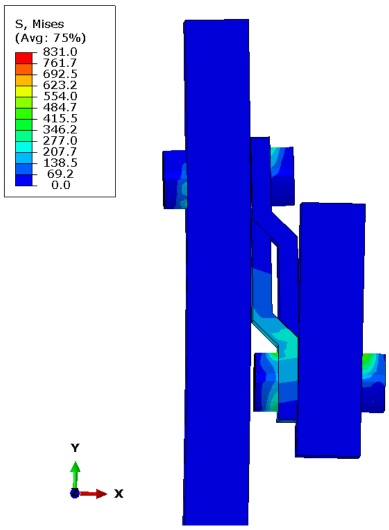


Figure 9.6: Side view connection of deformed shape at the end of first bi-layered analysis, with stresses given in MPa. Due to a 3 mm displacement load as self-weight

Wind load

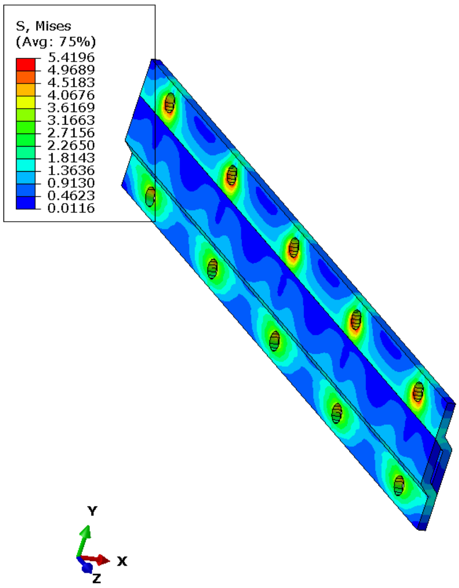


Figure 9.7: Stresses in connection due to wind load of 2.21 kN/m^2

9.1.2. façade

Wind load

A wind load with the value of 2.21 kN/m^2 determined from literature, is modeled in Abaqus as the exact load applied on the front surface of the façade. Results regarding the compressive and tensile stress occurring are presented in Figures 9.8 and 9.9. Respectively stresses of 1.2 MPa and 0.5 MPa are observed. Deflection on the façade are mainly caused by the wind load, values obtained from the analysis are presented in Figure 9.10, a maximum deflection of 0.186 mm is obtained from the analysis.

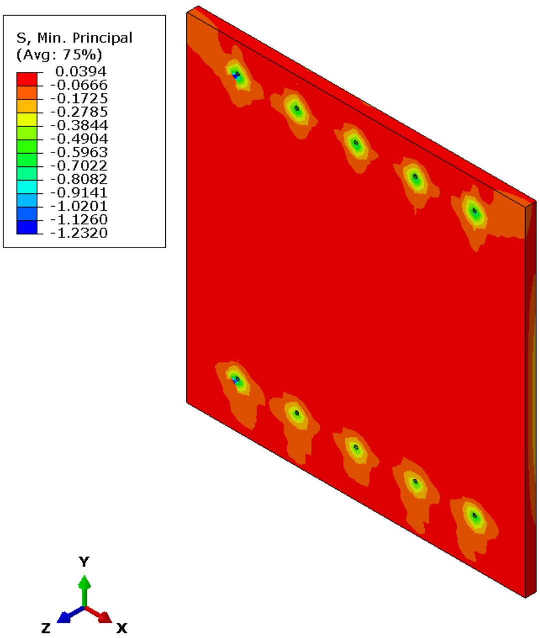


Figure 9.8: Compressive stresses in MPa of first analysis due to a wind load of 2.21 kN/m^2

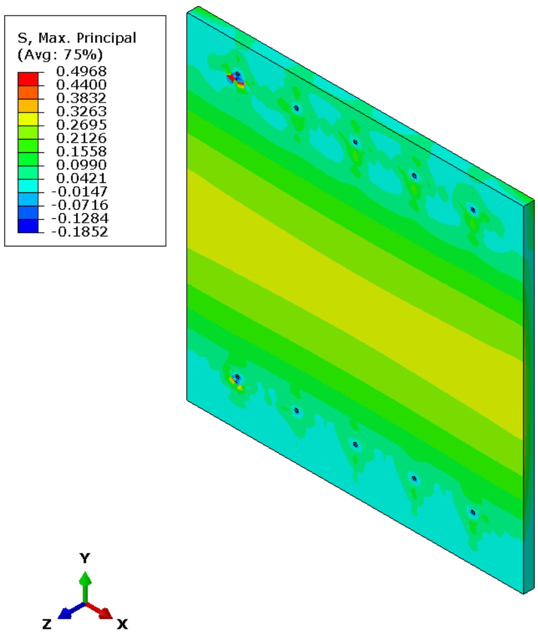


Figure 9.9: Tensile stresses in MPa of first analysis due to a wind load of 2.21 kN/m^2

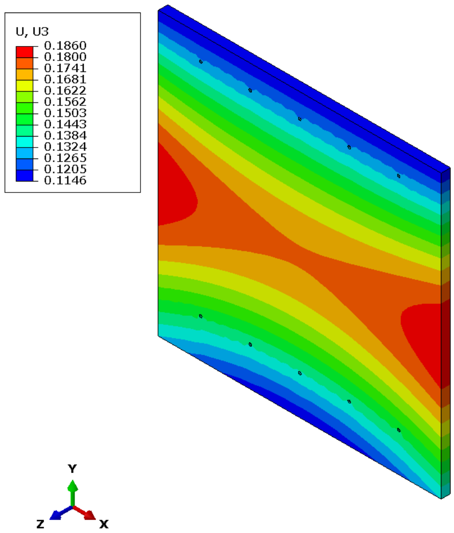


Figure 9.10: Deflection in mm caused by a wind load of 2.21 kN/m^2

Self-weight

The results shown in this section, belong to a higher force than applied in reality to the structure. As the forces in the analysis increase over time, the stresses are taken at a more relevant moment in time. At the exact moment the combination of stresses due to self-weight and due to wind are at the level of the maximum strength of the material. The previously determined stresses due to the wind load, are added to this value and together they reach the limit of the material. In Figure 9.11 the compressive limits, and in Figure 9.12 the tensile limits of the concrete material are shown for the corresponding forces applied. From the results it is observed that the compressive limit of 25 MPa of the c20/25 concrete is reached at a applied force of 17.5 kN, while the tensile limit of 2.21 MPa is reached at a force lower than 4.43 kN.

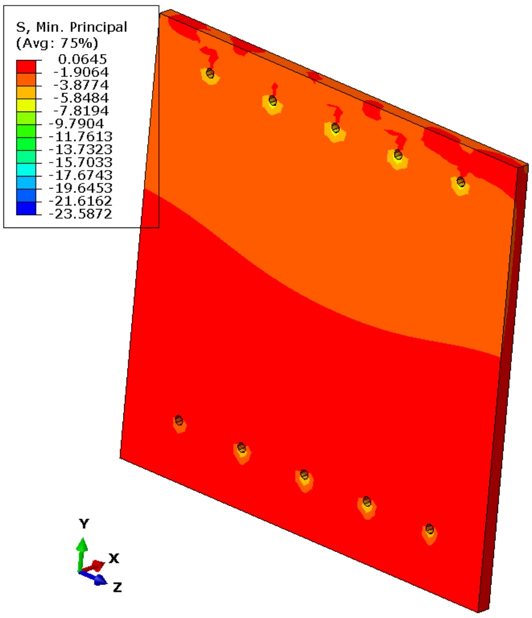


Figure 9.11: Compressive stresses in MPa of first analysis at compressive strength limit of 25 MPa for c20/25. Reached at a force of 17.5 kN

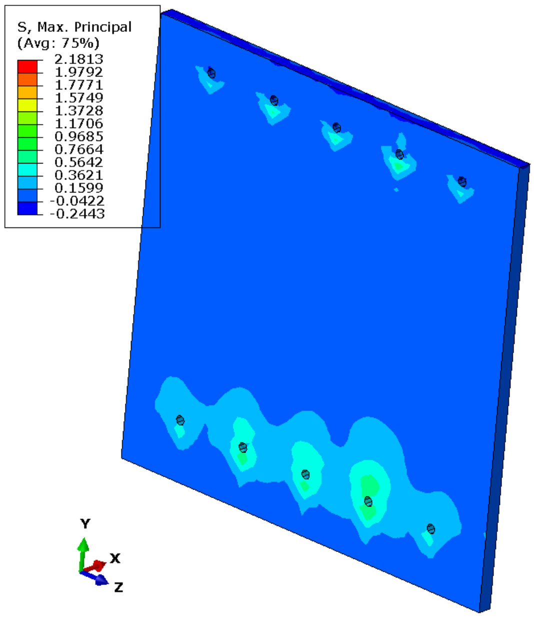


Figure 9.12: Tensile stresses in MPa of first analysis at tensile strength limit of 2.21 MPa for c20/25. Reached at a force of 4.43 kN

9.1.3. Results

Regarding the connection a stress of 33.3 MPa is observed at a load of 4.43 kN, where the actual self-weight load is 0.37 kN. A stress of 5.4 MPa occurs due to the wind load of 2.21 kN/m^2. The yield strength of the S355 steel is 355 MPa and the ultimate strength of 490 MPa. A stress of 10.9 % of the required stress for yielding to occur is present, therefore the results demonstrate the occurring stress is far within limits of the material strength.

Regarding the Façade its compressive and tensile limits are reached at a load of respectively 27.5 kN and 4.43 kN, demonstrating that the tensile strength is the limiting factor of the c20/25 concrete. The results present that the material is able to take up a self-weight load of 4.43 kN, where a actual self-weight of 0.371 kN is present. Which results in a safety percentage of 8.37 %. Regarding the deflection a maximum of 0.18 mm is observed due to wind load. Deflection due to self-weight is negligible as shown in Section D.4.

9.2. Optimized analysis Bi-layer design

As from the previous section it is concluded that the connection and façade are able to take up significantly higher forces than applied, they are over-dimensioned. The thickness of the façade is at its minimum and can therefore not be reduced any further, it is at its optimum size regarding weight and required thickness for bolt anchors. However, the dimensions of the connection are possibly adjusted, therefore the connection dimensions are reduced. Its size is scaled to half the original size, as shown in Figure 9.13.
The new force-displacement diagram is given in Figure 9.14. It is observed that less force is required for an equal amount of displacement.

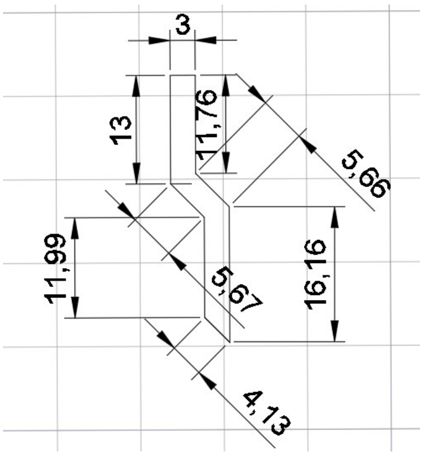


Figure 9.13: Connection dimensions of adjusted design in mm

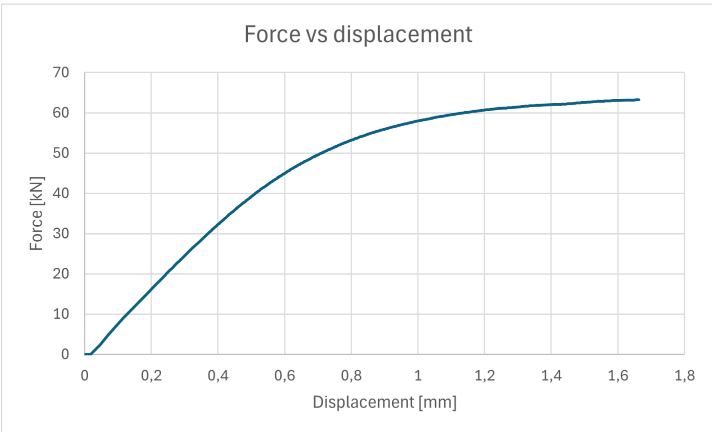


Figure 9.14: Force-displacement diagram of optimized analysis bi-layered system.

9.2.1. Connection

This section presents the results regarding the connection for the new dimensions. In Figure 9.15 it is shown that a stress of 400 MPa occurs at the end of the applied displacement, thus the stresses in the connection have increased, as expected. Figure D.12 of Appendix D shows a stress of 51.6 MPa occurs at a self-weight force of 2.28 kN, where the actual self-weight is 0.37 kN. Figure 9.16 shows the occurring stresses due to the wind load of the optimized connection. A stress of 20 MPa is observed.

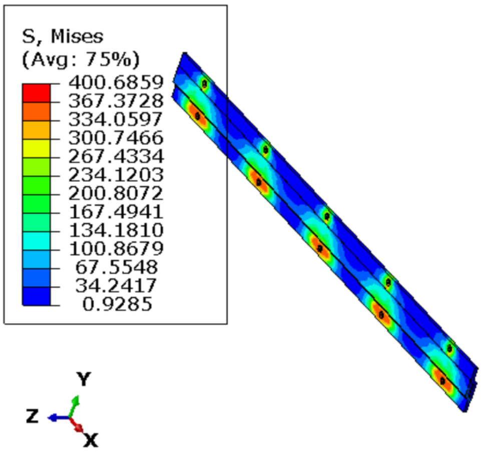


Figure 9.15: Von Mises stresses of connection due to self-weight for the optimized analysis bi-layered system, with stresses given in MPa

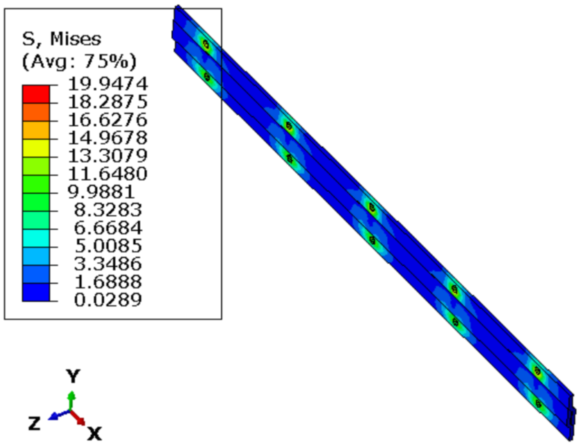


Figure 9.16: Stresses in optimized connection due to a wind load of 2.21 kN/m^2

9.2.2. façade

As the façade is not adjusted, and a lower force is applied to displace the element, the stresses in the façade have decreased. As the safety of the façade is checked in the previous analysis, it is not the main interest of this analysis. Taking into account the same stresses due to wind load as previously mentioned for the original design, results at the compressive and tensile limits are shown in Figures9.17 and 9.18. Showing the limits of respectively 25 MPa and 2.21 MPa are reached at a self-weight force of respectively 15.3 kN and 5.1 kN.

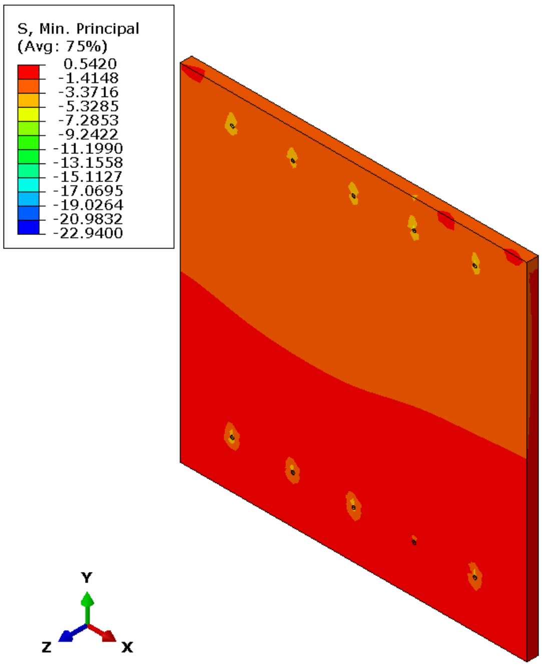


Figure 9.17: Compressive stresses in MPa of optimized analysis at compressive strength limit of 25 MPa for c20/25. Reached at a force of 15.3 kN

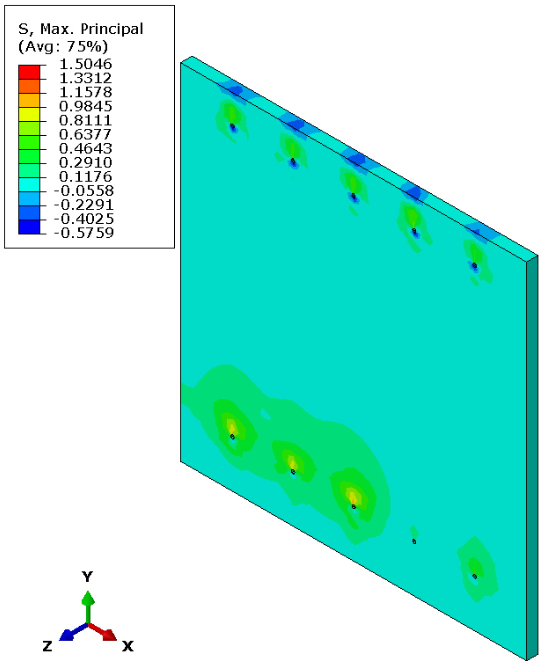


Figure 9.18: Tensile stresses in MPa of optimized analysis at tensile strength limit of 2.21 MPa for c20/25. Reached at a force of 5.1 kN

9.2.3. Results

Results regarding the optimized connection show a stress of 51.6 MPa at a load of 2.28 kN, however the actual self-weight load is 0.37 kN. Due to the wind load a stress of 20 MPa is oserved. With a known yield strength of 355 MPa it is concluded that the occurring stresses is 20.2 % of the yield strength, showing the stresses forming in the optimized design are within its limits. For the façade the compressive and tensile limits are reached at self-weight loads of respectively 15.3 kN and 5.1 kN. With a actual self-weight of 0.371 kN this results in a safety percentage of respectively 2.4% and 7.3% regarding compression and tension.

9.3. Analysis single porous layer

The single layered porous design weighs less compared to the bi-layered system, as no structural layer is present. Thus, the dimensions of the panel are increased, within the limits of the maximum weight allowed. This design has a dimension of 0.6 x 1.2 meter. For this design,the same forces are applied and transferred to the connection. Therefore, the original connection dimensions are used. In this analysis, the behavior of the porous layer is of importance. Furthermore, the local forces at the bolt holes are important as this is a critical location regarding the pull-out strength of the porous concrete. Figure 9.19 displays the displacement-force diagram for this analysis. This section requires extra information regarding the setup in Abaqus, as several material settings changes are required.

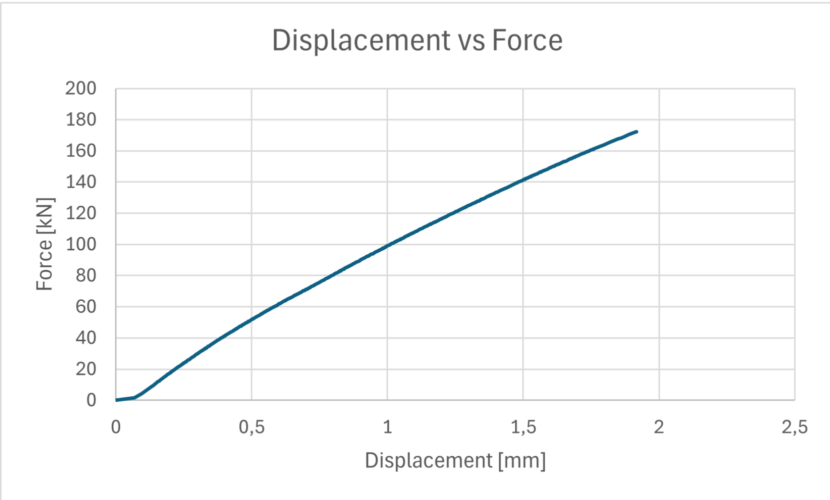


Figure 9.19: Force-displacement diagram of first analysis single layered system.

9.3.1. Porous concrete material settings Abaqus

For the design of a single porous layered façade different material properties are used. The same damaged concrete plasticity settings for Abaqus are used, as this are typical values used for FEA and are provided in Table 9.1. Information regarding the compressive strength is taken from previous research found in literature, giving a compressive strength of 7.9 MPa. However, this research does not provide the necessary information required to use this value in Abaqus. Information regarding tensile and compressive plastic behavior and damaged concrete is missing. Several of these properties are determined from the data generated during the Young's modulus tests. However, to use this data, also the corresponding compressive strength and Young's modulus are required to be used. This means a lower compressive strength is modeled compared to the value of 7.9 MPa. It is assumed that this value still represents the actual compressive strength of the material and is therefore used to determine the safety of the design.

Table 9.1: Concrete damaged plasticity settings porous design

Parameter	Value
Dilation angle	35-40
Eccentricity	0.1
fb0/fc0	1.16
K	0.66667
Viscosity parameter	0.005

The data related to the highest obtained compressive strength from the Young's modulus experimental tests are used for the FE analysis. Some properties are assumed based on the assumption that the porous material behaves similar to conventional concretes mentioned in Eurocode 2 and Equation 9.1. This same equation is used to determine the tensile strength in case that the compressive strength is 7.9 MPa. the resulting tensile strength is 1.19 MPa and is used to compare the obtained results to the actual strength. The properties are given in Table 9.2.

$$f_{\mathrm{ctm}} = 0.30 * f_{\mathrm{ck}}{}^{2/3} \tag{9.1}$$

Table 9.2: Porous concrete material properties obtain by experimental testing
* note that the Poisson's ratio, f_{ctm} and tensile behavior are assumed based on Eurocode 2.

Parameter	Value
Density	1770.6 kg/m^3
Young's modulus	15231 MPa
Poisson's ratio	0.2
f_{ck}	3.56 MPa
f_{ctm}	0.70 MPa

Data regarding the compressive behavior is directly obtained from the Young's modulus testing data. The damage compressive damage parameter is determined based on Equation 9.2. [45]. Table 9.3 shows the obtained values. Unfortunately no experimental data regarding the tensile behavior and damage is determined and therefore needs to be assumed based on Eurocode 2 and literature. Therefore for the tensile behavior only two values are used, namely the previously determined f_{ctm} related to a cracking strain of 0 and 1/3.6 of f_{ctm} related to a cracking strain of 0.00025. These values are not based on actual data for the porous material, however they are determined based on the relation found in experimental data for c20/25 concrete. No information regarding the tensile damage properties is implemented in the model.

$$d_{\mathrm{c}} = 1 - \sigma_{\mathrm{c}}/\sigma_{\mathrm{cu}} \tag{9.2}$$

Unfortunately during the analysis with the determined compressive damage properties, errors occurred regarding these parameters. This is potentially attributed to the fact that the material behaves differently than is expected by the software for conventional concrete. In standardized concrete data tests values of the yield stress decrease rapidly after reaching its ultimate strength. Therefore, the damage parameter increases rapidly. Which does not occur in the obtained data, causing an error. Due to this, the damage parameters are not taken into account during the analysis, solely the yield stress and inelastic strain is considered.

Table 9.3: Compressive behavior of porous concrete

Yield stress [MPa]	Inelastic strain [-]	Damage parameter [-]
2.8157	0	0
2.87079	4.77725E-06	0
2.9236	9.72575E-06	0
2.96682	1.39768E-05	0
2.99476	1.69848E-05	0
3.05397	0.00002222	0
3.09404	2.75798E-05	0
3.13566	3.31823E-05	0
3.16934	3.75588E-05	0
3.21921	4.38583E-05	0
3.25428	4.90243E-05	0
3.28995	0.000054562	0
3.3163	5.99768E-05	0
3.33461	6.35018E-05	0
3.35659	6.91268E-05	0
3.3972	7.39443E-05	0
3.41426	7.79168E-05	0
3.44458	8.47643E-05	0
3.47213	9.06343E-05	0
3.50558	9.65443E-05	0
3.53473	0.000103019	0
3.5517	0.000110107	0
3.55844	0.000116402	0
3.55506	0.000122619	0.000949854
3.55292	0.000127372	0.001551242
3.52734	0.000130034	0.008739785
3.50736	0.000130904	0.014354605
3.48463	0.000131534	0.020742235
3.47642	0.000132679	0.023049426

9.3.2. Connection

For this analysis the connection is not of high importance, as previously is determined that the connection is not at risk of failure. Therefore, the focus is on the behavior of the single-layered façade. Figures 9.20 and 9.21 briefly show the occurring stresses due to a self-weight of the first data point of 1.17 kN and a wind load of 2.21 kN/m^2. Observed is a stress of respectively 48.7 MPa and 8.4 MPa.

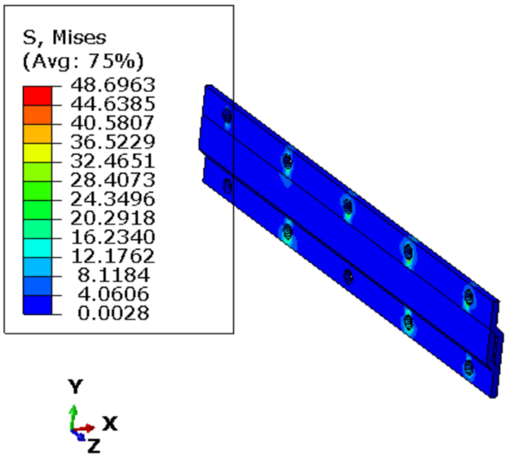


Figure 9.20: Von mises stresses in the connection of the single layered design at F=1.17 kN, with stresses given in MPa

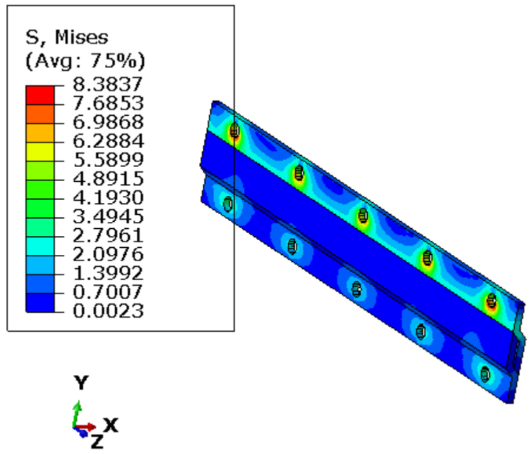


Figure 9.21: Von mises stresses in the connection of the single layered design due to a wind load of 2.21 kN/m^2, with stresses given in MPa

9.3.3. Porous façade

The porous façade is the main interest of this particular analysis. Firstly the obtained results regarding the wind load is presented, which together with the stresses due to self-weight show the safety of the element.

Wind load

This design is also subjected to a wind load of 2.21 kN/m^2 and modeled in the same way as previous analysis. Compressive and tensile stresses observed during the analysis are presented in Figures 9.22 and 9.23. Showing stresses of respectively 0.7 MPa and 0.3 MPa are present in the connection. Occurring deflections in the element are given in Figure 9.24 showing a maximum deflection of 0.22 mm occurs in the middle of the façade.

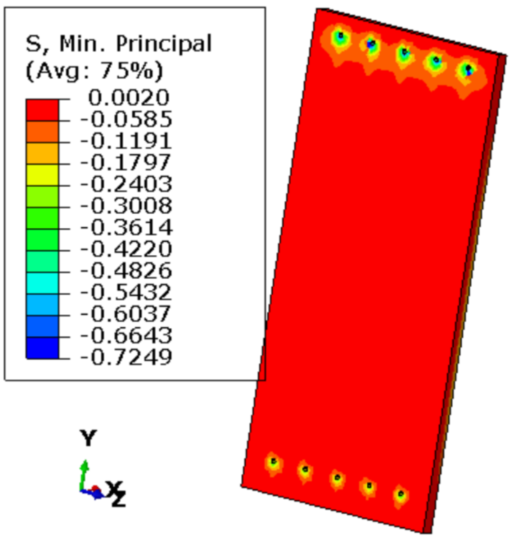


Figure 9.22: Compressive stress of porous concrete due to a wind load of 2.21 kN/m^2, with stresses given in MPa

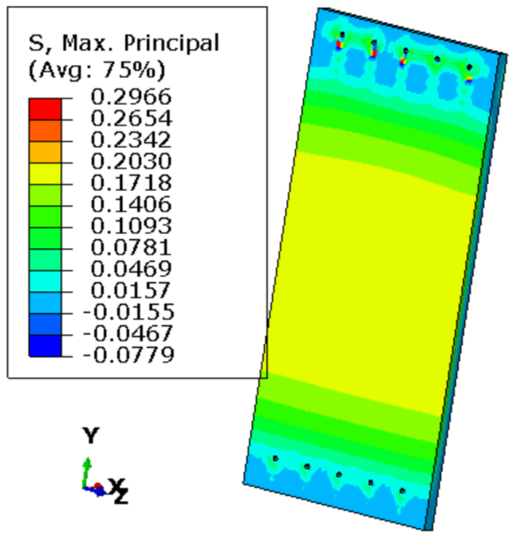


Figure 9.23: Tensile stress of porous concrete due to a wind load of 2.21 kN/m^2, with stresses given in MPa

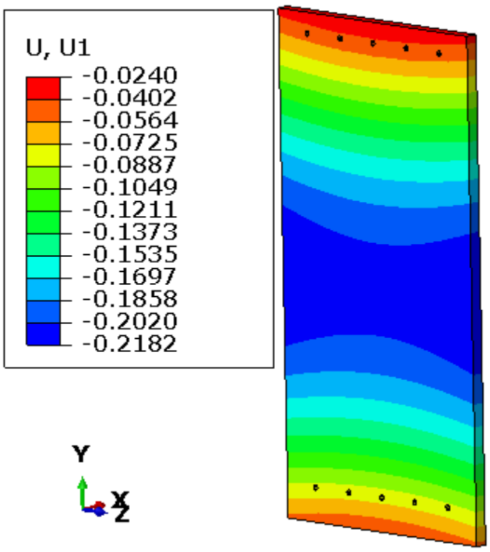


Figure 9.24: Deflection of porous concrete due to a wind load of 2.21 kN/m^2, with deflection given in mm

Self-weight

To check the safety of the porous façade element, the applied forces are obtained at the moment where the maximum compressive and tensile strength are reached when both wind and self-weight induced stresses are combined. In Figures 9.25 and 9.26 it is demonstrated that this limit is reached at respectively forces of 3.20 kN and 1.17 kN.

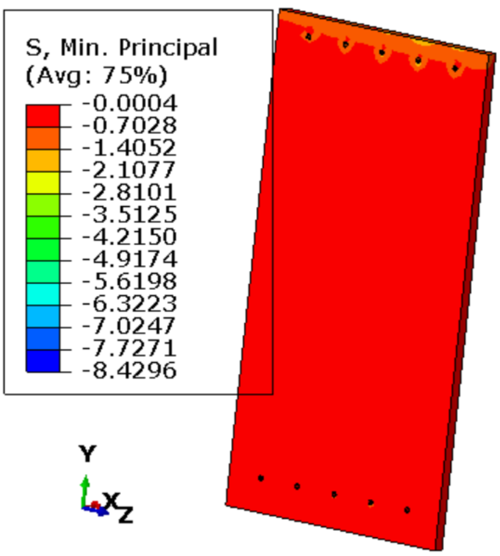


Figure 9.25: Compressive strength limit reached of porous concrete at force of F=3.20 kN, with stresses given in MPa

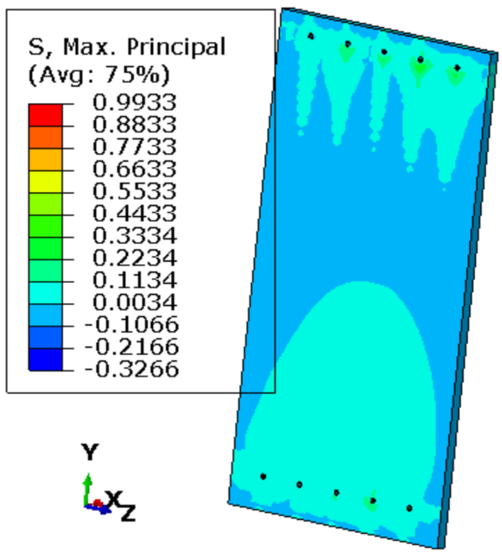


Figure 9.26: Tensile strength limit reached of porous concrete at force of F=1.17 kN, with stresses given in MPa

9.3.4. Pull-out forces

The pull-out forces are determined with the Mises stresses present at the middle of the bolt. These stresses are multiplied with the bolt area. Resulting in a force of 4.49 kN due to a self-weight load of 1.17 kN and a force of 0.97 kN due to the wind load present in the same direction. These two forces combined result in a force of 5.46 kN. However, the self-weight of the façade is 0.4 kN instead of 1.17 kN.

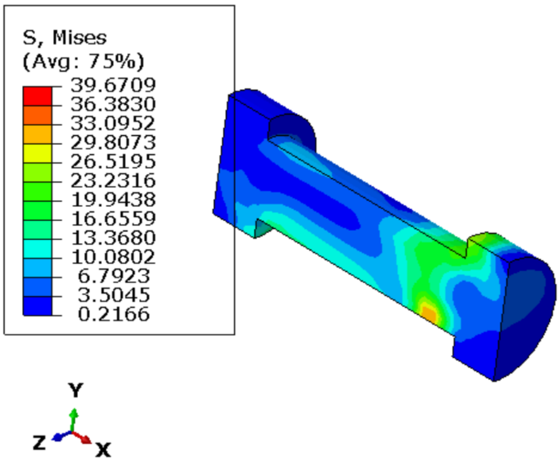


Figure 9.27: Mises stresses in a bolt due to self-weight at a force of 1.17 kN, with stresses given in MPa

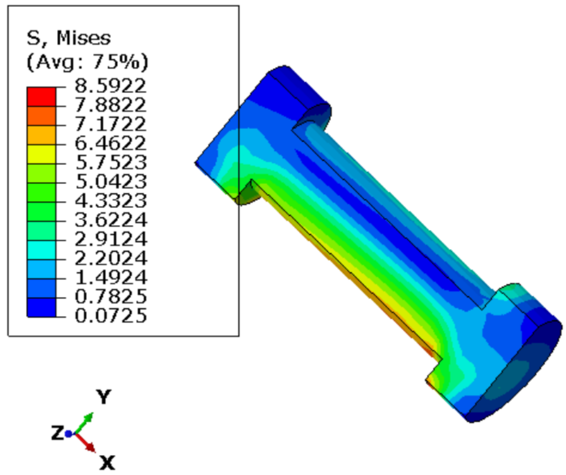


Figure 9.28: Mises stresses in a bolt due to a wind load of 2.21 kN/m^2, with stresses given in MPa

9.3.5. Results

This section analyzed the structural behavior of a single-layered porous façade element. Connection results demonstrate a stress of 57.1 MPa is observed at a self-weight force of 1.17 kN with a wind load of 2.21 kN/m^2. which is 16.1% of the yield strength and 11.6% of the ultimate strength. The results regarding the panel itself are the main interest. The compressive strength is reached at the same wind load with a self-weight of 3.20 kN, while tensile strength limits are reached at a force of 1.17 kN. Therefore, the tensile strength is the limiting factor. With a actual self-weight of 0.371 kN the safety percentage related to respectively the compressive and tensile strength of the porous panel is 11.6 & and 31.7% out of 100%. The deflection observed is 0.218 mm. The obtained value regarding the pull-out forces are of high importance as they are compared to the experimentally obtained pull-out strength. Due to wind and self-weight a pull-out force of 5.46 kN is observed.

9.4. Interpretation of results

It is known that the steel profiles fail at a stress of above 490 MPa. This stress level is never reached under the loads that are applicable to the presented situation. Therefore the results make it clear that the steel parts are sufficiently strong.
Regarding the c20/25 concrete, the governing strengths are the compressive strength of 25 MPa and the tensile strength of 2.21 MPa. The results obtained show that neither of these limits are reached under the applied forces, thus the structural layer is also sufficient. According to Eurocode 13830 the necessary check regarding deformation for façades, is the following: Max deflection allowed for the façade is Length/500. Length here is the distance between the connection points and in the situation of the bi-layered design is equal to 468 mm. Therefore, a deflection of 0.936 mm is allowed. Resulting in a unity check of 0.2, as a deflection of 0.186 mm occurs.
These remarks combined, conclude that the bi-layered system is a viable solution for the application as a green façade. However, it is noted that it is over-dimensioned, which does ask for further optimization of the design. This is discussed in the recommendations section.
Lastly the single layered design, this design has some uncertainties as some material properties are unknown. The results obtained conclude that a single layered design is viable, however it is to be observed that the tensile behavior of the material is unknown and is assumed on observations of a different type of concrete. Also information regarding the damage parameters are unknown and therefore not taken into account in the analysis. The results regarding the structural performance of the porous layer demonstrate a safe design, although some uncertainties remain present at the moment. As it is not determined what the impact of this assumed value is on the results, more research regarding the tensile behavior of the material is advised.

The pull-out forces occurring in the bolts are observed to be at 5.46 kN due to self-weight and wind load. Which is extensively lower compared to the pull-out strength forces of minimally 8.74 kN. Therefore, the value for the unity check is 0.625.

The length used for the deflection check of the porous design is 1068mm. therefore the allowed deflection is 2.136 mm. It is obtained that the deflection is 0.218 mm. Thus the porous façade is assumed safe with a safety percentage of 10.2% according to the Eurocode.[46] A summary of all obtained stress values compared to the material strength is provided in Table 9.4 and Table 9.5 presents the safety checks regarding deflection.

Table 9.4: Obtained stress results from FEM analysis in Abaqus, compared to material strength to obtain the safety percentage. *Safety is given here as a percentage, where values above 100% are deemed unsafe, meaning all values lower than 100% are safe.

Part	Self-weight	Wind load	Strength	Safety
Original connection	33.3 MPa (at F=4.43 kN)	5.4 MPa	490 MPa	7.9%
Optimized connection	51.6 MPa (at F=2.28 kN)	20 MPa	490 MPa	14.6%
Porous connection	48.7 MPa (at F=1.17 kN)	8.4 MPa	490 MPa	11.6%
Bi-layered compressive	22.9 MPa (at F=15.3 kN)	1.2 MPa	25 MPa	2.4%
Bi-layered tensile	1.5 MPa (at F=5.1 kN)	0.5 MPa	2.21 MPa	7.3%
Porous compressive	8.43 MPa (at F=3.20kN)	0.73 MPa	7.9 MPa	11.6%
Porous tensile	0.99 MPa (at F=1.17 kN)	0.3 MPa	1.19 MPa	31.7%
pull-out	4.49 kN (at F = 1.17 kN)	0.97 kN	8.74 kN	62.5%

Table 9.5: Deflection results obtained from Abaqus, compared to Eurocode safety checks

Part	Wind deflection	Allowed deflection	Safety
Bi-layered design	0.186 mm	0.936 mm	20%
Single-layered design	0.218 mm	2.136 mm	10.2%

10
Final design

This chapter presents the final design consisting of two steel rail connections, bolts, irrigation system, structural layer and porous layer. The relevant material properties are discussed here which are determined in previous sections or taken from literature. A complete visualization of the final design is given before the chapter is concluded with a brief result on the installation of the final design.

10.1. Material properties

Concluding this research two final designs are defined: a bi-layered design and a single-layered design. The results from this research confirm the bi-layered system is viable for this application. The single-layered system shows potential, however due to unknown material properties, it is not a proven system yet. Therefore, the bi-layered design is considered as the actual final design. Regarding the materials used for this final design, no changes are made. Therefore, this section summarizes the used materials with its properties.

10.1.1. Structural concrete layer

For the structural layer, conventional C20/25 concrete is used. As the Finite element analysis proved, it is sufficiently strong to ensure structural safety of the design with dimensions of 600 x 600 mm. Table 10.1 gives a summary of the C20/25 concrete material properties.

Table 10.1: Material properties C20/25 concrete (EN1992-1-1)

Material property	Value
Density ρ [kg/m^3]	2600
Unit weight γ [kN/m^3]	25.0
Poisson's ratio ν [-]	0.2
f_{ck} [MPa]	20
$f_{ck,cube}$ [MPa]	25
f_{cm} [MPa]	28
f_{ctm} [MPa]	2.21
E_{cm} [MPa]	29962
Shear modulus G [MPa]	12484

10.1.2. Porous concrete layer

In this thesis two mixtures for the porous concrete layer are mentioned. One mixture is taken from a thesis previously conducted at TU Delft, this mixture provides a compressive strength of 7.9 MPa and makes use of the admixture Cugla Colloidaal 100. Regarding the experimental tests performed during this research, this admixture was not available and assumed not necessary for the proposed tests. This absence of this admixture resulted in a too liquid concrete mixture, due to this the water/cement ratio was adjusted. Tests conducted on this new mixture resulted in different compressive strength values. However it is known that a strength of 7.9 MPa is achievable and this value is therefore used as a material characteristic. Several other properties determined in this research are provided in Table 10.2 together with the mixture components.

Table 10.2: Material properties pervious concrete mix design [14]

Material property	Value
Aggregate type	Lava stone
Aggregate fraction	8 / 16 mm
WCR	0.4
ACR	2
Binder	CEMIII/B 42.5
Modulus of Elasticity [MPa]	12947-15231
Stabilizer	No
Porosity [%]	22
Admixture	Cugla Colloidaal 100
Max water absorption capacity [g/L]	188.8
Max water absorption capacity with coarse soil [g/L]	265.1
Compressive strength [MPa]	7.9
Freeze Thaw cycles after >25% mass loss	53

10.1.3. Bolts

During this research, the bolts were not the main interest. However in the structural analysis standard M12 bolts of grade 8.8. were used for the installation of the connection to the façade and to the existing structure. As it was not part of the research no results were presented in this report. However, in the FE software it is observed that these bolts are sufficiently strong to withstand the applied loads. Some relevant properties are presented in Table 10.3

Table 10.3: Material properties M12 bolt grade 8.8 (EN-1993-1-8)

Material property	Value
Diameter [mm]	12
Nut width [mm]	18
Yield strength f_{yb} [MPa]	640
Ultimate tensile strength f_{ub} [MPa]	800
Hole diameter [mm]	13
Area unthreaded A_g [mm^2]	113
Stress area threaded A_s [mm^2]	84.3
Tensile resistance $F_{t,Rd}$ [kN]	48.6
Shear resistance per shear plane $F_{v,Rd}$ [kN]	32.4
Max bearing resistance of connected plate $F_{b,Rd}/t$ [kN/mm]	11.76
Min bearing resistance of connected plate $F_{b,Rd}/t$ [kN/mm]	3.12
Punching resistance of plate thickness under bolt or nut $B_{p,Rd}/t_p$ [kN/mm]	14.33

10.1.4. Steel S355 profile

The steel profile used is of standard S355 grade. The optimized dimensions, are presented one more time in Figure 10.1. This steel profile is applied at top and bottom of both the existing structure and the green façade. Its material properties are presented in Table 10.4. FE results provided proof that this connection design with these dimensions and properties is sufficiently strong to withstand all the applied forces that are relevant for a façade element. Appendix F discusses the production of the connection.

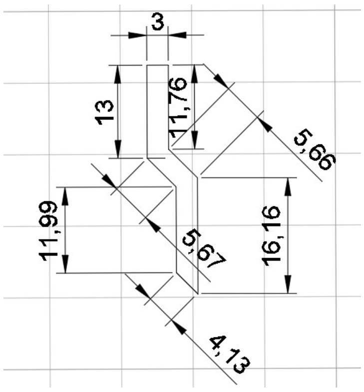


Figure 10.1: Connection dimensions of optimized design in mm

Table 10.4: Material Design Properties for Structural Steel S355 according to EN1993-1-1

Material property	Value
Density ρ [kg/m^3]	7850
Modulus of Elasticity [MPa]	210000
Shear modulus [MPa]	81000
Yield strength [MPa]	355
Ultimate strength [MPa]	490
Poisson's ratio	0.30

10.2. Final design

This section presents the final design, consisting of two rail connections on each panel and two on the existing wall. Figure 10.2 visualizes how the system looks on a masonry wall. For a better understanding, the connection and irrigation system are left visible on the side. After installation of the connection on the existing wall and on the green façade the panel is hung onto it. To encounter for irregularities, the holes in the connection pieces are slotted to ensure flexibility of the connection. Irrigation pipes are possibly installed directly onto the existing or onto the back of the façade panel by specific clips used for pipe installations.

Figure 10.2: Front view of final design installed on a masonry wall

Figure 10.3: Back view of final design

IV

Discussion, Conclusion & Recommendations

11

Discussion, conclusion and recommendations

This chapter concludes this thesis. Section 11.1 starts a discussion regarding the assumptions made in this research and discusses the results obtained in relation to information taken from literature and the research questions. Section 11.2 addresses the conclusions, and the chapter is concluded by Section 11.3 which presents the recommendations for further research.

11.1. Discussion

This section addresses the assumptions made and the method used to get to the obtained results. It relates the results to literature and links back to the research questions, finally it mentions the limitations of the research.

11.1.1. Assumptions, boundaries & methodology

This thesis aimed to design a demountable Living Concrete wall element, comprising a demountable connection, a porous layer and, if necessary, a structural layer. To achieve this, both layers are addressed. With respect to the structural layer, considerations included reducing its weight and size to increase efficiency during the (de)mounting process or leaving out the structural layer completely. The primary focus was on the porous layer and the connection between the two layers. It reviewed the possibility of reducing the dimensions of both layers and analyzed several connection types.

This research introduced the concept of reducing the weight and size of living façade elements, for them to be more suitable for demountability. The purpose of this approach, is that by minimizing the weight, it becomes possible to install and demount the elements manually. As a result, the first design requirement is set: the weight should be reduced to the maximum weight allowed to be lifted by two persons. However, it is up for discussion whether this weight limit is a necessary boundary condition, as many solutions are available today for the installation and demounting of elements heavier than the mentioned weight. Due to this boundary condition, the designs are over-dimensioned. If the dimensions and thus weight were increased, a larger vertical area of a building is potentially covered by a single panel. Motivation for this boundary condition is the fact that no heavy machines are required for a possible disassembly, increasing the speed of the process while reducing its costs. Although this boundary condition is questionable, it did address the first two sub-research questions:
Sub-question 1: *How can modifications to the shape, dimensions and weight of the individual layers of the Layered Living Concrete element improve its (de)mountability while maintaining its bio-receptive properties and structural integrity?*

The dimensions of the panels were reduced to comply with the lifting weight limit. As it is assumed this modification makes it more suitable for demountability due to the previous mentioned motivation. It adds value to the panel in that aspect. Additionally, the reduction in size did not negatively impact the bio-receptivity properties, as the thickness is sufficient to accommodate space for the soil.

Sub-question 2: *What is the optimal size of the wall element to ensure its suitability as a demountable green wall component, in such a way that individual elements are easy to replace, while considering efficient production and Installation?*

Regarding production, it is established that for the production of rectangular panels, dimensions of multiples of 300 or 400 mm are preferred. On top of that, from literature it is determined that common grid sizes used for the width of structures in cities are multiplications of 600 mm. Height of structures are less standardized, however multiplications of 600 and 1200 are observed. Therefore, dimensions of 600 x 600 mm and 600 x 1200 mm are optimal for the application as a living wall element, as these sizes results in a weight that is close to the lifting limit. It is realized that sizes of 600 x 600 mm mean that production of multiple panels at the same moment is not possible, as a space in between panels is required during production. However, matching dimensions with building grid sizes is ranked more valuable and is therefore prioritized.

Lastly an answer to sub-question 4 was found by performing a multi-criteria analysis, to compare several proposed connection designs.

Sub-question 4: *Which type of connections are suitable for the attachment of a vertical green wall element to a building structure?*

The MCA identified the steel rail system as the best performing design. However, it is worth noting that one other design, namely the bolted connection, got ranked a comparable score. To ensure the appropriate design was selected for further analysis, a sensitivity analysis was performed, confirming that the steel rail design was the optimal choice. However, the scores were so close to each other that it is up for discussion whether both design could be suitable. Therefore, recommendations for further research are given in section 11.3.

11.1.2. Limitations

To answer sub-questions 3, a structural analysis was conducted to gain insights in the structural behavior of a single porous layered element. For this analysis, basic material properties were required to be implemented in the Finite Element software, therefore two experimental test were performed.

Sub-question 3: *To what extent can the porous front layer achieve sufficient strength without relying on a structural back layer, in order to enable the front layer to be demountable?*

As concluded from the structural analysis, a single porous layer is capable of achieving sufficient strength on its own. Based on the comparison between the experimental tests regarding the pull-out strength and the ocurring forces around the bolts, it is feasibily to install a connection directly onto the porous layer. However, some limitation regarding this conclusion is considered. While the determined material properties did provide more insight into the material behavior, they did not provide information regarding all the relevant material characteristics. For example information regarding tensile behavior and damage parameters is missing. This research question is answered based on the obtained results, however it is noted that not the complete material behavior is taken into consideration while obtaining these results. Because of this limitation it is further mentioned in the recommendation section.
Furthermore, regarding the porous layer, in this research it was assumed that the porous layer does not contribute to the structural stability of the bi-layered design. Since not all material properties of the porous concrete are determined, this assumption can not be verified. Consequently, the structural analysis of the bi-layered system was performed based solely on the structural contribution of the c20/25 concrete layer. While it is a useful approach, it may not reflect the complete realistic structural behavior of the system. To perform a more realistic analysis, both layers need to be modeled and more information regarding the interaction between both layers is necessary.

Regarding the finite element analysis another limitation is to be discussed. Since the bolts were not the main focus of the analysis, they were not modeled in detail. Therefore, no pretension was applied to the bolts, which resulted in the entire system to displace downwards until the bolts made contact with the other materials. This is encountered by subtracting this initial displacement from the obtained results. As the analysis focuses on the behavior of the other materials, it does not influence the results significantly. However, it may have a minor impact on the final results, as the bolts can potentially take up more forces and the initial displacement would not have been present or be reduced.

A final limitation is to be addressed and regards the experimental test conducted to determine the pull-out strength. This test aimed to compare two methods of incorporating a reinforcement bar into porous concrete cubes, namely drilled holes and cast-in tubes to create holes. A limitation in this comparison comes from the fact that the holes were filled, with a strong cement mixture, at two separate moments. At the first moment it was observed that the mixture was too liquid, therefore the mixture was adjusted for the second casting moment. This was done to make sure the testing conditions of at least one of the sets was suitable to obtain useful realistic results regarding the porous concrete behavior. Due to this, the cement mixtures were not identical. As a consequence, the cast-in holes which were filled with a slightly more liquid mixture, resulted in having more outflow of this mixture into the voids of the porous concrete. The influence of this outflow on the results is uncertain. One possible outcome of this outflow is that the porous material could gain a higher strength, as the cement mixture has a higher strength compared to the porous material. However, the results do not support this hypothesis, as the pull-out strength of the drilled in holes were higher compared to the cast-in holes. This observation is potentially explained by the second consequence of the outflow, which is that the holes of the cast-in samples were not completely filled with cement until the top of the cubes, resulting in a smaller length of the reinforcement bar being covered by cement. Therefore, this potentially led to higher local stresses due to a decreased surface area of cement in contact with the reinforcement bar, causing the concrete to fail at a lower applied force. This hypothesis is more plausible, as the cast-in cubes did fail at a lower applied force. However, this can not be determined with complete certainty and further research is advised as mentioned in section 11.3. As a result of the change in cement mixture for the second set of tests, it is not possible anymore to compare the two connection methods and thereby limiting the purpose of this performed tests. However, the decision was made to ensure at least one of the two sets were cast in a correct manner, to ensure useful results are produced.

11.1.3. Relation to existing literature

In literature it is found that irrigation water is lost due to the fact that the porous concrete allows almost free flow of water, and the water is lost filtering through the pervious concrete. This specific paper recommends to install their 'bio-booster', a material similar to soil, directly onto the structural back layer, to prevent the loss of water [11]. This recommendation presented by the author, raises the question regarding the consequences for a panel without a structural layer. This allows water to flow out of the panel on each side. A possible solution is to install a thin impermeable layer at the back of the porous façade, however it may be necessary to research the impact of a single layered design on the behavior of irrigation water to find suitable solutions to this problem.

A specific paper mentioned that current living wall systems are often constructed out of materials with shorter lifespans than the buildings they are attached to, and they are made as light as possible to reduce their weight. Due to this their life cycle is limited, and therefore does not match with the life cycle of the building. To address this the author intents to integrate the living wall function into the façade, to match the life cycle of the living wall to that of the building [9]. This implicates that porous concrete is used, instead of for example felt based systems, to have the same life span as the building. This raises the following question: is a demountable design necessary for a porous concrete living wall, as it is intended to have the same life span as the building? Since such walls will therefore not have to be demounted during its service life. Instead, perhaps existing demountable system found in literature, constructed out of light-weight materials like EPP are more applicable for a replaceable purpose. Perhaps the porous concrete designs are left for the more permanent cases. On the contrary, a demountable design for a porous living wall could still be beneficial. It could provide the potential reuse of the living wall after the end of the building's life cycle, assuming that the life span of the porous design would allow this.

11.2. Conclusion

In this thesis green façade element designs were developed constructed out of porous concrete material. For each element design a suitable demountable connection is applied. After a multi-criteria analysis one final design was selected for further analysis in Finite element software. This final design is applied with a structural concrete back layer and without this layer. The porous concrete mixture used consist of lava stone 8/16 mm as aggregate, with CEM III/B 42.5 as binder. For correct application in FEM, practical tests of the Young's modulus are performed. Regarding the design with a single layer, critical area consists of the connection between bolt and porous concrete, therefore another practical test is performed regarding the pull-out strength of that combination. The following main conclusions can be drawn from the research.

Conclusion - Bi-layer suitable as demountable design

- **Main conclusion:** The results obtained in this thesis demonstrate that a structural layer composed of c20/25 concrete possesses the capacity to withstand the required forces acting on a 600 x 600 mm façade element installed on a low-rise building situated in wind area I of the Netherlands. Results demonstrate its safety by showing that forces of 14.6% of the strength of the steel connection are applied. Regarding the bi-layered panel the tensile strength is the limiting factor which only has to withstand a force of 7.3% of its ultimate tensile strength. Deflection of the panel caused by wind is only 20% of the maximum allowed deflection.
- The thickness of the structural layer is safely reduced to 20 mm which represents the minimum required thickness for the application of a bolt anchor. While the thickness of the porous layer is reduced to 30 mm, which is done without influencing the bio-receptive properties of the layer. These thickness reductions reduced the weight of a single panel to a weight which is within the limits two persons are allowed to carry.
- The above mentioned conclusions combined together conclude that a bi-layered system is a capable and structurally safe solution for the application as a light-weight demountable green façade element.

Conclusion - Single porous layer as demountable design

- **Main conclusion:** The findings of this research conclude that the implementation of a single porous layer design for a green façade is feasible, based on the obtained results. Determined safety checks regarding this design are 62.5% for the pull-out strength, 31.7% for the tensile strength (which is governing over the compressive strength and 10.2% regarding the deflection. All percentages are out of 100% which is the maximum limit for safety. As discussed in Section 11.1 some remarks are made regarding the results, however with the information available at this moment, it is concluded that the single porous layer is feasible. To confirm this conclusion further it requires evaluation regarding the missing material properties, as addressed in the recommendations section.
- This layer can, considering the structural performance, be reduced to 30 mm thickness. This conclusion is supported by previous research, which demonstrates that the soil used to fill the voids does not penetrate deeper than 30 mm. Consequently, this reduction of thickness is also feasible from the perspective of bio-receptivity.

Conclusion - Porous concrete material

- **Main conclusion:** Based on results obtained from experimental tests and Finite Element Analysis and compared to values taken from Eurocode, porous material behaves different compared to conventional concretes. Equations taken from Eurocode, if applied to porous concrete, do not match with values found in experiments.
- The material properties, including Young's modulus and pull-out strength, determined through experimental testing in this thesis, are adequate for the proposed application. However, as previously mentioned material properties regarding tensile and damage behavior remain unknown, which requires further investigation as is further addressed in the recommendation section.

Conclusion - Steel rail connection

- **Main conclusion:** The proposed steel rail connection has demonstrated to be suitable for use as a demountable connection in a living green wall. Where a safety percentage of 14.6% is observed, it effectively withstands all required forces and facilitates an efficient installation and demounting process.

Final conclusion

- Goal of this thesis was to determine the possibility of a modular, easy demountable system for green façade systems constructed out of porous concrete. The conventional systems consist of a bi-layered system. Results obtained in this research demonstrate that such a system is easily transferred into a demountable product, by applying simple and existing solutions.
- To take the research a step further, it introduced a new application for the porous concrete, in the form of a single-layered system. A single layered panel has a reduced weight, having a positive impact on the installation of the system and provides the option to increase the dimensions of the panels. Results from this thesis conclude that such a system is realized with the same simple solutions.
- This thesis has addressed several connection types, concluding that the final design is feasible for the proposed purpose. However, this conclusion does not imply that the proposed connection represent the most optimal or efficient solutions. Concluded from this research is that several of the other proposed connections received high scores based on the MCA criteria, showing their potential.

11.3. Recommendations

This research answers relevant questions regarding the possibilities of a porous demountable façade element. However, some questions remain unanswered and especially new questions have emerged. Therefore, the following recommendations are given for future research.

Recommendations - Compressive strength & Young's modulus
For the practical tests, an existing mixture for porous concrete has been used, however it was slightly adjusted based on available materials. The mix comes from a research conducted last year. Values regarding the compressive strength are also taken from that same research. However, during testing of the Young's Modulus, a significant lower compressive strength was observed. It can be of great interest to research why this difference occurs. In a possible future research it is advised to conduct own compressive tests for cubes, as in this situation the difference potentially occurs due to several reasons. The adjusted concrete mixture is a potential cause, also the fact that the tests were performed on rectangular shapes instead of cubes. Due to many different possible causes it is advised to ensure information is available of the exact samples used for testing.
This compressive strength can have indirect impact on the determined Young's modulus, it is therefore interesting to determine if a different value for the Young's modulus was determined in case the exact samples found in previous research were used. Besides, the results regarding the E-modulus, have shown to vary significantly. It is therefore interesting to determine what causes this difference and how to ensure a more homogeneous behavior of the material.

Recommendations - Designs
In this research, based on the suitability of connection types which comply with the design requirements, four designs were made from which a best performing design was picked. However, numerous different solutions for either connection or element exists and can therefore be designed. Although this research focused on the possibility of a demountable design, rather than finding the optimal solution, in a possible future research, where to goal is to develop a product, a more extensive design study is recommended.

Recommendations - Mock-up production
After the performance of Finite Element Analysis, a reasonable next step, is to produce actual size mock-ups. These mock-ups can be used to perform structural tests to validate the FEM model with real data. It can also give more insight in practical solutions for the connection system, as it can be tested extensively.

Recommendations - Single-layered porous design
This thesis structurally analyzed the capability of façade elements to withstand the forces applied to it, when it is installed in its final location. However, it does not encounter for the safety of the panel before its installation. Especially the single layered porous element, which is relatively thin and misses the stability provided by a structural back layer, is potentially damaged during transportation or installation. Taking this into consideration, further research is advised regarding the stability of the panels and it to find solutions to guarantee a safe transportation and installation. Potential solutions are, increasing its strength or thickness, or temporary stability frames which are used until final installation.

Recommendations - (High strength) porous concrete
A conclusion to the proposed research, is that a porous concrete design is feasible, however several questions have been raised. Literature proves the existence of high strength porous concrete, it is recommended to further research the characteristics of the porous concrete. If it is to be concluded that the material is not sufficiently strong to realize a single layered porous façade, research regarding high strength porous concrete is recommended. It is determined from literature that such mixtures exists. However, it is yet to be determined what the impact of these mixtures is on the bio-receptivity of the porous concrete, and if it even is suitable for the application as a green façade. Further research regarding this topic is recommended, as it can provide new insights in the development of green façades. Furthermore, the impact of a single layer on the irrigation water is recommended for further investigation as mentioned in section 11.1.

Recommendations - Pull-out strength

In this research to determine the pull-out strength of bolts cast into porous concrete, 10 by 10 cm cubes are used. It is determined that the failure mechanism of these cubes is the cracking of the surrounding porous material. It is interesting to research the contribution of the porous concrete to the pull-out strength if more coverage is present. Therefore a research with bigger cubes is recommended as the thickness and edge distance contribute to its strength. Furthermore, pull-out tests of mock-ups is recommended, as the final design will have more porous concrete cover surrounding the bolt, however the elements are significantly thinner. The consequences of this on the pull-out strength should be determined as it can provide important knowledge regarding a realistic situation.
On top of this, it is important to ensure equal conditions. Therefore, it is advised to cast in the reinforcement bars at the same moment with the same mixture. In this research it was done on two separate days, therefore the mixture for the Cast-in samples was more liquid compared to the one for the Drilled-in samples. It is difficult to determine the influence of this error on the results.

Recommendations - Material properties porous concrete

For further precise analysis of a single layered porous design, more material characteristics of the porous concrete have to be determined. Much is known about conventional concrete, such as plastic behavior, compressive strength, tensile strength, Young's modulus and friction coefficients. This information is of high important to correctly model the behavior of porous concrete in Finite Element software and research is therefore recommended. In this research the tensile strength of the porous material is assumed based on equations provided in Eurocode, related to conventional concrete. However, from this research it is concluded that the porous material behaves differently compared to conventional concrete types, as is seen in the obtained Young's modulus. Therefore, the assumed tensile strength is likely unrealistic and should be determined by experimental tests in a future research.

Recommendations - FEM analysis

Regarding the validation of the FE model, performing physical structural tests is an advised next step to compare the obtained results to a real life situation. It is concluded that the design is over-dimensioned, therefore a next step is to adjust the design to find the limits. Several options are available, a few are mentioned here. Firstly the design criteria of having the possibility to install the element by hand is potentially lifted. This means that the weight limit is lifted and therefore bigger dimensions can be used for the panels. This requires more strength from the connection, making it less over-dimensioned. Another option is to make the decision to use a better suited connection material, such as aluminum, or decrease the dimensions further.

Recommendations - Multi-criteria analysis

Two designs are ranked almost equally well in the MCA. Therefore it is recommended, for further research, to also continue the FEM analysis with design 1. This can provide a better comparison between both design. On top of that, some criteria are based on assumptions, such as costs and production steps for example. It is recommended to perform a full analysis on these criteria, to provide for more information which can be used for a more thoroughly investigated MCA, which is less prone to errors. Based on the conclusions drawn in this research, more design options are potentially created and therefore a new design sequence is advised based on these results.

Recommendations - Installation final design connection

The connection used in the final design consists of two parts, one attached to an existing structure and one to the green façade. As this is installed at top and bottom of the panel, a good alignment is required, which is possibly hindered by production imperfections. To account for these imperfections slotted holes in both connection parts are to be installed. This provides more tolerance to accompany for a perfect fit.

Recommendations - Installation on existing structures

As the proposed design are suitable for new and existing structures, recommendations regarding the installation on existing structures are necessary. In any proposed installation a specific investigation of the capability of the existing structure is required. As extra weight is added to the structure, a structural safety analysis regarding any type of wall is to be performed.

A

Appendix: Wind load

This appendix provides additional information regarding the determined wind load on the structure in the most challenging situation in the Netherlands: wind area I for terrain category 0.

Z_0 = 0.005 m Z_{min} = 1 m Assumed is flat terrain meaning $C_0(z)$ and k_i = 1.0 As a result $C_e(z)$ = 3.0.

h/b = 1 as the shape of the building is assumed as a cube of 10 x 10 x 10 m.
So e = b and Z_e = 10 m.

The effects of wind friction on the surface is disregarded as the total area of surfaces parallel and perpendicular to the wind are equal to each other.

wind pressure on external surfaces is calculated with Equation A.1

$$W_e = Qp_{Ze} * C_{pe} \quad (A.1)$$

where $Q_p(Z_e)$ = 1.58 kN/m^2 at C_0 = 1
$C_{pe,1}$ and $C_{pe,10}$ are according to Table A.1
Resulting in:
$W_{e,A} = -2.21$ kN/m^2 $W_{e,B} = -1.74$ kN/m^2 $W_{e,D} = 1.58$ kN/m^2 and $W_{e,E} = -0.79$ kN/m^2

Where A,B,D and E area the building zones orientated to the wind, D is windward, E is leeward, A and B area the side area as presented in Figure A.1

wind pressure on internal surfaces are calculated with Equation A.2

$$W_i = Qp_{Zi} * C_{pi} \quad (A.2)$$

The internal pressure coefficient depends on the distribution of openings over the building façade. It is assumed that each façade, so all four directions, have the same an equal area of openings. Therefore $C_{pi} = -0.22$
So $W_i = 1.58 * -0.22 = -0.3476$ kN/m^2

For façades, the wind force becomes equal to the difference between the external and internal resulting forces. Where the internal and external forces are calculated with Equations A.3 and A.4. Where $C_sC_d = 1$. However in this situation the internal pressure is equal to 0, as the green façade is not in direct contact with the internal environment. With previously mentioned equations the wind forces on the façade elements is calculated relative to varying reference areas.

$$F_{w,e} = C_sC_d * \sum * W_e * A_{ref} \quad (A.3)$$

$$F_{w,i} = \sum *W_i * A_{ref} \tag{A.4}$$

Table A.1: External pressure coefficients for vertical walls of rectangular plan buildings according to EN-1991-1-4

Zone	**A**		**B**		**C**		**D**		**E**	
h/d	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$
5	-1.2	-1.4	-0.8	-1.1	-0.5	-0.5	+0.8	+1.0	-0.7	-0.7
1	-1.2	-1.4	-0.8	-1.1	-0.5	-0.5	+0.8	+1.0	-0.5	-0.5
$\leq$ **0.25**	-1.2	-1.4	-0.8	-1.1	-0.5	-0.5	+0.7	+1.0	-0.3	-0.3

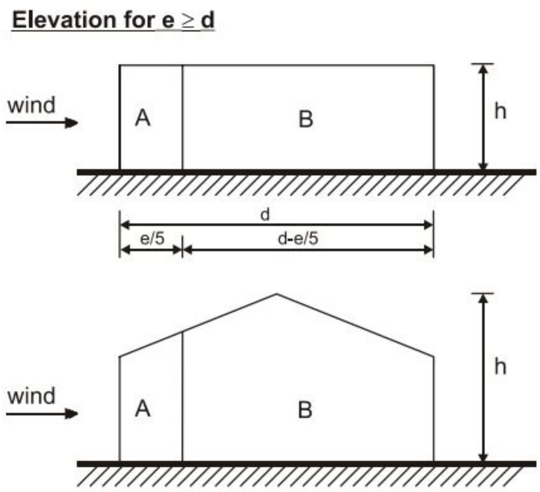


Figure A.1: Vertical wall building zones according to EN-1991-1-4

B

Appendix: Multi-criteria analysis

B.1. Weights of criteria

Table B.1: Influencing factors to rate each design option per sub-criteria

sub-criteria	factors
[1a] Weight of design	weight of design
[1b] thickness of design	thickness of design
[1c] dimensions of design	bigger area means faster installation of complete façade
[2a] production costs	Special equipment needed
	labor intensity
[2b] material costs	costs of material
[2c] Environmental costs	mki-value of materials
[3a] production complexity	amount of production steps
	difficulty of production steps
[3b] transportion complexity	transportability of element dimensions
	weight of design
	size of design
[3c] installation complexity	ease of installation
	required labor time
	safety and accessibility requirements
	Irrigation installation
[4a] area of greenery	full area of element minus parts which will not be covered by plants
[4b] connection visible	visability of connection parts
[5a] connection complexity	amount of different parts
	necessary tools
[5b] reachability of connection	ease of reaching the installation
[5c] Load transfer efficiency	Effectiveness of load fransfer from façade element to main structure

Table B.2: Weight of each sub-criteria

sub-criteria	subtotal weight	score	weight
[1a] Weight of design	1.5	0.5	0.033
[1b] thickness of design		0.5	0.033
[1c] dimensions of design		0.5	0.033
[2a] production costs	4	1.5	0.1
[2b] material costs		1.5	0.1
[2c] Environmental costs		1	0.067
[3a] production complexity	4	1.33	0.089
[3b] transportion complexity		1.33	0.089
[3c] installation complexity		1.33	0.089
[4a] area of greenery	1.5	1	0.067
[4b] connection visible		0.5	0.033
[5a] connection complexity	4	1	0.067
[5b] reachability of connection		1.5	0.1
[5c] load transfer efficiency		1.5	0.1

B.2. Performance of designs

Table B.3: Performance of design 1 with a direct bolted connection

sub-criteria	Performance
[1a] Weight of design	Besides the standard weight of the concrete, no extra weight is added by the connection except for the small addition of weight by the four bolts.
[1b] thickness of design	The thickness of the design is only depending on the thickness of each layer, the connection does not add any thickness to the design.
[1c] dimensions of design	The dimensions of the system are equal to the maximum dimensions related to a bi-layer system, (0.6 x 0.6 m)
[2a] production costs	To produce this design no extra specific equipment is required, just a mall of the mentioned dimensions with 4 holes in both layers. four extra holes have to be drilled into the existing/new structure.
[2b] material costs	besides the costs for both layers, only the costs of four bolts are present
[2c] Environmental costs	Considerably low as besides the standard concrete, only four bolts are added.
[3a] production complexity	The porous layer has to be produced first, where the structural layer will be casted onto it in a later step. Steps are conventional and do not require any new technique
[3b] transportion complexity	As dimensions will never become the limiting factor for transport, the weight can influence the amount of elements that can be transported The weight of this design, is equal to the weight of both layers and the weight of four bolts. The element easily fits on a standard trailer used for the transport of construc-trion materials.
[3c] installation complexity	Installation of the proposed design is straightforward, it can either be installed on to the main structure immediately in the factory, in case of new buildings. In case of application on existing buildings, the elements need to be installed on side. Which can easilily be done with 2-3 persons with a small lifting machine Installation of the irrigation system, is more complicated as there is no available space behind the element. Meaning the irrigation needs to be installed in front or in between elements. holes in the main structure need to be drilled
[4a] area of greenery	Due to the difficulties with the irrigation system and the connection being in front of the element, it can not provide a full green area. However it will still cover most of the wall.
[4b] connection visible	The four bolts will be visible on the front side of the design
[5a] connection complexity	no extra parts beside the element and bolts no specific tools required for installation beside a standard wrench.
[5b] reachability of connection	Connection is easily reachable as it is free accessable at the front of the design.
[5c] Load transfer efficiency	The load is transfered at four different points by bolts to the main structure.

Table B.4: Performance of design 2 with a indirect bolted connection

sub-criteria	Performance
[1a] Weight of design	Besides the standard weight of the concrete, weight of eight corner pieces and twelve bolts are added to the design
[1b] thickness of design	Besides the thickness of the two layers, the connection adds an extra 100mm thickness to the system. This 100mm consists mostly of open area.
[1c] dimensions of design	The dimensions of the system are equal to the maximum dimensions related to a bi-layer system, (0.6 x 0.6 m)
[2a] production costs	To produce this design no extra specific equipment is required, just a mall of the mentioned dimensions where four anchors can be casted in. four extra holes have to be drilled into the existing/new structure.
[2b] material costs	besides the costs for both layers, the costs of eight corner pieces and twelve bolts are present
[2c] Environmental costs	Compared to previous design slightly higher due to the extra material of bolts and corner pieces
[3a] production complexity	The porous layer has to be produced first, where the structural layer will be casted onto it in a later step. Steps are conventional and do not require any new technique
[3b] transportion complexity	As dimensions will never become the limiting factor for transport, the weight can influence the amount of elements that can be transported The weight of this design, is equal to the weight of both layers and the weight of twelve bolts and 8 corner pieces. The element easily fits on a standard trailer used for the transport of constructrion materials.
[3c] installation complexity	Installation of the proposed design is straightforward, it can either be installed on to the main structure immediately in the factory, in case of new buildings. In case of application on existing buildings, the elements need to be installed on site. Which can easilily be done with 2-3 persons with a small lifting machine Installation of the irrigation system is straightforward as the design provides room behind the element. It can be pre-installed in the factory and connected on site. holes in the main structure need to be drilled and corner pieces need to be attached
[4a] area of greenery	To ensure reachability of the connection, some area on the sides and/or above the elements need to be kept open. Meaning not a full area is provided.
[4b] connection visible	Connection will be completely on the backside of the element and therefore be out of sight.
[5a] connection complexity	besides the element and bolts it consists of eight equal corner pieces no specific tools required for installation beside a standard wrench.
[5b] reachability of connection	Connection is not easily reachable as it is installed in the back of the element, to keep a high area of greenery the reachability of the connection is kept to a minimum
[5c] Load transfer efficiency	The load is transfered at four different points by bolts and connection pieces to the main structure.

Table B.5: Performance of design 3 with a Plug-and-play hang connection

sub-criteria	**Performance**
[1a] Weight of design	Besides the standard weight of the concrete, weight of four connection pieces and two heavy rails are added to the design with ten bolts
[1b] thickness of design	Besides the thickness of the two layers, the connection adds an extra 100mm thickness to the system. This 100mm consists mostly of open area.
[1c] dimensions of design	The dimensions of the system are equal to the maximum dimensions related to a bi-layer system, (0.6 x 0.6 m)
[2a] production costs	To produce this design no extra specific equipment is required, just a mall of the mentioned dimensions where four anchors can be casted in. six extra holes have to be drilled into the existing/new structure.
[2b] material costs	besides the costs for both layers, the costs of the four connection pieces, two heavy rails and ten bolts are present.
[2c] Environmental costs	Due to the extra material of bolts, rails and connection pieces it contains relatively many extra parts. Which has a unfavorable result on the environmental costs.
[3a] production complexity	The porous layer has to be produced first, where the structural layer will be casted onto it in a later step. Steps are conventional and do not require any new technique
[3b] transportion complexity	As dimensions will never become the limiting factor for transport, the weight can influence the amount of elements that can be transported The weight of this design, is equal to the weight of both layers and the weight of ten bolts, four connection pieces and two rails The element easily fits on a standard trailer used for the transport of constructrion materials.
[3c] installation complexity	Installation of the proposed design is straightforward, it can either be installed on to the main structure immediately in the factory, in case of new buildings. In case of application on existing buildings, the elements need to be installed on site. Which can easilily be done with 2-3 persons with a small lifting machine Installation of the irrigation system is straightforward as the design provides room behind the element. It can be pre-installed in the factory and connected on site. holes in the main structure need to be drilled and rails need to be attached
[4a] area of greenery	To be able to lift the element out of the rails, only a small area needs to be kept free above the elements, providing a almost completely covered green wall
[4b] connection visible	Connection will be completely on the backside of the element and therefore be out of sight.
[5a] connection complexity	besides the element it consists 10 bolts, four connection pieces and two rails no specific tools required for installation beside a standard wrench.
[5b] reachability of connection	Connection is not easily reachable, but also not required as the element can be lifted out of the connection from the front
[5c] Load transfer efficiency	The load is transfered at four different points by bolts and connection pieces through the rails to the main structure.

Table B.6: Performance of design 4 with a Plug-and-play rail connection

sub-criteria	**Performance**
[1a] Weight of design	Besides the standard weight of the concrete, weight of four connection rails and 12 bolts are added
[1b] thickness of design	Besides the thickness of the two layers, the connection adds an minimum of 6 mm thickness to the system. This 6 mm consists mostly of open area and can be increased by increasing the thickness of the connection
[1c] dimensions of design	The dimensions of the system are equal to the maximum dimensions related to a bi-layer system, (0.6 x 0.6 m)
[2a] production costs	To produce this design no extra specific equipment is required, just a mall of the mentioned dimensions where six anchors can be casted in. six extra holes have to be drilled into the existing/new structure.
[2b] material costs	besides the costs for both layers, the costs of the four connection rails and twelve bolts are present
[2c] Environmental costs	Several extra bolts are needed, besides that four thin rails contribute to the environmental costs.
[3a] production complexity	The porous layer has to be produced first, where the structural layer will be casted onto it in a later step. Steps are conventional and do not require any new technique
[3b] transportation complexity	As dimensions will never become the limiting factor for transport, the weight can influence the amount of elements that can be transported The weight of this design, is equal to the weight of both layers and the weight of twelve bolts and four rails The element easily fits on a standard trailer used for the transport of constructrion materials.
[3c] installation complexity	Installation of the proposed design is straightforward, it can either be installed on to the main structure immediately in the factory, in case of new buildings. In case of application on existing buildings, the elements need to be installed on site. Which can easilily be done with 2-3 persons with a small lifting machine Installation of the irrigation system is straightforward as the design provides room behind the element. It can be pre-installed in the factory and connected on site. holes in the main structure need to be drilled and rails need to be attached
[4a] area of greenery	To be able to lift the element out of the rails, only a small area needs to be kept free above the elements, providing a almost completely covered green wall
[4b] connection visible	Connection will be completely on the backside of the element and therefore be out of sight.
[5a] connection complexity	besides the element it consists of twelve bolts and four connetion rails no specific tools required for installation beside a standard wrench.
[5b] reachability of connection	Connection is not easily reachable, but also not required as the element can be lifted out of the connection from the front
[5c] Load transfer efficiency	The load is transfered at two lines, at the top and bottom of the element, by the rails to the main structure. This provides a great load distribution

B.3. Sensitivity analysis MCA weights

It is important to note that not a complete new Multi-criteria analysis is performed, solely the influence of minor changes to the weights are evaluated.
From Table 7.1 it is noticed that design option 1 scores slightly better in criteria 1 and criteria 2 compared to design option 4. Therefore these criteria are of interest for the sensitivity analysis. In this analysis the importance of each main criteria compared to criteria 1 and 2 is changed in favor of these two criteria. Results of this adjustment are given in the following tables. A new comparison between criteria 2 and 4 is not performed as criteria 2 is already ranked more important as 4.
As presented below, even with the adjustments in importance of criteria, design 1 never receives a higher score compared to design 4. Of course, if all the changes are applied together it will influence the results of the MCA, however this would mean creating a complete new MCA. As the original MCA was performed with care, based on previously determined criteria, it is assumed to be performed correctly and therefore no completely new MCA is performed. However, it is noted that the scores are still very close together, therefore it is further discussed in the recommendations.

Table B.7: MCA results when criteria 1 is ranked more important than criteria 3

Sub-criteria	Weight	Option 1		Option 2		Option 3		Option 4	
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
[1a]	0.056	5	0.278	4	0.222	2	0.111	4	0.222
[1b]	0.056	5	0.278	2	0.111	2	0.111	4	0.222
[1c]	0.056	1	0.056	1	0.056	1	0.056	1	0.056
[2a]	0.100	1	0.100	1	0.100	1	0.100	1	0.100
[2b]	0.100	5	0.500	4	0.400	2	0.200	4	0.400
[2c]	0.067	5	0.333	4	0.267	3	0.200	4	0.267
[3a]	0.067	1	0.067	1	0.067	1	0.067	1	0.067
[3b]	0.067	5	0.333	4	0.267	3	0.200	4	0.267
[3c]	0.067	3	0.200	4	0.267	5	0.333	5	0.333
[4a]	0.067	4	0.267	4	0.267	5	0.333	5	0.333
[4b]	0.033	3	0.100	3	0.100	5	0.167	5	0.167
[5a]	0.067	5	0.333	4	0.267	3	0.200	4	0.267
[5b]	0.100	5	0.500	2	0.200	5	0.500	5	0.500
[5c]	0.100	3	0.300	3	0.300	3	0.300	5	0.500
Total Score			**3.644**		**2.889**		**2.878**		**3.700**

Table B.8: MCA results when criteria 1 is ranked more important than criteria 4

Sub-criteria	Weight	Option 1		Option 2		Option 3		Option 4	
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
[1a]	0.044	5	0.222	4	0.178	2	0.089	4	0.178
[1b]	0.044	5	0.222	2	0.089	2	0.089	4	0.178
[1c]	0.044	1	0.044	1	0.044	1	0.044	1	0.044
[2a]	0.100	1	0.100	1	0.100	1	0.100	1	0.100
[2b]	0.100	5	0.500	4	0.400	2	0.200	4	0.400
[2c]	0.067	5	0.333	4	0.267	3	0.200	4	0.267
[3a]	0.089	1	0.089	1	0.089	1	0.089	1	0.089
[3b]	0.089	5	0.444	4	0.356	3	0.267	4	0.356
[3c]	0.089	3	0.267	4	0.356	5	0.444	5	0.444
[4a]	0.044	4	0.178	4	0.178	5	0.222	5	0.222
[4b]	0.022	3	0.067	3	0.067	5	0.111	5	0.111
[5a]	0.067	5	0.333	4	0.267	3	0.200	4	0.267
[5b]	0.100	5	0.500	2	0.200	5	0.500	5	0.500
[5c]	0.100	3	0.300	3	0.300	3	0.300	5	0.500
Total Score			**3.600**		**2.889**		**2.856**		**3.656**

Table B.9: MCA results when criteria 1 is ranked more important than criteria 5

Sub-criteria	Weight	Option 1		Option 2		Option 3		Option 4	
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
[1a]	0.056	5	0.278	4	0.222	2	0.111	4	0.222
[1b]	0.056	5	0.278	2	0.111	2	0.111	4	0.222
[1c]	0.056	1	0.056	1	0.056	1	0.056	1	0.056
[2a]	0.100	1	0.100	1	0.100	1	0.100	1	0.100
[2b]	0.100	5	0.500	4	0.400	2	0.200	4	0.400
[2c]	0.067	5	0.333	4	0.267	3	0.200	4	0.267
[3a]	0.089	1	0.089	1	0.089	1	0.089	1	0.089
[3b]	0.089	5	0.444	4	0.356	3	0.267	4	0.356
[3c]	0.089	3	0.267	4	0.356	5	0.444	5	0.444
[4a]	0.067	4	0.267	4	0.267	5	0.333	5	0.333
[4b]	0.033	3	0.100	3	0.100	5	0.167	5	0.167
[5a]	0.050	5	0.250	4	0.200	3	0.150	4	0.200
[5b]	0.075	5	0.375	2	0.150	5	0.375	5	0.375
[5c]	0.075	3	0.225	3	0.225	3	0.225	5	0.375
Total Score			**3.561**		**2.897**		**2.828**		**3.606**

Table B.10: MCA results when criteria 2 is ranked more important than criteria 3

Sub-criteria	Weight	Option 1		Option 2		Option 3		Option 4	
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
[1a]	0.033	5	0.167	4	0.133	2	0.067	4	0.133
[1b]	0.033	5	0.167	2	0.067	2	0.067	4	0.133
[1c]	0.033	1	0.033	1	0.033	1	0.033	1	0.033
[2a]	0.113	1	0.113	1	0.113	1	0.113	1	0.113
[2b]	0.113	5	0.563	4	0.450	2	0.225	4	0.450
[2c]	0.075	5	0.375	4	0.300	3	0.225	4	0.300
[3a]	0.078	1	0.078	1	0.078	1	0.078	1	0.078
[3b]	0.078	5	0.389	4	0.311	3	0.233	4	0.311
[3c]	0.078	3	0.233	4	0.311	5	0.389	5	0.389
[4a]	0.067	4	0.267	4	0.267	5	0.333	5	0.333
[4b]	0.033	3	0.100	3	0.100	5	0.167	5	0.167
[5a]	0.067	5	0.333	4	0.267	3	0.200	4	0.267
[5b]	0.100	5	0.500	2	0.200	5	0.500	5	0.500
[5c]	0.100	3	0.300	3	0.300	3	0.300	5	0.500
Total Score			**3.617**		**2.929**		**2.929**		**3.707**

Table B.11: MCA results when criteria 2 is ranked more important than criteria 5

Sub-criteria	**Weight**	**Option 1**		**Option 2**		**Option 3**		**Option 4**	
		Score	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
[1a]	0.033	5	0.167	4	0.133	2	0.067	4	0.133
[1b]	0.033	5	0.167	2	0.067	2	0.067	4	0.133
[1c]	0.033	1	0.033	1	0.033	1	0.033	1	0.033
[2a]	0.113	1	0.113	1	0.113	1	0.113	1	0.113
[2b]	0.113	5	0.563	4	0.450	2	0.225	4	0.450
[2c]	0.075	5	0.375	4	0.300	3	0.225	4	0.300
[3a]	0.089	1	0.089	1	0.089	1	0.089	1	0.089
[3b]	0.089	5	0.444	4	0.356	3	0.267	4	0.356
[3c]	0.089	3	0.267	4	0.356	5	0.444	5	0.444
[4a]	0.067	4	0.267	4	0.267	5	0.333	5	0.333
[4b]	0.033	3	0.100	3	0.100	5	0.167	5	0.167
[5a]	0.058	5	0.292	4	0.233	3	0.175	4	0.233
[5b]	0.088	5	0.438	2	0.175	5	0.438	5	0.438
[5c]	0.088	3	0.263	3	0.263	3	0.263	5	0.438
Total Score			**3.575**		**2.933**		**2.904**		**3.660**

C
Appendix: Young's modulus

Table C.1: Young's modulus values of series 001

Series 001	Load 1	load 2	load 3	load 4
σ_1 [Mpa]	0,328725	0,199083	0,0939167	0,127477
σ_2[Mpa]	2,38535	2,46797	2,41997	2,43689
ϵ_1 [m/m]	2E-05	2,87687E-05	2,20688E-05	2,66375E-05
ϵ_2 [m/m]	0,000188	0,000199981	0,00019945	0,000201413
E [Mpa]	12211,83	13251,87705	13113,29862	13213,63467
max F [kN]				27,6071
Avg E [Mpa]				**12947,66035**

Table C.2: Young's modulus values of series 002

Series 002	Load 1	load 2	load 3	load 4
σ_1 [Mpa]	0,187552	0,115107	0,10031	0,121127
σ_2 [Mpa]	2,33489	2,48625	2,50987	2,43945
ϵ_1 [m/m]	1,0257E-05	2,07053E-05	2,23422E-05	2,50749E-05
ϵ_2 [m/m]	0,000169784	0,00018582	0,000189901	0,000186721
E [Mpa]	13460,62234	14360,57433	14380,38092	14341,98455
Max F [kN]				32,3623
Avg E [Mpa]				**14135,89054**

Table C.3: Young's modulus values of series 003

Series 003	Load 1	load 2	load 3	load 4
σ_1 [Mpa]	0,394193	0,0721143	0,108386	0,0988832
σ_2 [Mpa]	2,27206	2,41851	2,45062	2,4046
ϵ_1 [m/m]	2,24E-05	1,59601E-05	2,04776E-05	1,96526E-05
ϵ_2 [m/m]	0,000155	0,000167412	0,000169884	0,000167525
E [Mpa]	14162,97	15492,65106	15676,96563	15592,57929
Max F [kN]				35,5844
Avg E [Mpa]				**15231,29158**

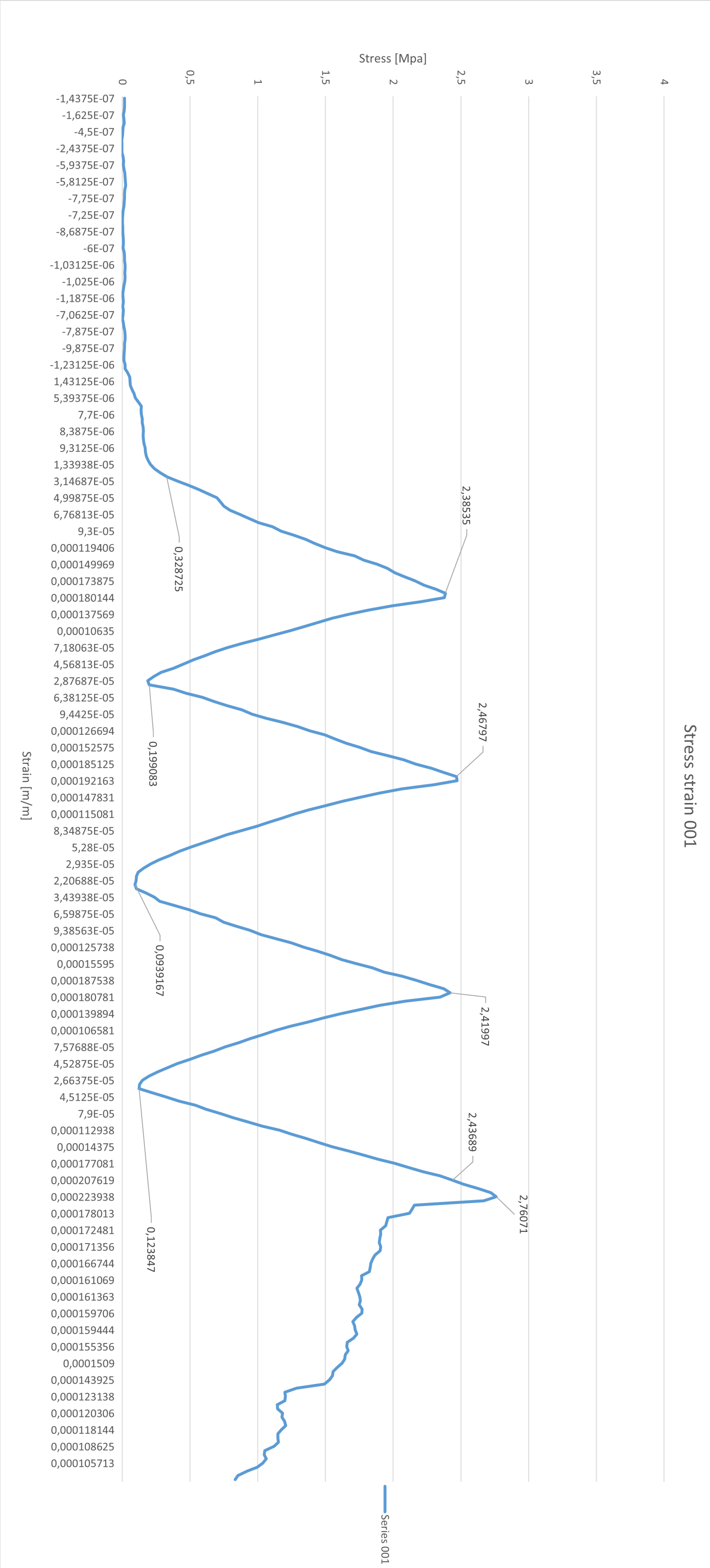


Figure C.1: Stress-strain diagram of series 001

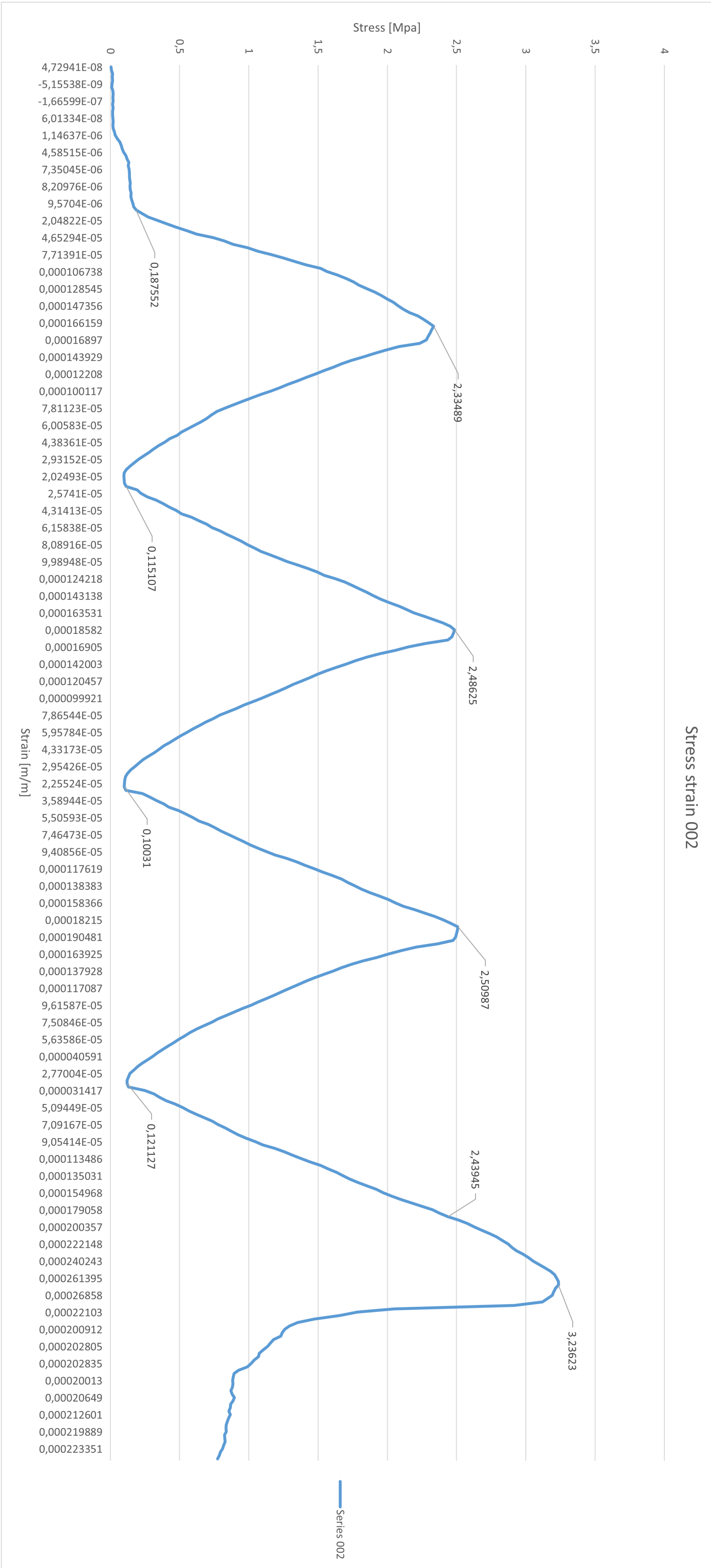


Figure C.2: Stress-strain diagram of series 002

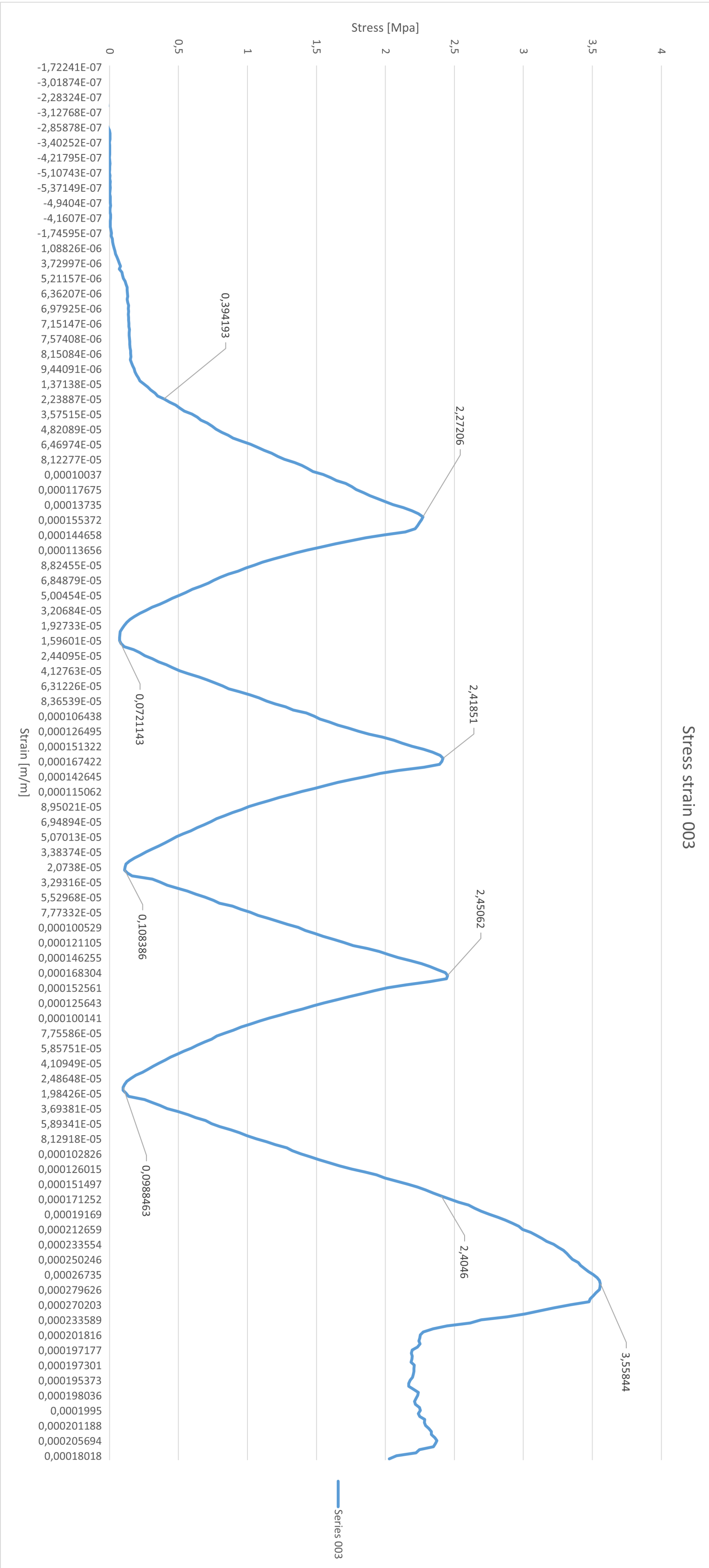


Figure C.3: Stress-strain diagram of series 003

D

Appendix: Finite Element Method

D.1. First analysis Bi-layer design

D.1.1. Connection

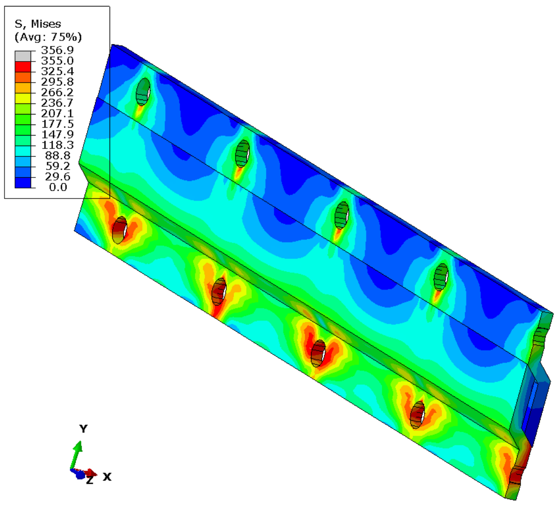


Figure D.1: Front view of connection cut at a bolt hole for first analysis, with stresses given in MPa

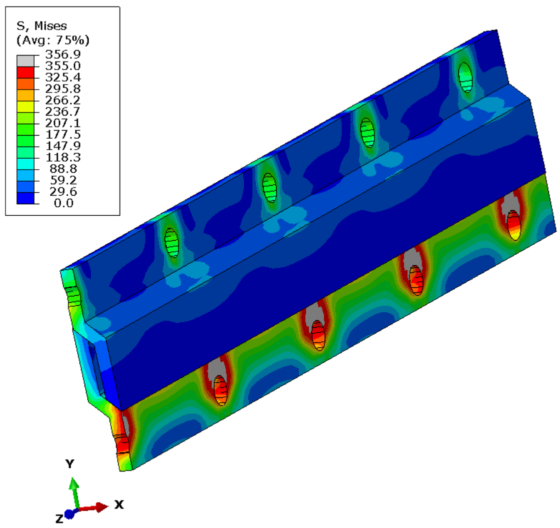


Figure D.2: Back view of connection cut at a bolt hole for first analysis, with stresses given in MPa

Figures D.1 and D.2 present the same connection as shown in Figure 9.5, but with a cut made at the location of the bolt holes, to show the inner stresses of the material.

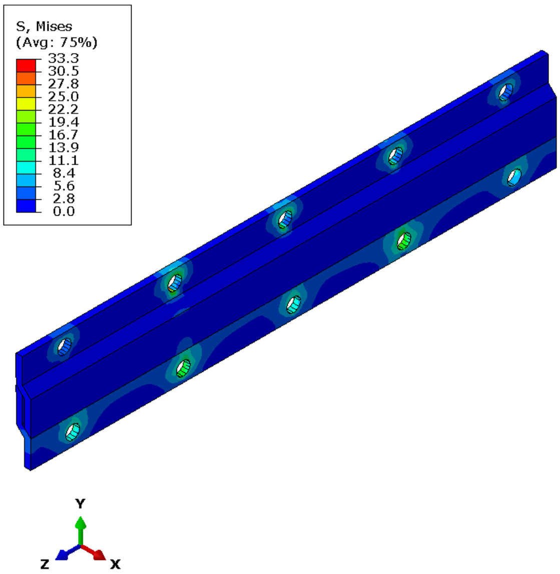


Figure D.3: Connection stresses [MPa] first analysis at lowest force of F = 4.43 kN

D.1.2. Façade

Relevant for concrete are the present tensile and compressive stresses. FiguresD.4 - D.9 present the front and back view of these stresses in the façade element.

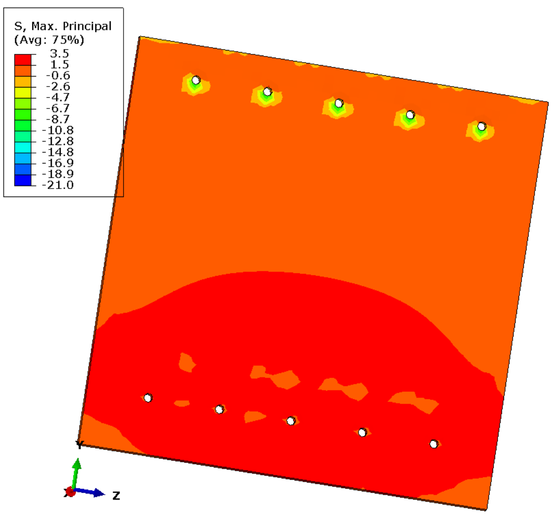


Figure D.4: Tensile stresses front side façade at the end of the first analysis, with stresses given in MPa

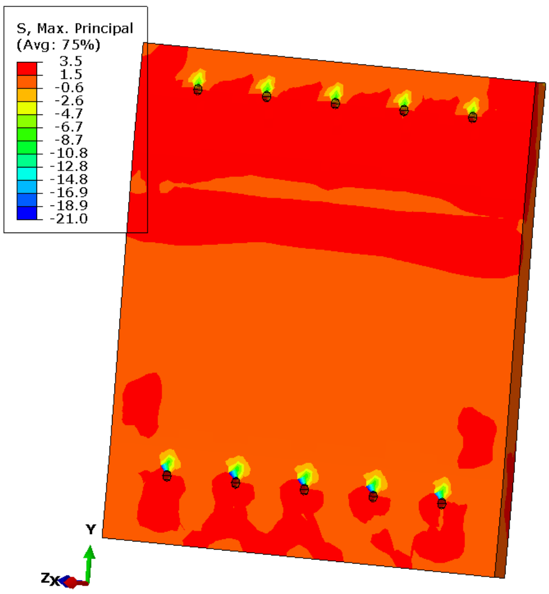


Figure D.5: Tensile stresses back side façade at the end of the first analysis, with stresses given in MPa

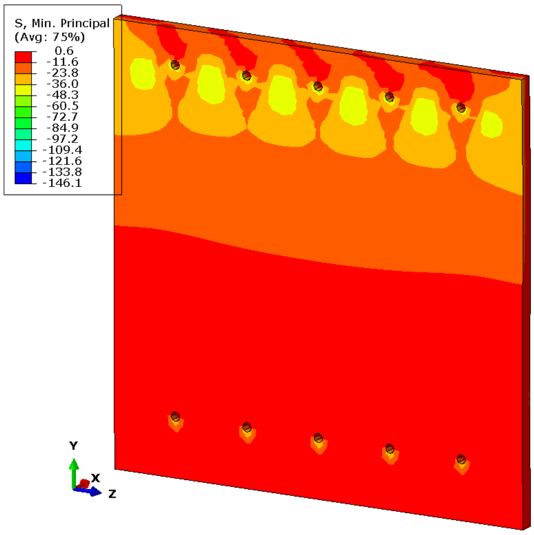


Figure D.6: Compressive stresses front side façade at the end of the first analysis, with stresses given in MPa

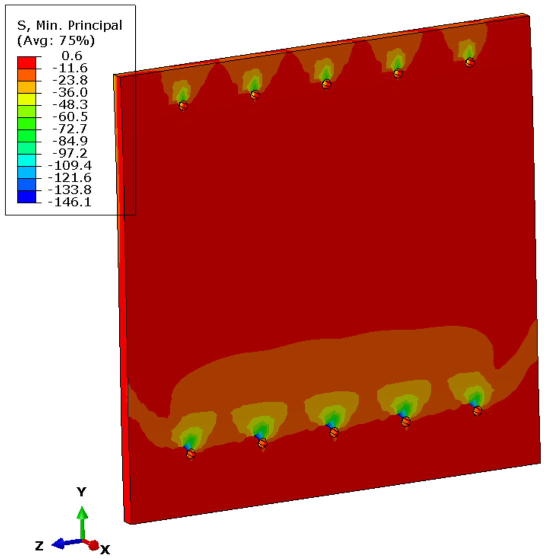


Figure D.7: Compressive stresses back side façade at the end of the first analysis, with stresses given in MPa

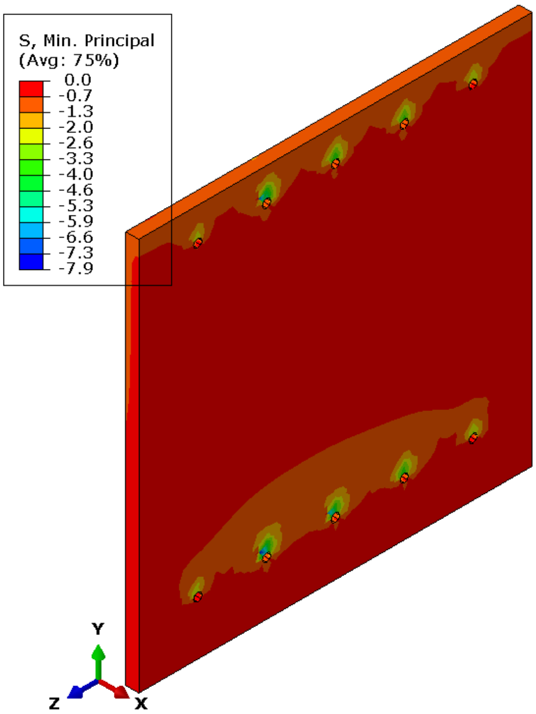


Figure D.8: Structural layer c25/30 compressive stresses [MPa] first analysis at lowest force of F = 4.43 kN

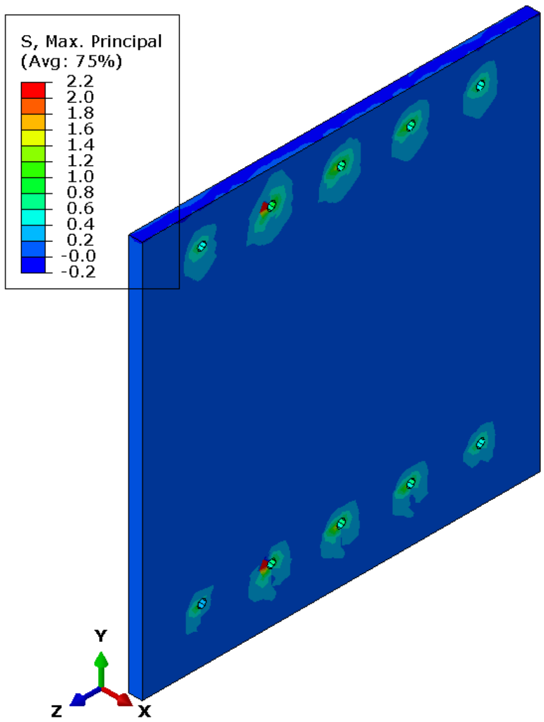


Figure D.9: Structural layer c25/30 tensile stresses [MPa] first analysis at lowest force of F =4.43 kN

D.2. Optimized analysis Bi-layer design

D.2.1. Connection

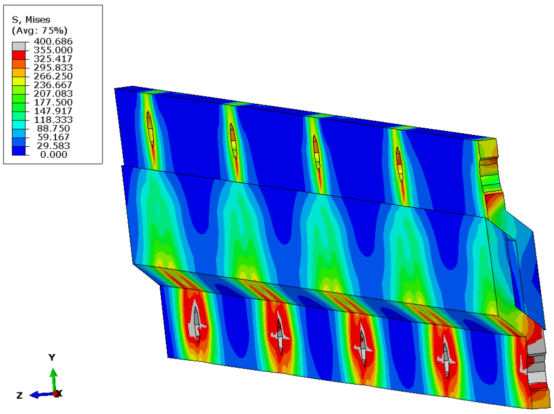


Figure D.10: Front view of connection cut at a bolt hole for optimized analysis, with stresses given in MPa

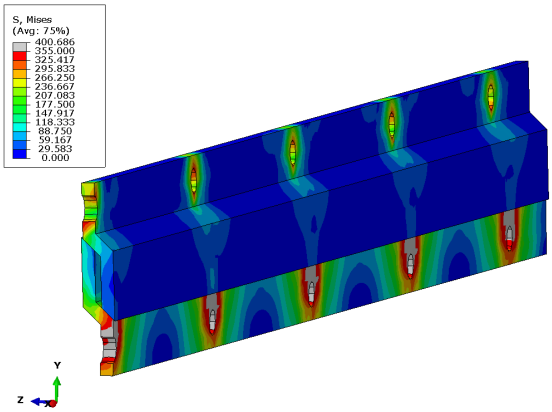


Figure D.11: Back view of connection cut at a bolt hole for optimized analysis, with stresses given in MPa

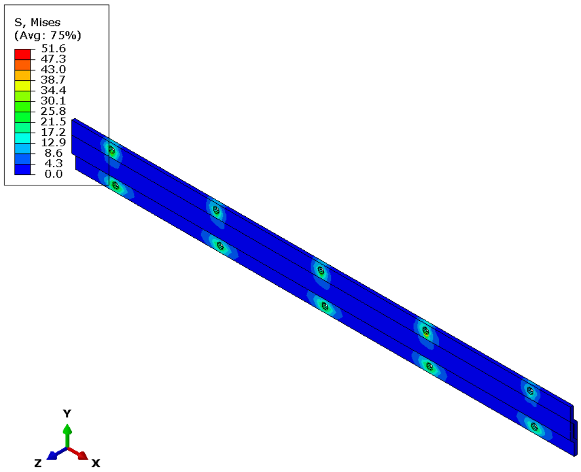


Figure D.12: Connection stresses [MPa] optimized analysis at lowest force of F = 2.28 kN

D.2.2. Façade

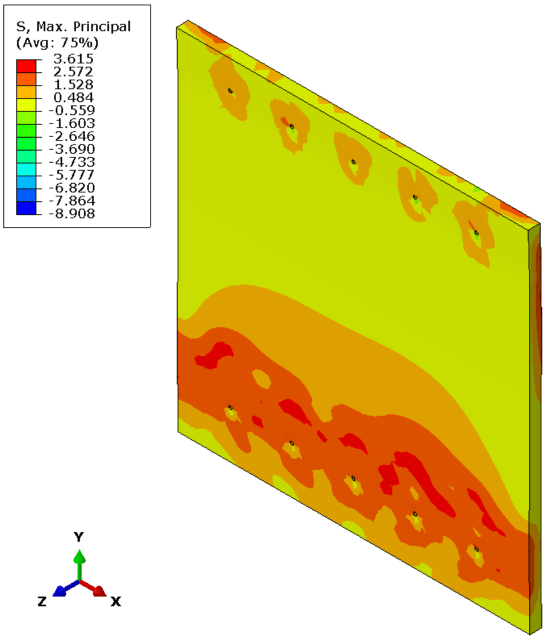


Figure D.13: Tensile stresses front side façade at the end of optimized analysis, with stresses given in MPa

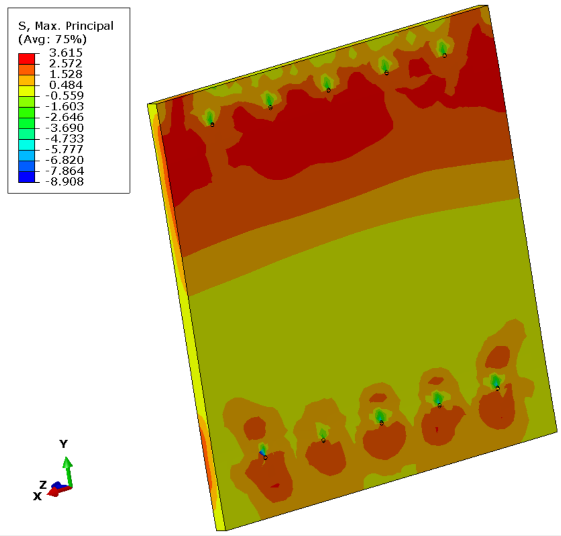


Figure D.14: Tensile stresses back side façade at the end of optimized analysis, with stresses given in MPa

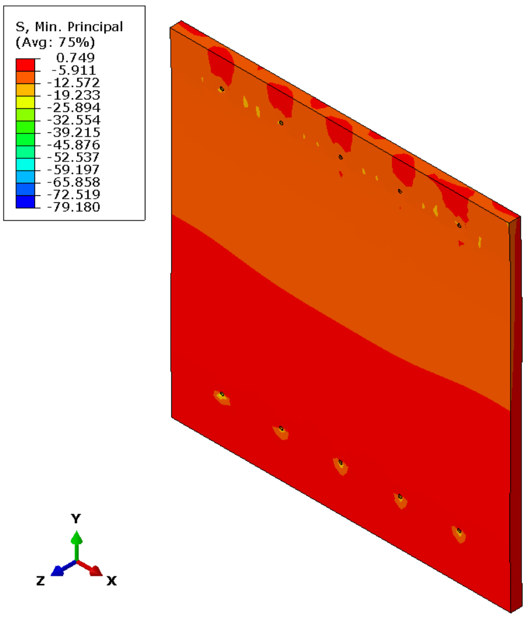


Figure D.15: Compressive stresses front side façade at the end of optimized analysis, with stresses given in MPa

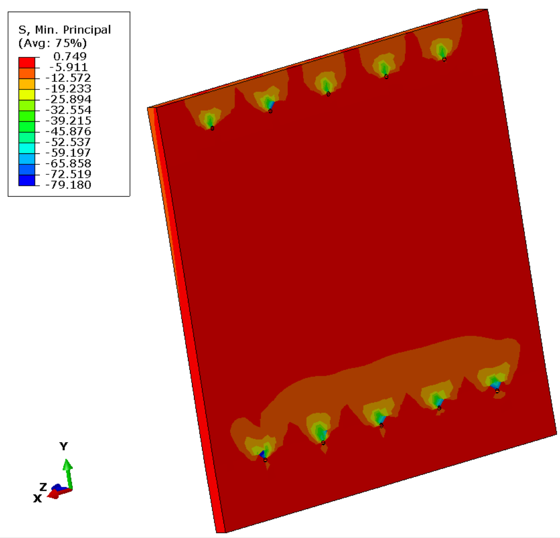


Figure D.16: Compressive stresses back side façade at the end of optimized analysis, with stresses given in MPa

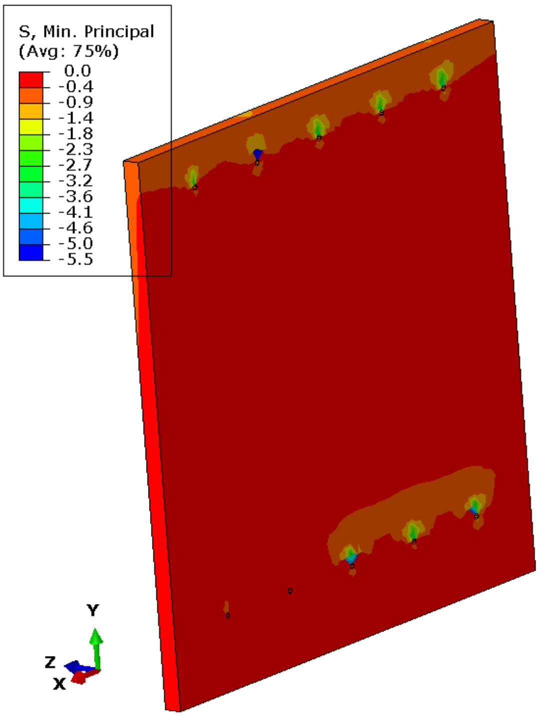


Figure D.17: Structural layer c25/30 compressive stresses [MPa] optimized analysis at lowest force of F = 2.28 kN

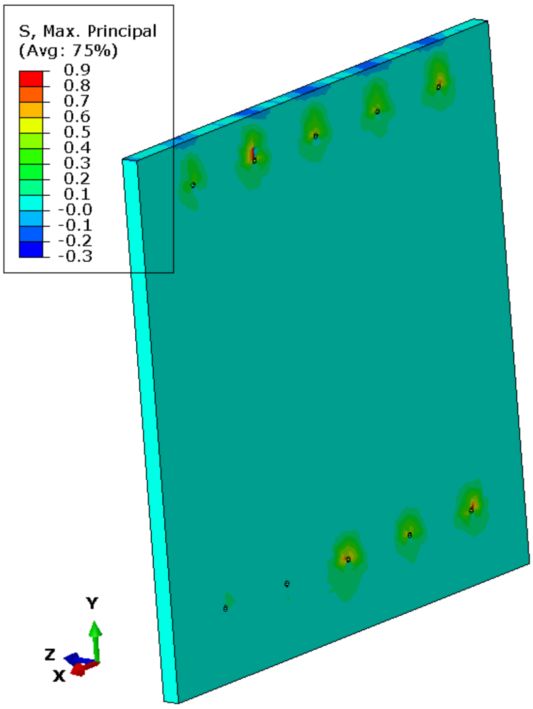


Figure D.18: Structural layer c25/30 tensile stresses [MPa] optimized analysis at lowest force of F =2.28 kN

D.3. Analysis single porous layer design

D.3.1. Façade

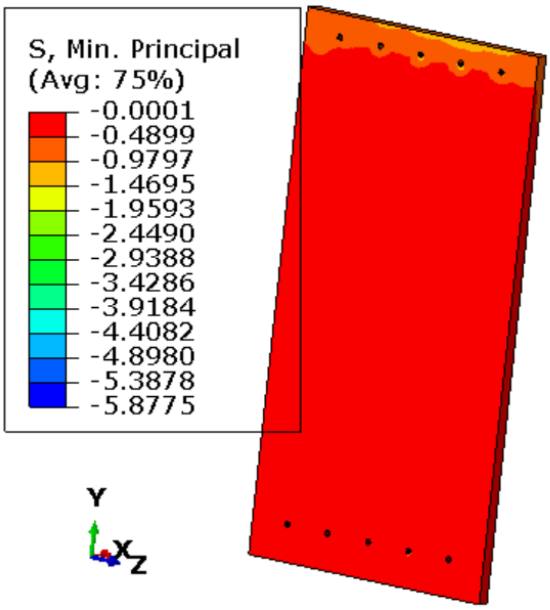


Figure D.19: Porous layer compressive stresses [MPa] analysis at lowest force of F = 1.17 kN

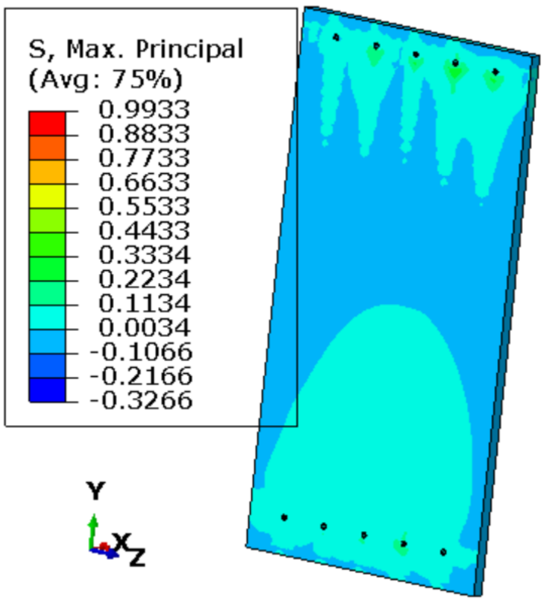


Figure D.20: Porous layer tension stresses [MPa] analysis at lowest force of F = 1.17 kN

D.4. Deflections due to self-weight

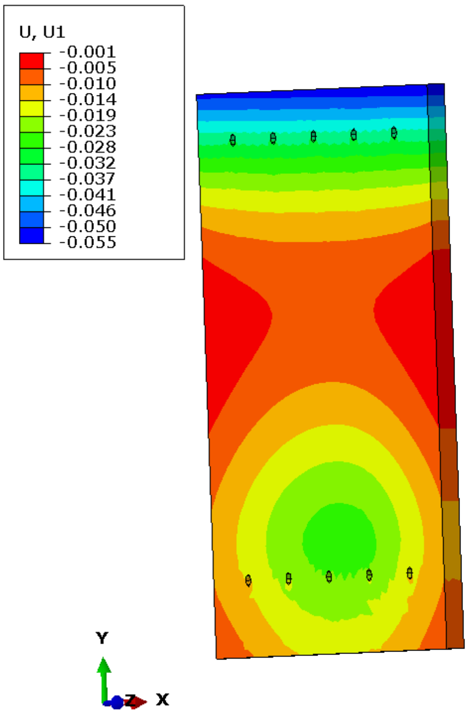


Figure D.21: Deflection façade in first analysis due to a self-weight load of F = 4.43 kN

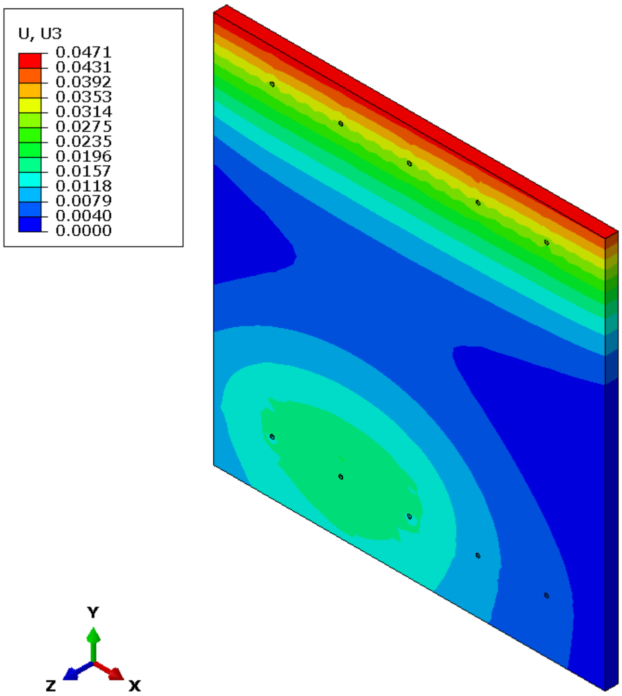


Figure D.22: Deflection façade in optimized analysis due to a self-weight load of F = 2.28 kN

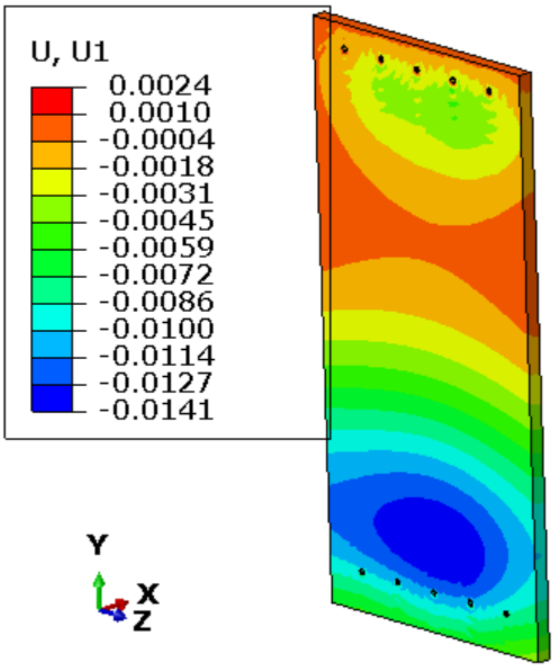


Figure D.23: Displacement of single layered porous design at lowest force of F=1.17 kN

E

Design review by Holcim

How does Holcim view the proposed design? Does it see a future for such a demountable connection in combination with the porous concrete green façade?
The proposed design is not optimal and requires refinement. While it holds potential, further adjustments are necessary to improve its functionality and performance. The demountable connection in combination with the porous concrete green façade could have a future, but it needs to be more carefully developed to achieve the desired balance between practicality and structural integrity.

Do the results of this research provide helpful insights for further implementation of such systems?
The results provide some useful insights for the further implementation of these systems, but they lack creativity. While several important points have been identified, more innovative approaches could enhance the overall design. Some aspects offer a good foundation for future development, but further exploration of more creative solutions is recommended.

As a system consisting of a single porous layer is new for this application, does Holcim think such an implementation adds extra value to the system?
The implementation of a single porous layer introduces several risks, primarily due to its thin thickness. The reduced structural integrity and potential vulnerability to environmental factors make it challenging to guarantee the long-term performance of such a system. While it may offer some value, the risks associated with the thin layer should be carefully evaluated, and additional reinforcements or considerations may be necessary to mitigate these concerns.

Does Holcim think the proposed single and bi-layered designs are producible in its factory?
Both the single and bi-layered designs are technically producible in our factory; however, there is room for optimization in terms of shape and production efficiency. Refining the design to ensure it is both manufacturable and cost-effective would be beneficial for production scalability.

Does Holcim believe the proposed connection is a suitable solution or does it foresee problems with the connection and assume better solutions are available? The proposed connection solution leaves limited room for movement during installation, which could lead to difficulties in ensuring precise alignment and adjustments during the assembly process. It may not be the ideal connection method, and alternative solutions that offer more flexibility and easier installation should be developed.

Does the conclusion of the research fulfill the wishes of Holcim?
The conclusion of the research partially meets Holcim's expectations. Many variants are considered for the connection in the research which is good. The design can be optimized for manufacturability and adjustability during installation, but the current state of the design is quite straight forward and easy to install. Most conclusions are not definitive, as most conclusions end as recommendations, indicating that further investigation and refinement are required.

F Appendix: Production connection

The proposed steel connection is produced out of 3 mm thick steel sheets. Which is bended using a press brake machine. According to literature the dimensions and angles used for the connection are within the limits of such machines, it is a producible design. Limits for steel sheet thickness are within 0.75 mm and 12 mm. As angles used in the design are at 135 degrees, they are within the limits of the machines, since only very sharp angles cause collisions with the machinery. From literature it is unclear if the angles being close to each other potentially cause problems, however in the case that it does, another option is a 3D metal press which has smaller tolerances and higher precision. [47], [48], [49].

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